Measurement Technique in Multiphase Flows
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Lecture - 11
Gamma ray and X-Ray Tomography

Welcome back last class what we were discussing is about the volume fraction measurement technique and we have covered the invasive techniques; in which we have discuss about the capacitance probe and optical fibre probe. Then we have started with the non invasive technique and we have discussed about the ECT; Electrical Capacitance Tomography and it is approximately TRT and EIT which is electrical resistance tomography and in electrical impedance tomography; which are very close to whatever the ECT way we have discussed; so we have discussed that. And then we have moved to the radiation base technique and we started with the gamma ray tomography or gamma ray densitometry.

So, what we have discussed in the gamma radius densitometry or gamma ray tomography is that we use a source and we use the detectors. Now the source and detector in this case is outside of the column or may in case of radioactive particle tracking; what we were doing, we are putting the source inside the column and we are tracking the phase of interest. Now this gamma ray tomography work on the transmission principle; transmission principle means both the source and detector will be outside. The column of interest will be aligned in between this aligned source and detectors.

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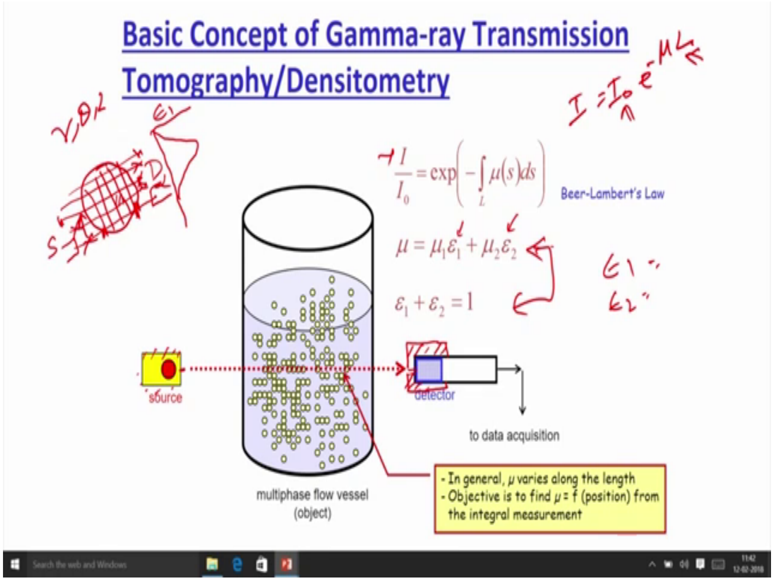

So, what will do? We will take a source which is radioactive source; we will put it a column meter which will be kind of a small hole say here and this whole yellow box you can say consider it as a lead box; where you put a small particle. Now the lead box we use because lead have the maximum attenuation coefficient; so, it attenuate the gamma rays.

And the gamma rays which is coming out from a small hole actually passed through the this system of interest. And we use a detector which is similar to the detector, we have discussed in the radioactive particle tracking technique which is scintillation detectors and at job the gamma rays emitted by the source. And proportional to the adsorption of the intensity it emits a current; it generate the current which is recorded with the kind of amount of the gamma rays fall on the detector. And what we do? We collimate the detector too; so, we do the collimation of the detector, we put a lead sealed here in such a way; so, this is also a lead sealed.

And only a small hole is there through which the rays can be passed. Now the source and detectors are perfectly aligned on the moving carriage and that carriage has a capability to move with all our theta and z direction; if you are talking about the tomography experiments. And if you are talking about testamentary experiment which is actually first generation tomography, where you get the line average instead of the pixel wise information as we have already discussed; carriage will move in our direction or you can say the x direction and z direction.

So, that will be having the capacity; so, suppose if this is the column of interest which is being placed here; in case of densitometry; the source and detector say this is source, this is detector which is collimated will move along this direction. So, it will cover all the location in this side with the time and it will have a movement in the vertical direction. So, both the lateral and vertical; both direction movement will be there and it will scan your whole column in case of densitometry, where you will get the line average volume fraction. In case of tomography, the carries should have a capability to moves in r theta and z.

So, what will happen this will be your one projection and then you will keep on moving it. So, you will move it in the r direction you will also move in the theta direction and you will move in the z direction. So, a spiral kind of a motion will be generated and you will able to scan the whole column and you will get the pixel wise information inside. So, instead of line average you will get the pixel wise information and you will find that volume fraction within each cell how it is varying with the location.

So, that is about the gamma ray; densitometry or gamma ray tomography which is worked on the transmission principle. So, what we do? We first actually we use be Beer Lambert's law to find the volume fraction inside and for doing that, using the Beer Lambert's law which is nothing, but I equal to I naught into exponential raised to the power minus mu L..

So, I equal to I naught into exponential raised to power minus mu L where L is the distance between the source and detector, but in this case as the source and detector are placed in atmosphere which is generally air. And air has a negligible attenuation coefficient, we assume that whatever that innovation is taking place is within the system itself. So, we scan the empty column first to get the; I naught value which also corresponds to the attenuation because of the wall.

Then we work, we scan the system under the intensive operating condition it means under the operating condition and we get the; I value and if you solve this Beer Lambert's equation, you get the mu value. And now this mu whatever you are getting is the line integral value, it means it is a function of this line whatever the attenuation coefficient is taking place within the line and from there you can calculate the line average volume fraction data.

So, how it is can be calculated? As we discussed that this is line average data and this mu can be correlated on the line average mu can be correlated as mu 1 epsilon 1 plus mu 2 epsilon 2; where mu 1 is your volume mass attenuation coefficient of the pure species of for the phase one; say if the phase 1 and phase 2 is present; mu 1 is the mass attenuation coefficient for phase 1, mu 2 is mass attenuation coefficient for phase 2; once they are in pure form, they are not mixed together and epsilon 1 and epsilon 2 is the line average volume fraction of the phase 1 and phase 2 respectively.

So, what do we do? We get this equation and we know that in two phase flow; the summation of this phases, volume fraction value will be equal to 1 because that will be the total volume of the reactor inside. So, that is epsilon 1 plus epsilon 2 will be equal to 1.

So, now you have a two equation and you have two variable epsilon 1 and epsilon 2 and you can get the epsilon 1 value and epsilon 2 value. Now this value whatever you will solve will be for line average volume fraction values because you are solving for one chordal average; one line average and that is the region that we do it in the integral form.

Now, if I want to find that radial variation then what I can do? The chordal average variation I can find; I can first scan at this location say and then I can move the detector to this location; again I will get the value of epsilon 1 and epsilon 2 for this location. Then I can move the source and detector to this location, I will get some value here.

Similarly, I will keep on scanning and everywhere I will get the volume fraction value. So, says volume fraction is coming something like this I will get that gas liquid system, this is my radial position and this is my volume fraction say epsilon 1. Similarly I will get the profile for epsilon 2 and this profile will be line average profile.

So, that is what the way the densitometry we do; we find the line average values. Now once we do the tomography experiments what we need; we need actually the pixel information. Now to do that we need modify some way, we will have to put more detectors and the post processing need to be modified, need to be kind of changed. Now this post processing for this densitometry is very simple, very straightforward and that is why for most of the system maybe the densitometry data itself is sufficient till you do not want a very rigorous analysis; densitometry material itself is very sufficient to analyze the system, how to get the firsthand idea. And it is very simple you just need a source, you just need a detector there is no typical post processing involved; you can just solve it.

So, that is in excel sheet or with a calculator you can easily solve all this problem. And that is why the densitometry is a very popular technique for the industry also to get a first hand idea about the system.

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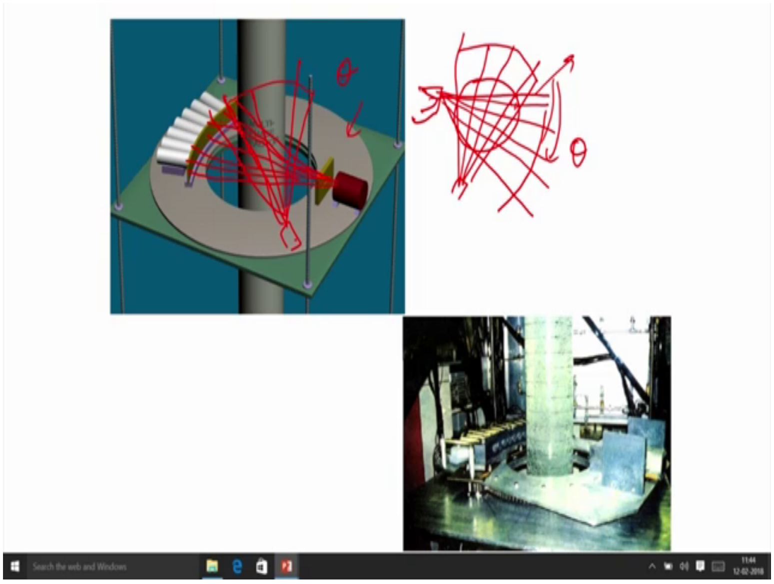

So, what we do actually; in tomography what you need to do? We need to actually scan the whole column, I need now pixel wise information. So, in this densitometry what we do? We use one detector, one source; while in tomography this is divided in two part one is called parallel beam and one is fan beam.

So, what we do in the parallel beam; you need several source and several detector we will discuss about that, but most commonly fan beam is being used in which; so you use one detector and the collimator is not now a point source, you can see this is a small area a curvature which is being used and that curvature actually generate a fan beam; this kind of a beam is being generated. Now what happened with this beam? You put the several detectors like here whatever you can see here detector; each detector will see one line; each detective can see one this red line.

Now, what you do there is a moving carriage if you see this carriers; this table can move in r and theta direction is you can say this mostly theta motion. So, what will happen this carriage will move it; in this way. So, you will able to scan with the r; so the theta; different theta. So, for this theta suppose then you can move the source here and detector somewhere will be aligned here and again you will get this kind of symbol; this scan.

So, what you will do? You will scan with the theta, you will move this carriage in theta direction. So, your theta direction is scanning is possible; r direction scanning is already been done through the fan beam, theta directional scanning will be done. So, what you will get? You will get a matrix; so in this way if I see this, if I put a source, if I put detectors here I will see the first scan it in this way; then this whole system will move at angle theta, this source will move here, detector will say move here, source will move here and again we will see the scan.

So, similarly you will do it for different theta and what you will happen; you will get the line average for each this line, each detector and that line average information can be reconstructed back to the pixel information. Why? Because you have now so many equations, so you can break that equation into the small nodal solution and that average can be said that that is the solution for this each pixel.

So, that is the way it is being operated and we will discuss about this that how the fan beam and cone beam work or kind of a fan beam, parallel beam and cone beam work we will discuss about this more.

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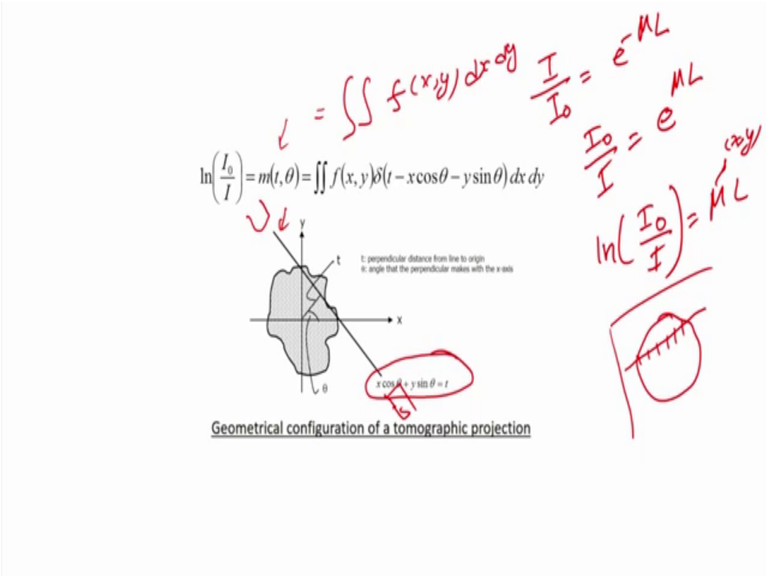

So, what is happening mathematically? Mathematically what you are doing? You are actually using the Fourier transform and what we are going to do is, we are just saying that how to find? How to reconstruct it? So, we know that I equal to I naught e to the power minus mu L that we can write it in terms of I by I naught; we can take a L n say we know the equation I upon I naught is e raised to the power minus mu L or you can say that I naught upon I is e raised to the power mu L.

If I take a L n of this. So, this will be I naught upon I it will be equal to mu L where mu is a function of x and y. Now I want a pixel wise information, so mu will be the function of x and y. So, mu will change at each location inside; it will be the function of x and y; if I write it into the Cartesian coordinate or r and theta; if I write it into the polar co-ordinate. So, what we need to do? We need to find that how this value will change. So, what we do? We actually take a projection and I will discuss it again, now that projection can be written as a straight line equation.

So, suppose this is a projection; this is a projection measurement which we are doing. So, detector and source is their aligned, suppose this is one source; one detect source and one detective and this is the projection whatever you are receiving here. And if suppose from the origin; the distance of this projection is t and it is being taken at an angle theta, which is the angle beyond the source to this perpendicular distance of this; so, that is the theta. So, what we can do? We can light this projection; each projection will represent a straight line equation because we have collimated the source, we have collimated the detector. It means only the gamma ray which is coming through directly from the source to the detector we are measuring. So, I can write it as a straight line equation and that will be x cos theta plus y sin theta will be equal to t.

So, that will be the straight line equation we can write. Now what will happen, what will be the mu? mu will be the function of x and y. So, we can define that L n I by I naught as a function say m t theta and with t and theta this m attenuation whatever the projection line you are measuring, that will be the function of t; how much far it is from the centre? And then what angle it forms? So, that is t and theta and that will be actually the integral of; this will be the integral of mu and mu will be the function of x and y. So, I am writing it as in mu I am writing it as a function of say f into x y. So, I am instead of mu I am saying that; this m, this function will be a integral of f into x y.

Now because x and y is integral is available you have to do the double differential to solve this value; so this will be d x; d y. So, I can say that projection; this projection line P is; m; this projection is actually the integral of f x y, where f is a function which is representing the mass attenuation coefficient or attenuation coefficient and that is going to change with the x and y.

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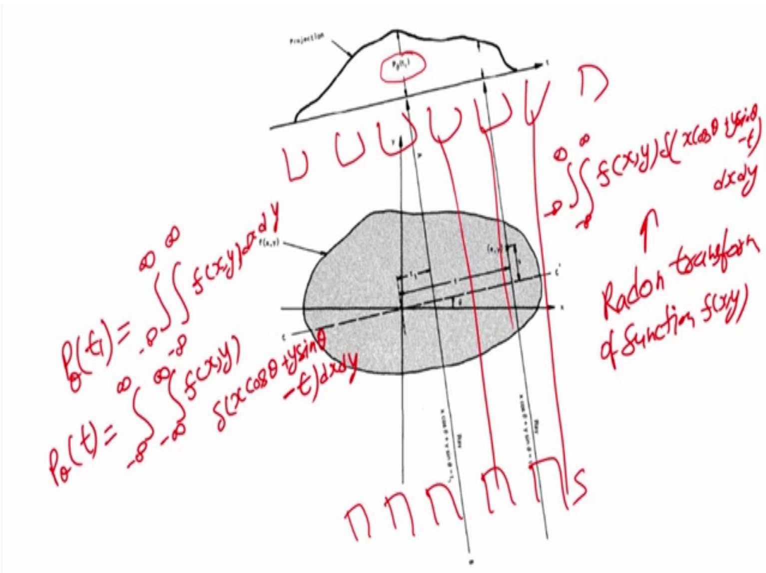

So, you can write it in this way; so, suppose this is the object you will scan it from a particular distance and for this particular distance you will be knowing that what will be the distance from the origin and you will get a projection data.

So, that will be the projection data we will get if we scan it everywhere either one by one or we are using say multiple source, multiple detector; so, I can put several source here, several detector and I am getting the projection. So, several source several detector and each where I am getting a projection. So, these are the source; these are the detective; so each line I am scanning and I am getting a equation. So, what I will get? I will get a projection.

Now, what will be the projection will be written as? If I want to write the projection which is at angle theta; at a distance t 1 it will be what? Your projection will be retained; P which will be the P theta t 1 will P double integral of f x y into d x d y. Now, this is you can say from minus infinity to plus infinity; now I am taking a just domain, It will be in a domain integral will be your domain; so, that will be the projection.

Now this projection can be written in terms of the line equation; if I take a delta function. So, if I take a delta function this whole P I can write it P theta t as a minus infinity to infinity minus infinity to infinity f x y and I am just introducing a del function and that del function is this is multiplication of del; x cos theta plus y sin theta minus t and this will be d x; d y. So, you can say that whole P is double integral of minus infinity to infinity; minus infinity to infinity f x y which is the function and I am using a del function which is x cos theta plus y sin theta minus t and this is integral with d x d y.

So, I will get the projection domain that what would be the projection value for this straight line and that is going to be the function of x and y. Now this is the projection and similarly I will get the projection for all the locations once we will do it. So, in that projection we can calculate in terms of the volume fraction; we can calculate that how the mu is changing with the x and y. And then by solving that equation mu is epsilon 1 plus epsilon 2 and then epsilon 1 plus epsilon 2 is equal to 1. So, if you do that you solve those equations together, you can find the distribution of the volume fraction inside. Now this is also called the Radon transform of function x y well f x y.

So, this is the radon transform of the function f x y and by using the radon transform what you get? You get the projection and now you are getting the projection along one line. What you want in tomography? This you want this projection to the pixel wise information still light now it is a line averaged information.

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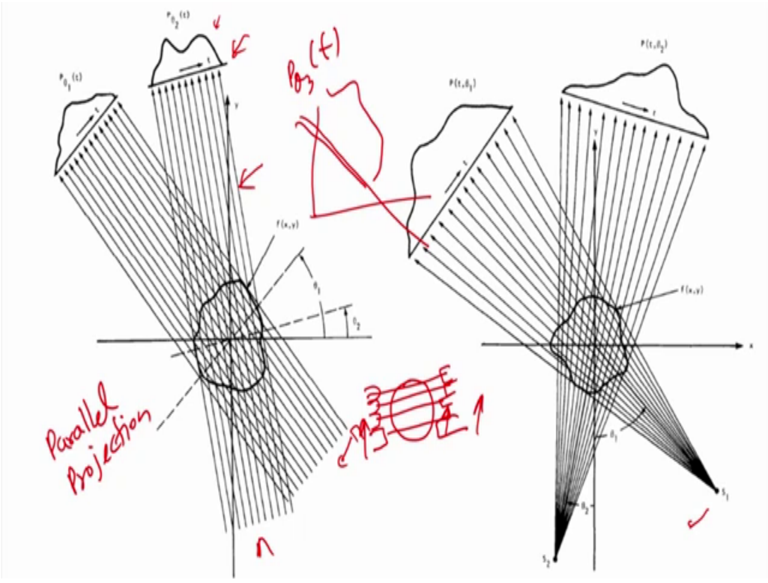

Now, if you want a pixel wise information what you can do? We can use two type of projection one is called parallel projection and we will discuss how the parallel projection look.

So, what we do in the parallel projection? Several such projection; so we were discussing about the equation of one line and that was what the radon transform which is function of x y into del function you introduced for that projection line equation, which will be del x cos theta plus y sin theta minus t, where t is the distance and theta is the angle from the centre to that vertical distance. So, that you can get the value for each line and several such line can be combined. So, you can have a several such projection to cover the entire zone; like this is the several such projection and we get the whole that with the r, how this value will change that is for a particular theta.

So, say we are getting this for P theta 1; this is the projection I have got; for one line we will get one line one point. Similarly if I scan the whole column I will get that how this theta is changing with the theta or with the r this location; with the radial this coordinate; how this projection is changing, then what we will do? We will change the angle; if I change the angle I will get another set of the parallel projection and you will see that for this location how the projection is changing and that will be P theta 2 t.

Again you change it you will get the another projection that will be say P 3 theta 3 t and that will be another set of same projection. Now you will have several such projection and that projection is what you are going to do each projection is going to give you one line averaged. So, you will get the line averaged value for each; now similarly we will solve several such equations what you will get? You will get that what is the pixel wise information.

And to do that what you need to do? You have to do the radon transform, you have to pull that radon transform, you have to do the FFT. Once we do this Fast Fourier transform of that radon transform function, what you will get? You will get a line equation, for each projection you will get a line; so each projection you will get a line equation. So, each line equation you will solve and that each line equation is the function of mu x y, and if you solve several such line equation; what you will get? You will get that what is the solution where each line is cutting.

So, you will get the complete solution in the pixel wise; then you do the inverse FFT and you get to the pixel wise information. So, that is the way we reconstruct in the gamma ray tomography and we get the pixel wise information. Now here what we have done? We have taken the parallel projection. So, several such set of information which is for the parallel rays, we have combined together and we have rotate it at the theta.

The only problem is who either you have to do this will take very huge time. If suppose you use only one source, one detector then what we need to do? You have to first generate this parallel projection; so, what you need to do? You have to move the source and detector along the column; so, it means in this direction. So, suppose this is source, this is detector you have to move both simultaneously along this direction so that you can get this. And then you have to change the theta; again you have to scan along the whole column. So, either that is the one way of doing it or you use many source and many detectives together; it means you can use several sources and severally detected together.

And then you use move this on a moving carriage; so it will be easier to do your number of experiments or the time of experiment will be reduced; drastically reduce. Suppose if you are acquiring for 1 minute at one location and if you are radially doing 10 locations; so 10 minutes for that and then you are keep on rotating it.

So, for each theta projection you will be required say 10 minutes. If I am using several sources for each theta projection I will require only 1 minute. So, that way the experimental time will be reduced; so just giving you the idea. Now to overcome this; what is the problem in the parallel beam and we will discuss again; that you will be required multiple sources, it means your overall radiation activity will increase; so you require more and more safety gadgets.

The safety requirement will be very very stringent and safety gadget requirement will also be higher. So, that is why different type of beam is being preferred which is called fan beam. So, what we do? We use one source as I said here and one several detectors as we discussed in the previous photograph also. So, what will happen and we make a fan beam, we make a curvature of this the collimator in such a way that you generate a fan of a particular angle and we keep the distance until in such a way that this fan angle covers the entire range of interest and for each rays day is a detector available which is acquiring that data.

So, what we do? We get this way and then we change it with the theta. So, again what the procedure remains same the post procedure remains same; you get a projection. Now you again move it at angle theta, you get another projection, you do the radon transform of for the each projection then you take the FFT. And if there is any filtering requirement is there any noise, you do it in the frequency domain. Then you solve this and then you do the inverse FFT to get the pixel wise information. So, that is the procedure is being used and we follow this method.

So for the parallel beam and cone beam to get the pixel wise information.

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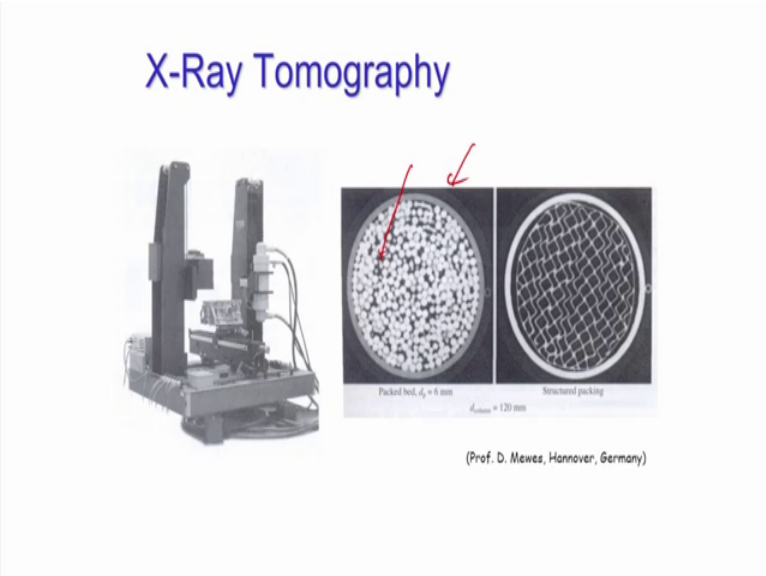

Now, this X-Ray tomography and gamma ray tomography as I mentioned earlier also in the last class, they are very same; the principle wise they are same. Only thing is that in gamma ray tomography, you use gamma ray source; in X-Ray tomography, you use X-Ray source. The X-Ray can also be generated by passing very high electrical current through a coil. So, that is the big advantage in X-Ray tomography that if you do not use the setup, you can switch on the electricity supply and there will be no generation of the X-Ray.

While in gamma ray the problem is that you whether you want to use or not, your gamma ray; the source will always emit a gamma ray because it is a natural gamma ray emitting source. So, you cannot restrict the emission of the gamma ray you can (Refer Time: 24:02) them by keeping that source in a very thick lead sealed or lead kind of a container, very thick lead container..

So, that is the advantage of the X-Ray; procedure remains same if you want you can use the X-Ray densitometry, where you can kind of scan it. You can have X-Ray tomography, where you can do the pixel wise information like one of the photographs I have shown here; that how it looks like, this is a packed bed and in this particle this means is constructed that how the particle are being placed and where are the wide fractions.

So, that is being done with the X-Ray tomography; now the major disadvantage of the X-Ray tomography everything remains same, advantages, your source, your radiation, you have a control on the radiation, if you want; you generate the radiation, if you do not want; you do not generate the radiation. But there is a issue and the issue is that the system is very bulky; like the photograph can show you and you might have seen in X-Ray device.

So, what will happen? The system is very bulky; so moving the system if you want to scan for the different theta; moving the system is ruled out, you cannot do that; the system is very very heavy. So, what is needed? You need to rotate your column; now once you rotate the column, though we say that we are rotating at a very small speed, but you are changing actually the flow dynamics and that is the problem with the axial tomography; though the rotation speed is very slow, we can say that this rotation may not affect anything inside, but we are not very sure about it, we are not very confident about it because we know that once you will start rotating the column; even with a very small RPM, it may affect the dynamics inside.

And that is the major disadvantage of X-Ray tomography technique, while other processing whatever I have said is going to be valid there also and that is why I have introduced the X-Ray in between.

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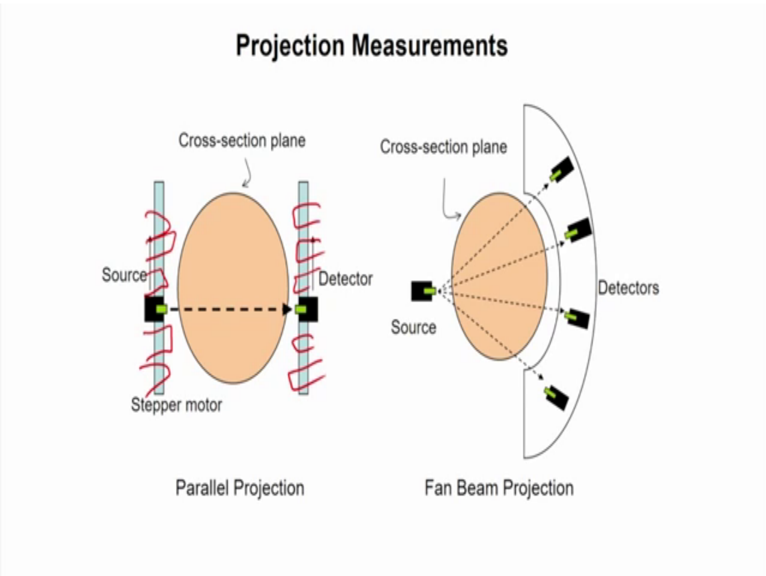

So, what we are doing? We have two ways to do that measurement, one is the parallel projection and one is the fan beam projection. As I mentioned, the parallel projection what you can do? You can use one source, one detector and you can generate several such line equation or several such projection; to get a complete projection profile across the radial variation. Or you can use several sources, you can say that several sources and several detectors are being amounted.

So, generally what we do? We work with the several sources so that my experimental time can be reduced significantly neither the experimental time will be enormous; as I already told you. Other ways to do the fan beam, in fan beam what we do? We put a source inside, we collimate the source in such a way that it generate a collimator generator fan angle and the angle can be fixed. And the angle should be such that it is the distance of the source to the column is such that this angle can cover the entire column zone.

So, in that way like this is not the proper way; it should be like that the entire column zone or entire area of interest can be covered. And if that is the case what you need to do? You have to use only one source. So, again your safety requirement will not be that much astringent; not that much stuff because you have only one source, you will use the several detectors and you will save this experimental time drastically, considering only one source is being used.

So, in that way the fan beam and parallel beam projections are different.

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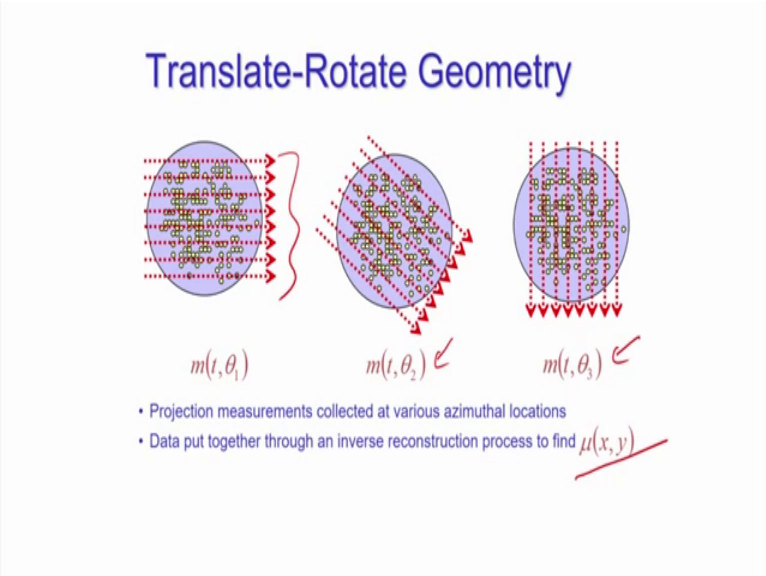

And what we need to do? Whether you use the parallel beam or fan beam, you should have the several projection for each you will get a projection curve. So, that is empty theta 1; then you have to do the same thing for t theta 2, then t theta 3 and then you have to solve this together to get the mu value, which will be the function of x and y.

So, you will get that how the mu value is changing inside x and y. Now once you know that, we can solve that we know that the mu will be equal to mu and epsilon 1 plus mu 2 epsilon 2 and epsilon 1 plus epsilon 2 will be equal to 1. So, from there you can get the pixel wise information, similar thing we can also do for the fan beam.

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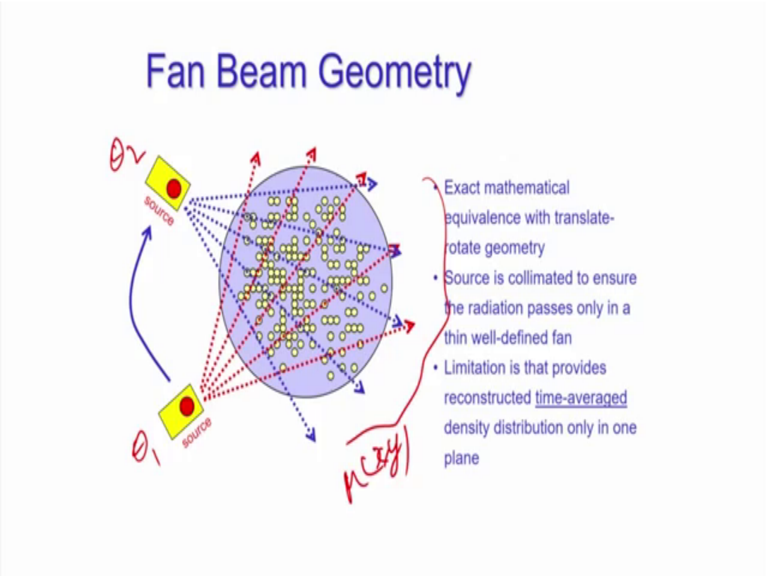

So, like this is for the fan beam again saying the same thing, you will have the rotation say this is for a particular theta red value is for a particular theta; so, theta 1; once we will move it again you will get the theta 2 and for each line you will get a projection. And then you can solve those all the projections together to get the value of mu as a function of x y and then that can be converted in terms of your volume fraction distribution.

So, that is what I already searched that this is the fan beam and there the only limitation of this technique because you have to get the sufficient statistics, it gives you a time average data, it does not gives you time resolve data or time resolve volume fraction; it gives you the time average volume fraction. And that is the major disadvantage of this technique because you do not get the temporal variation in the volume fraction with this technique, well the ECT, you get the temporal variation.

But the good point in the gamma radiance densitometry or tomography that your spatial resolution is very very good; that depends on that how much you are moving far, how much close you want. And if you want to make a device which is very accurate, you can move it even as low as 0.1 mm or 0.2 mm or 0.5 mm or 1 mm whatever you want you can move the detector and source together.

So, that is the major advantage of this technique that the spatial resolution is very very high; while the temporal resolution is not very high. So, if you want to find both temporal resolution and the spatial resolution you have to do gamma rho tomography along with the ECT so, that you get both the information here. Now as I said that what you need to do; again we are looking to minimize the number of experiments in fan beam or parallel beam; what we do? We scan it at one place, then we change the angle theta; we again scan it, then we again change the theta and to scan the whole volume what we need to do? We have to lift it up and then again we need to scan it for the different theta.

So, if I want to scan the complete volume of the system, it will take enormous time and that is why a concept of cone beam geometry is being emerging in which instead of having a fan beam; I can generate a cone beam and the series of detectors can be amounted here which will absorb the data.

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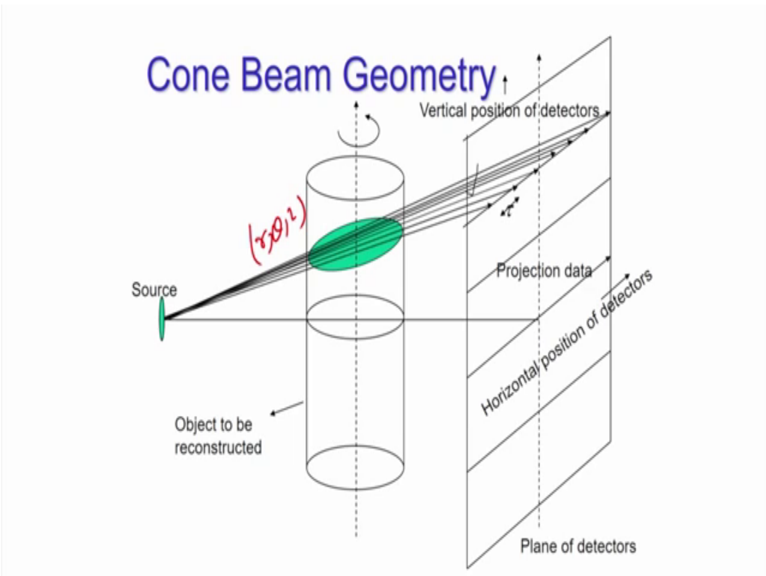

So, then again what we will do? We will move the source and detector again at angle theta and we can get the value or what we can do? We can rotate if the detector system is very bulky and it is difficult to move, then we can rotate the column again; it is like X-Ray to a small angle or small RPM and we can scan that what is happening inside and we can do have a scanning of all the volume; which is changing with the r theta tangent like this. So, it is going to be r theta tangent all together.

So, that is the cone beam geometry again it will save enormous time because the time requirement are huge, systems are bulky so you have to have several theta emotion. So, it takes huge time while in cone beam tomography, you can minimize the time further because in one go, you are scanning approximately whole volume for the particular theta.

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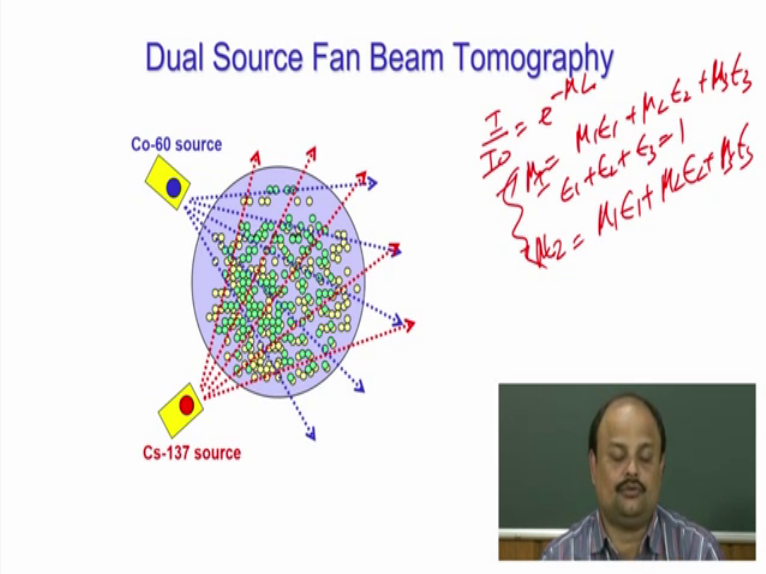

So, that is about the single source tomography or densitometry; now these things is being used in 2 phase flow. Now, if suppose I have a 3 phase flow; so what will happen? We will not able to solve that with the current situation whatever I have discussed, you cannot solve a 3 phase flow problem; why? Because now you have 3 phases; so, suppose if you solve I upon I naught is e to the power minus mu L and that mu is mu 1 epsilon 1 plus mu 2 epsilon 2 plus mu 3 epsilon 3; why? Because now you have a 3 phase that line averaged what attenuation coefficient will be the function of all the 3 phase volume fraction and epsilon 1 plus epsilon 2 plus epsilon 3 is equal to 1.

So, what will happen? Now I have a three variable, two equation I cannot solve it. So, what I need? I need another equation; if I have one more equation, I will able to solve this and that is why the dual source tomography kind of system has immersed to solve the 3 phase flow problem. So, what we do here? Rest of the concept remains same instead of one source we use two sources.

Now, what does the steel sources do? That these two sources suppose one is cesium and one is cobalt have different energy; now because they have different energy, they have different penetration capacity. So, the attenuation coefficient for cobalt and for the cesium which have a two different energy is going to be different. And that gives the luxury; so, it means what? I can use one source, I can change the theta and I can scan that column then I can put the second source; again I can change the angle theta and again I can scan the whole column.

So, what I will get? I will get two such equation. So one for source 1, another source 2; so mu 2 will be mu 1 epsilon 1 plus mu 2 epsilon 2 plus mu 3 epsilon 3 and now epsilon 1 plus epsilon 2 plus epsilon 3 is equal to 1. So, what I am going to get? I am going to get the volume fraction again for the 3 phase. So, that is another beauty of gamma ray tomography that depending on the number of phases, you can increase the number of sources and because each source have a different energy; it will have a different attenuation coefficient at the same system or in the same medium. And that can be utilized that fact can be utilized to calculate the volume fraction in 3 phase flow.

And that the same equation is there; as I said that what you are going to have? You will have 1 I equal to I naught is power minus mu L..

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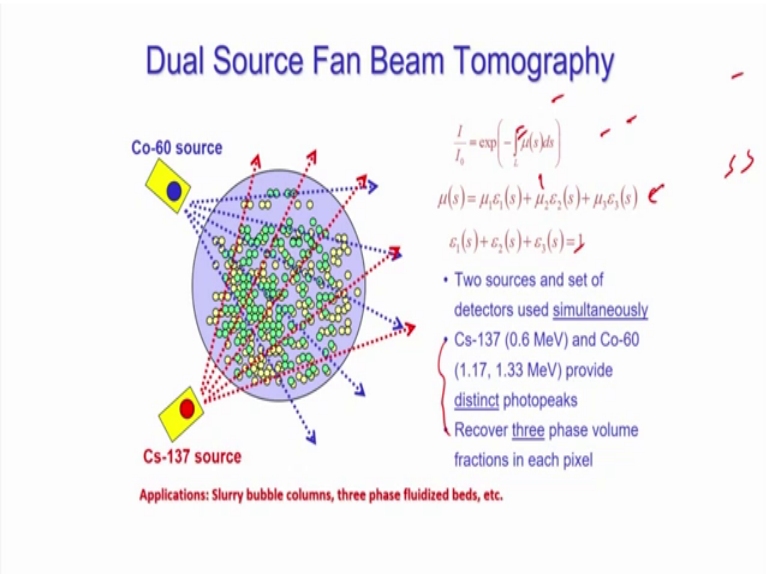

And then you will have one source, you will have the equation which will be mu n will be x mu epsilon 1 plus mu 2 epsilon 2 plus mu t epsilon 3. And then to get that too you get this equation twice actually one for the source 1 and another for the source 2.

So, now you will have 3 equations, 3 variable; you can easily solve it. So, that is being used and because again as I said that, they have different energy, they are going to have different attenuation coefficient. And that can be used to calculate the 3 phase volume fraction and that 3 phase column like slurry bubble column, 3 phase evaluated column even kind of a riser which is being used for the cracking the bottom section of the 3 phase all these things can be utilized, can be found by using the dual source tomography.

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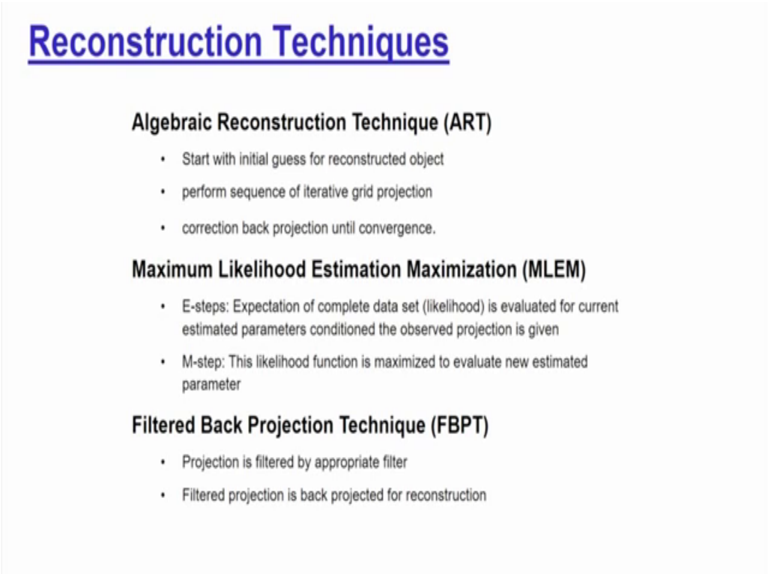

So, now the reconstruction again I am not going in detail of that, but the reconstruction there are mainly 3 algorithms are being used; the first and third is most popular, the first one is the algebraic reconstruction technique; I will discuss about that technique.

So, what we do in this technique? We use the first guess, we first guess that what will be the attenuation distribution? And then from there we do the iteration, we do this grid; so, for each we get the kind of guess that what would be the attenuation coefficient distribution. Based on that, now we perform the equation we divide the whole section in a several grid. And then we collect the information from the projection; the d inverse it we calculate the value of this projection, this volume fraction and we assume that whether this guess is matched or not; if it is not matched again we start doing the same iteration.

So, this is an iterative based method; ART this is method is mostly very accurate, but has certain issues we will discuss about this. Then there is a maximum likelihood estimation maximization method in which actually what we do? The expectation the complete data set which is likelihood is evaluated for current estimated parameter condition and the observed projection is given. So, we first see that how what is the estimated parameter condition.

Based on that we get this observed projection; then in the M step; this likelihood function is maximized to evaluate the new estimated parameter. So, it is being maximized again to get the new parameters and this step is being keep on repeating till you get a converse solution. In filtered back projection, again there is the name suggest; that you do the filtering and then you back project it.

What we do? We do the radon transform, we take the FFT of it the radon transform; whatever the filter is required, if you put the filter in the frequency domain and then v g kind of inverse FFT we do and calculate the pixel wise information at the pixel wise information.

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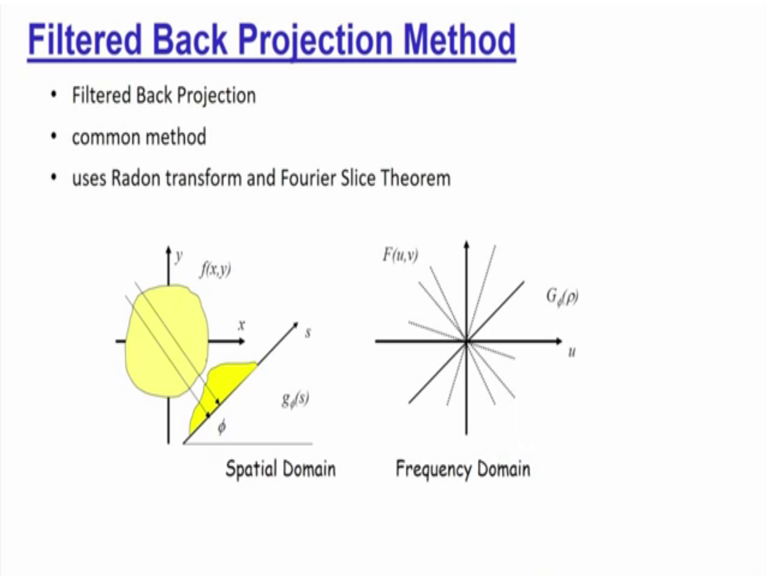

So, that is filtered back projection method each technique has its own advantage and disadvantage like in filtered back projection method; as I said that, you use the filtered back projection method that is very commonly used method and what you do? You form a radon transform and then you take the FFT of the radon transfer into this. So, it means you convert this detain to the frequency domain.

So, you will have the line equation and for different projection; we have different line equation which can be solved together. And then from the inverse FFT, you can get the value of the volume fraction which will be the pixel wise information.

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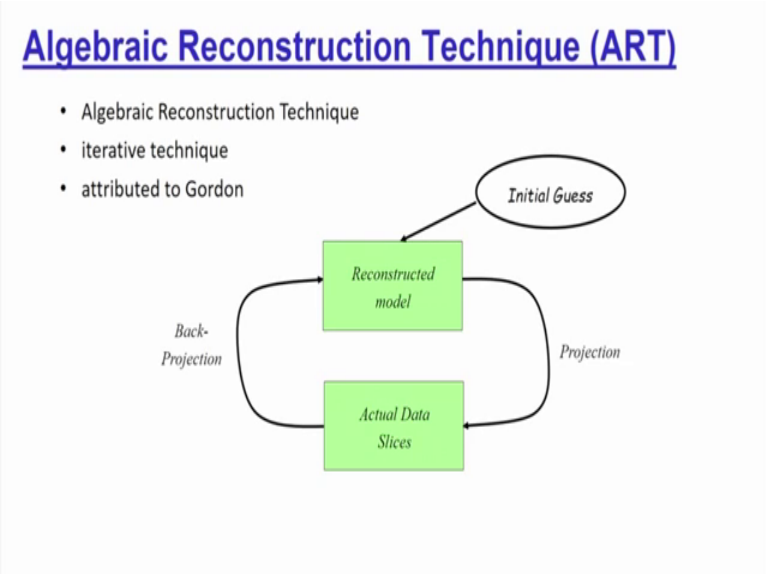

In ART as again I said the same thing that what you do? It is algebraic construction technique; this is the iterative technique and attribute to Gordon who has developed this; so what we do? We use the initial guess and we reconstruct that whole pixel wise information of the volume fraction.

Now, once that initial guess is there; what we do? We take the projection of it and then once we do the projection, we actually do that this projection means we do the FFT of this; then we do the projection the actual data slices we actually found it out and from there, we do the back projection to come back again to the model and we keep on iterative it.

So, first what we have done initial guess; then we taken the projection of the initial guess; from that projection we can find the actual slice information that what have been a slice information. Then we do the back projection again and then this slight information will be used as next guess and just loop keep on working till that the solution is not conversed.

So, that is the algebraic reconstruction method which is being used in the gamma ray tomography.

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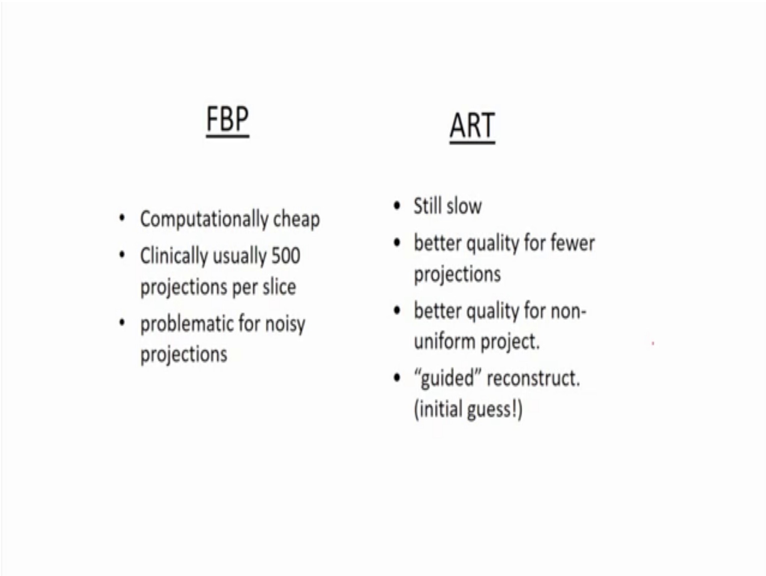

Now, what is the advantage and disadvantage? The big advantage of FBP filtered back projection is that is computationally very cheap; it does not require that much computational effort and this effort. For the clinical purpose say, if I say the clinical purpose; we can have 500 projection per slice; this is a huge number of projection you can get and this; the problem is that it will have little bit noisy.

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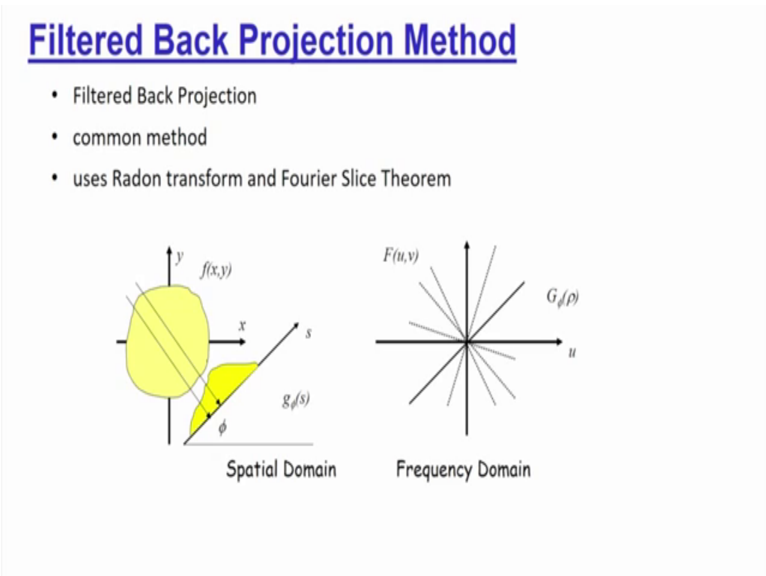

Why it is going to be noisy? Because we are doing that we are taking it; in the FFT we are taking one line signal and then we are using the filter on the one line. So, it can be little bit noisy; ART the major problem with the ART is it is very slow because you have to do lot of processing here; so this is very slow. The projection quality is very good; so, you get a very good quality projection.

Non uniform object again this is very good, you can perform this objects here also and the instruction whatever the reconstruction is there in this ART; it is very good and depends on the initial guess and you have a guided reconstruction. So, you can take initial guess; you calculate the projection from that initial guess and then from that projection again you go back and calculate the; modify your initial guess.

So, a systematic approach is there towards the moving the problem or towards the solving the problem.

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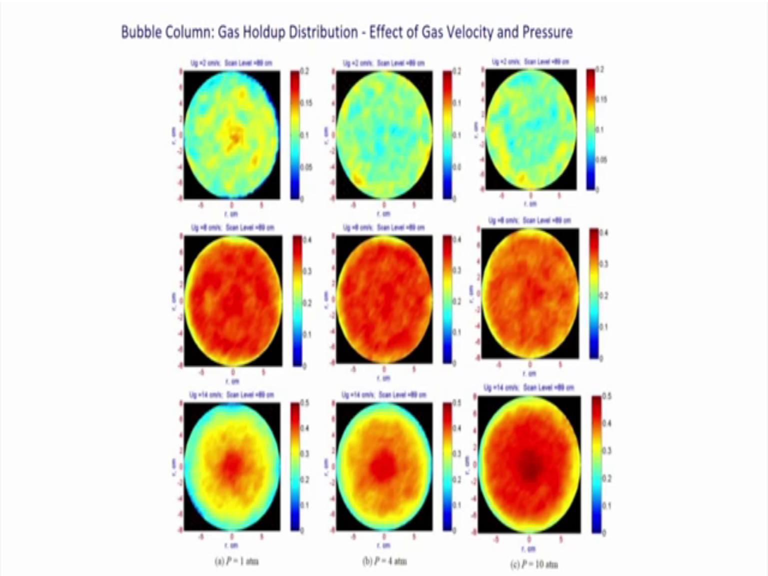

This is a typical diagram which has been taken from the literature, where we have tried to show that effect of velocity and pressure on the volume fraction by using the gamma ray tomography. So, you can see that it can clearly say that ways which phase involved and there is no preference that it is better near the wall or lesser at the centre of the column. And that is mainly because you are using gamma ray which is highly penetrating.

So, we can clearly solve this distribution along with the pressure that how with the pressure volume fraction is changing at different location. So, that is the beauty of this; if you see the spatial resolution is very good compared to the EIT or ECT; the only problem is the temporal resolution which is not that good because your experimental time is very high. And that is the major area of work, which one need to do in the measurements technique to develop a gamma ray tomography where the temporal resolution of that tomography technique is very high.

So, with this the gamma ray tomography part is over; now we will move to the next part magnetic resonance imaging. And as I said that the same technique is being used to measure the velocity also and the volume fraction also; this is very advanced technique, the problem in this technique is it is very costly and require huge magnetic field. The advantage is it does not required any radiation; so all your radiation sphere will go, you do not need extra gadgets for the radiation safety equipment devices and approved lab and all, but here also you need to take a lot of precaution because the magnetic field requirement is very very high.

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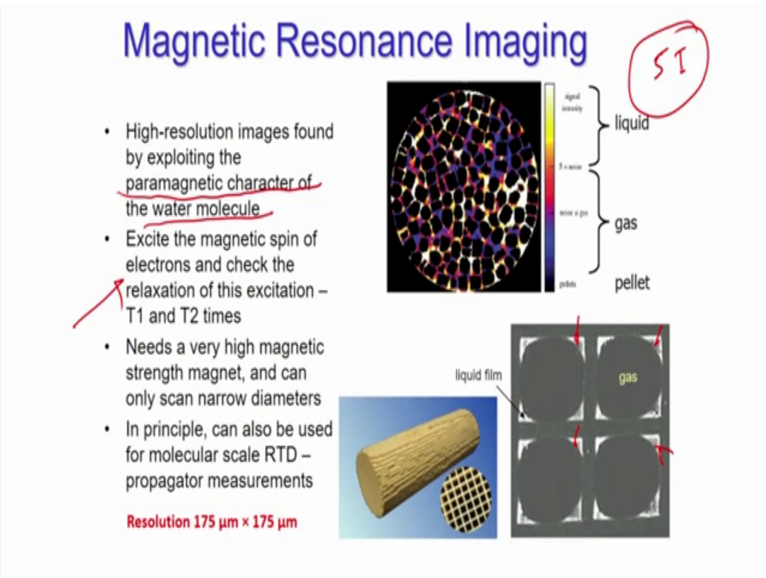

Generally, for scanning in the multi phase flow reactor we use a magnetic source of 5 tesla. So, 5 tesla source we generally use and what is the principle? The principle is very simple; this have a very high resolution image has been found, exploiting the paramagnetic characteristic of the water molecule. So, particularly if you have water molecules or any gas where the paramagnetic characteristic is there the resolution accuracy is very very high.

So, what it does? The magnetic field actually excite the spin of your electrons. So, any electron which is kind of having the odd numbers will actually get excited once they will be put under the magnetic field and the spin will change. So, what we do? We change the spin and then we relax it; so, for that relaxing time between the t 1 and t 2, we try to find that how the spin change is being recorded and that is being calculated in that way; it is being calculated, the phase is being reconstructed and the velocity is being calculated..

So, that is the major advantage of this that you based on the electronic structures what you are going to have? You are going to have a very very high accuracy; both in terms of the spatial resolution and in terms of the temporal resolution. Why? Because the spatial resolution again will be very high, the reason is you are generating the magnetic field and though you are solving at the molecular level or atomic level.

So, the spatial resolution is going to be very high; it goes minimum in the order of micron level and the temporal resolution is very high because that depends on that the relaxation time which you give to the system to calculate the thing. So, this is a typical photograph of MRI of a packed bed; 3 phase flow actually where the gas liquid solid is there. And you can see that this black colour, dark black colour spots are showing the solid phase; this is the yellow colour is showing that way is the liquid and the red colour is showing that way is the gas. So, you can see that the gas is making a film around the particle and then around that the liquid is flowing inside.

So, this is a typical figure of electrical bed, this is monolith reactor and you can again find it out how the flow is taking place inside; where the gases are flowing and we can see that near the wall gases are not going. So, this is about the magnetic resonance imaging; I am not going in detail of this because this is the application why is the major problem is it require a very huge magnetic field of around 5 tesla.

And by using the 5 tesla; with the column you can integrate or you can scan is only 2 inch; for more than 2 inch column, you cannot scan; you have to use even a higher magnetic field and that magnetic field will be very dangerous. The resolution wise it is very good resolution you can get and we can achieve a resolution of 175 micrometer cross 175 micrometer.

So, it is very high resolution you can get it will 0.1 mm region, you can get the resolution and that is the beauty of this technique. Second thing you can use the RF frequency and you can calculate the velocity at the same time. So, both volume fraction and the velocity can be calculated with high accuracy at the same time and that is all about the magnetic resonance imaging which we are going to discuss.

Now, what I am going to move on whatever we have discussed till now is about the invasive and non invasive technique to measure the velocity to measure the volume fractions. And as you have seen that these techniques whatever I have done, discussed is very very sophisticated technique and use at the industrial scale may be limited particularly for the non invasive techniques.

So, therefore, a class of the problem for most of the troubleshooting in multi phase flow industry or multi phase flow system is being done by using the RTD experiments; RTD measurements. And that RTD measurements is generally performed by using the radio tracer experiments or radiotracers. Now why we use the radio tracers? The reason is it is again the same motivation that it can penetrate error wall and you do not need to intrude anything inside. If you suppose use RTD experiment with some chemical tracer, then you need to put some probe inside to measure the conductivity of pH of the liquid.

Now, many times it is not possible to put a probe; why we will discuss the cases and I will tell you why. So, some of the crude technique is being used not I will say crude, but not very accurate where you will not get exact data, but you will get a hands on data which will be very needed a very useful for doing the troubleshooting or analyzing the experiments.

So, what I am going to do? I am going to now discuss some of the techniques which is very popularly used in the industry for the troubleshooting and most of this is based on the radio tracer. So, I will say it as a radio tracer experimental techniques I am going to discuss that how it can help. And what I will do? I will take a small cases and we will discuss that use of this technique.

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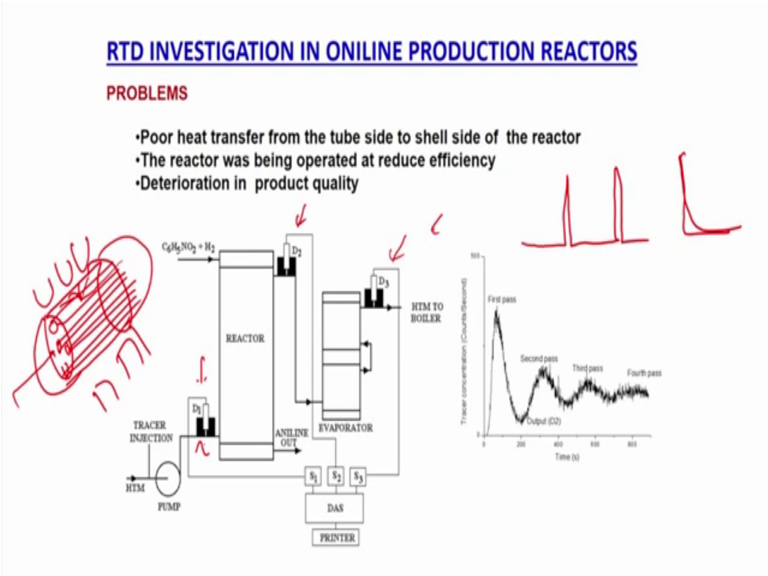

So, suppose if I have a reactor; this is a shell and tube heat exchanger is there and that is the connected with the reactor which is operated. And we found that the operation efficiency is very low and you want to find it out what is happening in site. So, what we can do? We can have; there suppose the pump this is the whole schematic and we want to find that what is the problem in the system? In this reactor what is the problem?

So, what we did? We put a detector and we inject a tracer before the pump. So, the tracer will mix in the pump completely and it will be get injected. So, we put a detector at the inlet of the reactor, we put the detector at the outlet of a reactor and then we put another of detector at the outlet of the evaporator which is being used. Now we inject a small tracer; so what will happen? This is a typical RTD experiment.

So, what will happen the tracer will go here; this detector will first see a peak, which will be the injection. And then you will go to detector 2; you can convolute these two detectors want to find the RTD of this detector this whole system.

Now, if suppose that this reactor has been defined at the plug flow, you can get a plug flow system. So, it means it will be say if you would give a tracer response after residence time it will come out at it in this way. If it is a CSTR; then it will come out immediately in this way. So, what is being found? If it is not working in between what will be happening? You will get the curve in between. So, the radio tracer experiment will immediately tell you that whether your reactor is performing up to the mark or not. So, like in this system; if you inject it we get the response at it in this way.

Now, you see that they certain portion is being actually reverted back; the certain portion is being recycled. So, now, if you do that recycling part; if you are recycling then it will be kind of you will get the multiple peak that where the peaks are being multiple. Because you are recycling certain part, if you are not recycling that part if you are not doing that recycling purpose; then what you should get? You should get only one peak why we are getting the several peak here.

So, if you are getting the several peak; what does it mean? That they certain they are the internal recirculation is there or dead zone is there where the particle is being stabbed, the radio tracer is being stabbed and it is coming in the cyclic way. So, generally this is the thing that something is recirculating inside.

So, I will get that; I have generated a path, I have generated a reactor which should ideally work as a plug flow, but some internal recirculation is there and that is why I am getting the multiple peaks inside; so I will get that information immediately. And these things help us in analyzing the system in detail and widely used in the industry. So, suppose some heat exchanger is there and there is a leak in the heat exchanger; suppose there is a heat exchanger and say this is the tube seat which is different tubes and there is suppose one tube is leaking.

So, how you will able to find that tube? So, what we will do will inject a fluid in the tube seat, we will put the detector and wherever this suppose it is moving in the tube; the radiation count will be the same and it will keep on decreasing. While if there will be a leak; what will happen? That tracer will start coming out from this place..

So, and it will be spread in this. So, what you will get? You will not get that the radiation is reducing, but at a certain location you will able to get that it is now spilling outside and you count on the detector will increase; now again the Beer Lambert's law because the distance is going to be reduced. So, you can find it out; you can pinpoint that where is the leak taking place and you can generate you can replace that tube.

So, that is the benefit of these techniques which is being used widely in the industry to analyze the reactor performance without disturbing the flow through the radio tracer

RDD experiments. Again the chemical tracer cannot be used because if suppose you are using a heat exchanger, you want to find a lake, you use a chemical tracer then what you need to do? You have to insert the probe inside; so to see that how the where the pH or conductivity of the liquid is changing.

Similar thing, suppose if I have pipeline and I want to find it out the velocity say crude oil transportation. And I discussed in the measurement technique that in the crude oil transportation because of the wax formation any single phase flow measurement devices like venture, pitot, a rota meter cannot be used because it will choke it immediately.

So, if you want to measure that velocity inside what is the way? Either you perform a typical ID experiments or the PIV experiment or the RPT experiment or if I am just interested if I do not want to get the detailed information of the velocity profile; I am interested in average velocity or average flow rate what I can do? I can put inject a small tracer inside.

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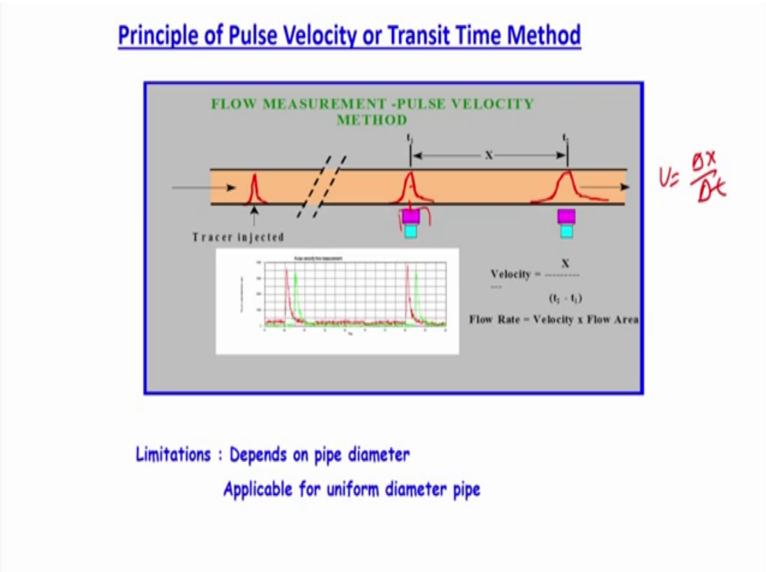

I can put two detectors which are placed at two different location and I know the distance between these t X. So, these detectives I will call him it; so I will know that at a particular location only this whatever the radiation which will be emitted by this source will enter at a particular location when the source will come to a particular location.

So, X I know I will inject the tracer once the tracer will come in front of it, it will give a peak. Once the tracer will move at this place again it will give a peak. So, just peak to peak distance I will measure; I know the delta X; I know the delta t, I can calculate the velocity. So, I will get the average velocity immediately; so, this is another way of you; if you are just interested in the average information, your flow conditions are hostile all your flow conditions are very; the fluid are very contaminated or susceptible to blockage or corrosion. You can use this method to calculate the velocity and in crude oil we actually use this method to calculate that average flow rate.

So, that is the another measurement which is being done in the industry to measure the flow rates also this radio transfer technique can be used.

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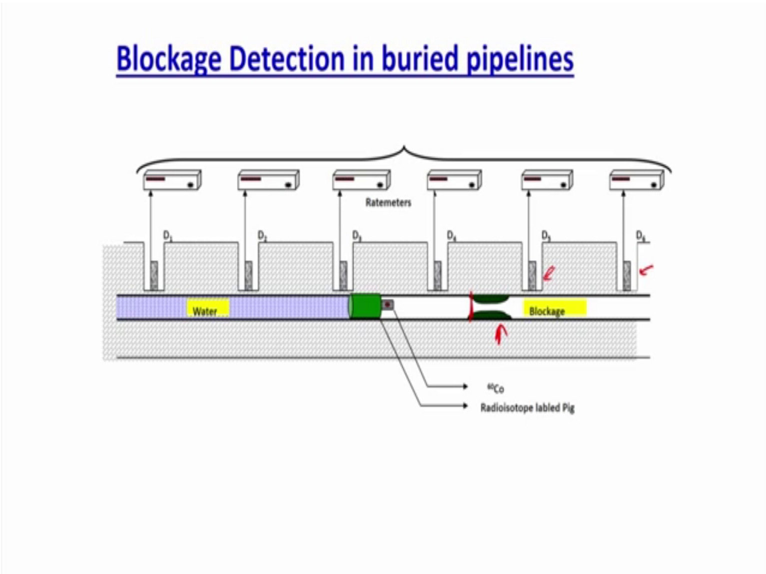

Then again suppose you have a pipeline, we transport the crude oil through underground pipelines. Now, if you have underground pipeline and suppose you are not getting the desired flow. So, how you will do this? Now because the pipelines are buried inside say several meters inside; obviously, all your technique whatever we have discussed we cannot use. And the another problem is say radiation based technique like RPT; we can use, but the problem is your length of the pipe is several thousand kilo meter.

So, suppose you are transferring from Assam to Bihar or Assam to Haryana somewhere in Panipat refinery. So, your distance are very very huge and suppose some of the tubes are blocked because of the wax deposition or something has happened and you want to find what happened with my tube. So, how to do that experiments? So, what we do? We take a pig in which some wheels are there or we put it with the some pneumatic pressure or we can put it with motor and wheel connection and there I can put a radioisotope on top of it.

And I can put some holes and certain distance I can put a detector several detectors like this; I can put this we can make a small hole and put a detector inside we can hang the detector inside and I can do it for the say several kilometres 1000; 1000 kilometres or say 200; 200 kilometres and I post this pig inside.

Now, this pig will move say this is the blockage location; this pig will move all through the location and with this is what I have solder we are pulsing it with the pneumatic pressure, it means we put the water and with the water pressure this pig is moving; it will pass and all the detectors will absorb the counts. What will happen? Once the blockage will be there, this pig will not able to pass after this location and so, I will never detect the peak; the count on these detectors. So, what I will know? I will know that this is the location, after this location there is blockage again I can rescan this area if needed; if this area is very high.

So, if we have miss scanning after 100; 100 kilometres what I can do? I can pinpoint, I can again do say 10; 12 dig I can make a 10; 12 digs and again I can scan that; where particles worth of my pig are stuck. So, in that way I can find it out the exact location of the buried pipe that where is the blockage happens, I can make a dig, I can cut only that section and replace the pipe.

So, these are the techniques; radiation based technique or radio tracer based technique which is widely used in the industry for all the practical application where you will not get the detailed information, but you will get a very good idea of overall picture.

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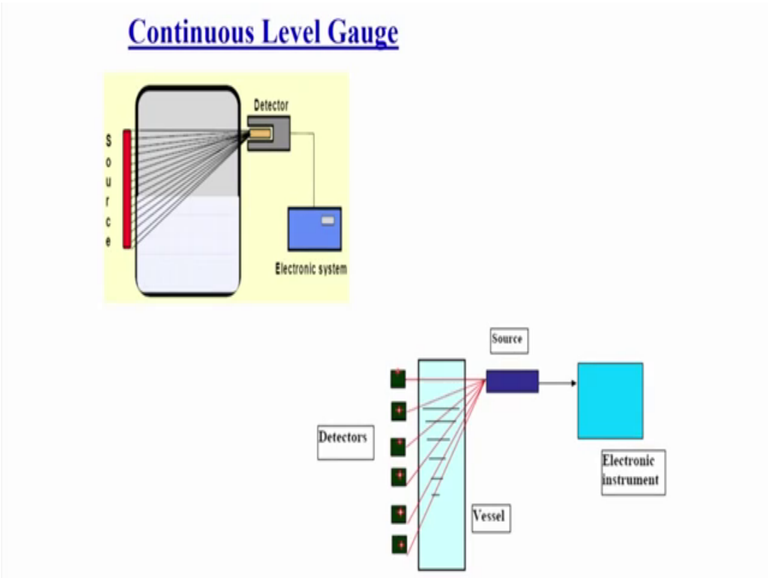

Similarly these techniques are also used to do the measurement say if I have a tank and I want to measure the liquid level inside that what is the level inside and the level is continuously changing. So, there is two way you put this glass tube inside and someone goes and always see that reading or what you can do? You can use your source and that source will have a fan beam kind of high structure and there will be a detector which will be detecting it.

So, what will happen? You can have a source and detector assembly and you can see that which is the attenuation; how the attenuation on this is changing. So, we know that the liquid will have more attenuation compared to the gas. So, as the level will change; this lines attenuation will keep on changing. So, earlier say in this line will have no attenuation; now, once the liquid level will increase we will say that this line also is having an attenuation now..

So, I can have a digital reading for the level measurement that how this level is changing. Similarly we can do it in both way; source can be multiple, detector can be one detector source can be 1, detector can be multiple; we can measure the liquid level inside continuous liquid level measurement can be done inside.

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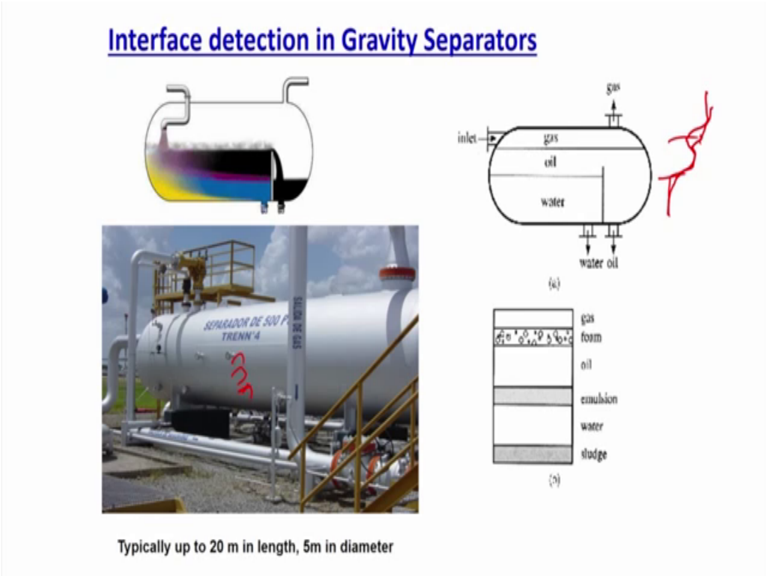

Then one of the major problem in industry particularly for the petroleum industry; once we do the exploration, you get oil, you get gas and for the second exploration you inject some water.

So, you get all the 3 layer and then what you do? You take a gravity settler and you try to settle them because everyone have a different density. Now, if you have to find that from which layer I should take the water, which layer it will be oil. So, what is the length of the layer inside; how you can do it?

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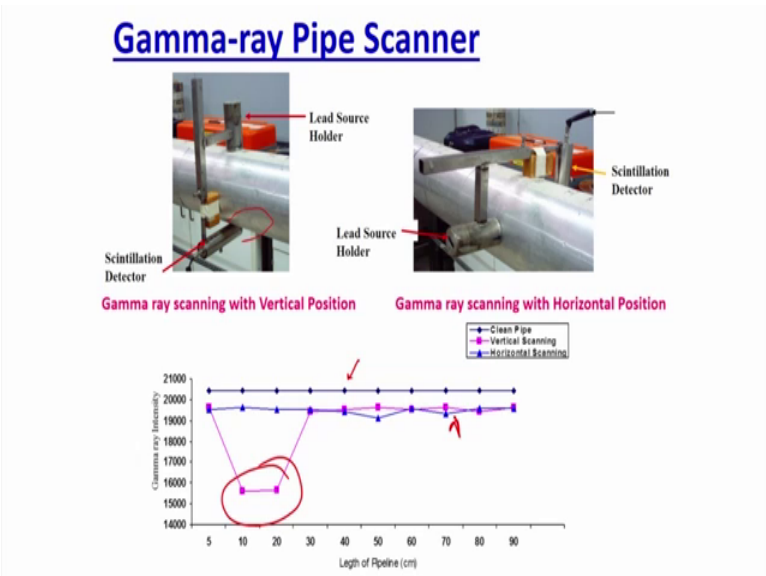

So, what I can do? I can use the radiation based technique, I can use this kind of a pipe scanner and I can scan it. So, what I know that if I scan it the column inside say source our detector inside; we know that if I move it up I will have different attenuation coefficient, water has different attenuation coefficient, gas has different attenuation coefficient.

So, what I will get? Along the length I will get the attenuation coefficient will be say something; then suddenly it will shift, then suddenly it will again shift. So, we will say this kind of a count pattern the count pattern will change. And wherever the count pattern will change that will be the level of the oil gas and water inside. So, you can find it out easily, you can see that whether they have been settled down properly and you can design the viewers, you can design that what is the level and how much oil will need to be pulled out?

So, all these things can be done with the base densitometry kind of experiments by scanning the pipeline. Similarly, you can do the pipeline is scanning; suppose there is a blockage happen in the pipeline which is the; not the buried pipeline on the top there is some blockage or something what you can do? You can again do the pipe scanning..

So, where they were there will be no blockage; this count will be flat at the blockage point the attenuation will decrease. So, you can find it out that this tube has been blocked; you can do the scanning vertically, you can do the scanning horizontally. So, in the corrosion wise if suppose some internal which has been fallen down or something has been dampened, some blockage has been created; definitely that blockage have a different attenuation.

Now, attenuation will increase; so, you count will reduce you will see the count whatever the intensity you are recording; it will be immediately decreased. So, this is for the clean tube, this is horizontally scan and this is the vertical scan and vertical is scan is showing the blockage; it means at this point somewhere in this is can here the blockers has taken place. So, you know that this is being blocked; if it is not blocked it will be always flat the count will remain same.

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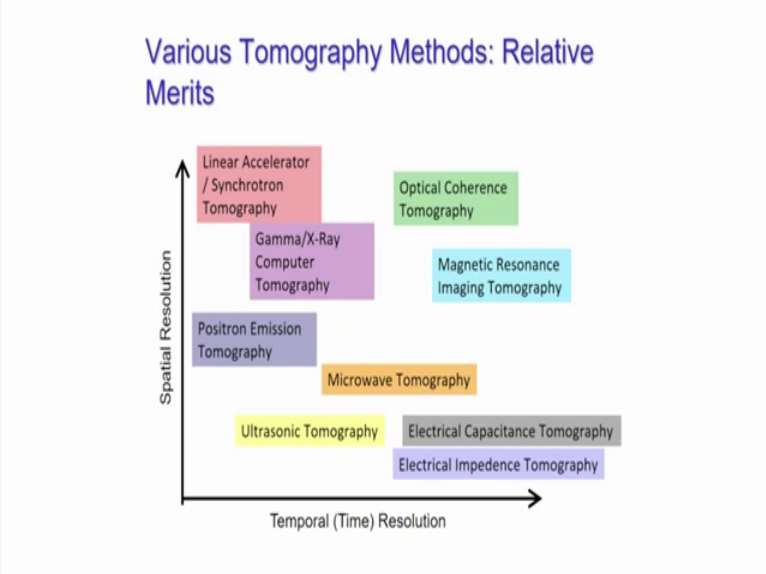

So, these are the scanner which is being used and these techniques are widely used; there are several such technique you can see there, these are the techniques which is used widely in the industry to do the overall diagnosis purpose. So, these are also a measurement techniques the radioisotope based technique which is being used. Now to summarize the tomography; this is the slide where I would like to summarize it. I will say that the spatial resolution and temporal resolution we are looking for this tube and as I said that none of the technique can give you both the information other than the MRI which can give you, but it is very very costly..

So, the cost wise it is very difficult; the gamma rays based technique or the radiation based techniques has gives very good spatial resolution, but poor temporal resolution because for the sufficient statistics; we have to wait for sufficient time ECT, EIT gives you higher temporal resolution, but poor a special resolution; MRI fits well, but it is very costly.

So, together with if you want to analyze the system; the combination of ECT and gamma ray will gives you both the information together and you can combine it and you can use this and still the cost will be much cheaper than the MRI. So, this is all about the tomography based measurement technique. Now one measurement technique, which is being left and widely used in industry and to get the first hand experience is the pressure probe. So, what we do we use the pressure transducer we put it along the wall.

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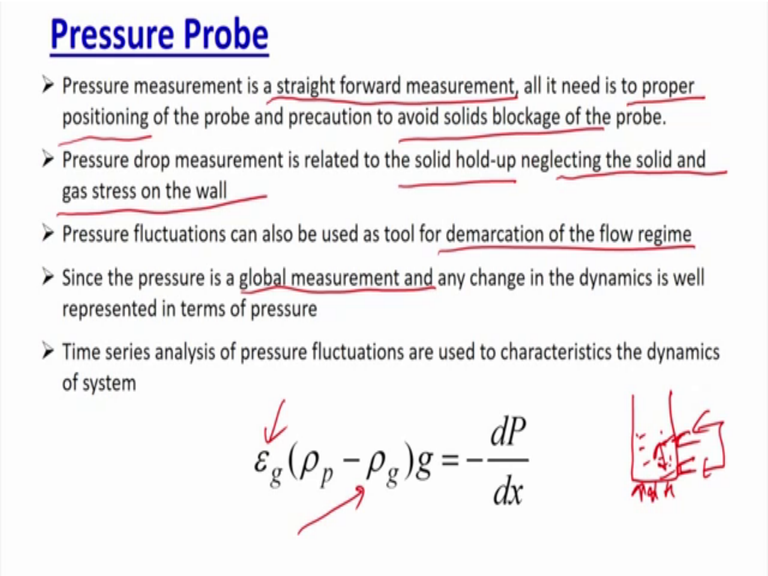

So, suppose this is my column say gas solid column and I am passing the gas from the bottom; I will put the pressure probe here; pressure transducer or pressure probe here. Now what is the benefit of using the pressure probe? Again it is widely used in the industry and to get the firsthand idea; because it is a very straightforward measurement. We are putting a pressure transducer, we are getting the pressure reading that how the pressure is changing with the time; at that location..

So, this is a very straight forward measurement and what does it need is nothing big; no alignment issues, no major issues that only think what we need to see that it is properly positioned on the wall; the position is properly and it has been properly fitted on the wall. And if you are using the solids, you should be made sure that the pressure flow should not be blocked.

So, generally what we do we put a small mesh in front of the pressure probe so that it will not be blocked; in that the solid will go and it will block the pressure probe, the pressure probably damage. Other than that, there is no precaution available; it is a straightforward measurement. And in case of the gas solid, what will happen? That the pressure drop measurement is directly correlated with the solid holdup that how much solid is there.

So, major pressure loss you will get because of the solids. So, the pressure drop is directly proportional to the solid holdup provided you neglect the solid and gas stress on the wall. Because you are measuring the pressure at the wall, you should neglect that then it is directly correlated with the solid holdup. And how it is correlated? It is being correlated it in this way that overall delta P whatever you will see.

So, you are measuring the pressure at two different location; the delta P between these two locations will be mainly because rho g h whatever we do we are going to be x will be multiplied and that is what rho the effective rho will be rho p minus rho g into epsilon g; because I am interested into the particle. So rho p minus rho g into challenge into g; so, that will be the delta P; you will see because of this and here you do that you will find the epsilon g. Once you know the epsilon g, you can calculate the epsilon s because epsilon g epsilon s is equal to 1.

So, that is the major advantage if you want to get a overall volume fraction or bulk volume fraction or average volume fraction; how it is changing with the time, you can have a pressure probe, you can put two pressure probe between the two location, you can calculate the delta P and you can find it out how the delta P is; how the volume fraction is changing with the time in that volume. Or you can use the differential pressure probe and there itself you can see that how the pressure volume at that cross section is changing with the time.

So, that is the major advantage; again change in the pressure suppose I take the pressure data the change in the pressure fluctuation can also be used to discriminate different the flow regime. Because if the flow regime will be changed, you will see that the pressure is at a certain range; the moment you have changed the flow regime, the pressure will shift either towards the up or down depending upon where you are going; whether you are going for more denser regime or you are going for more dilute regime.

So, the change in the pressure rating can also be correlated directly to the change in the flow regime. So, it can also give you the idea about the flow regime change and again this is very straight forward measurements; so, that is the major region. Second thing, it is a global measurement and change in the dynamics is well represented in terms of the pressure. Why? Because anything happen anywhere, it will be recorded in terms of the pressure. So, a bubble burst it will change the pressure inside; so, we put the probe anywhere; it will take that reading. So, it is not like if the bubble does not burst at that axis; you will not have that information.

So, if I use optical probe; if my velocity of the bubble passes through bypass the optical probe; I will not get that. In case of this, I will not get that bubble and if I do not get that bubble; I will not get the volume fraction of that bubble. But in case of this; pressure if the bubble burst or bypass or do anything, what will happen? It will change this is because it is a global measurement, you will get that information inside; you will see the pressure change.

So, any change in the dynamics of the system will be represented in terms of the pressure and that is the region that why the pressure change can be correlated directly to the regime change. And many people do the time series analysis of the pressure probe to find the dynamics of the system; the detailed characterization of this system like the FFT of this they have taken. And they found that if depending on the FFT, you can find it out the number of bubbles or dominating bubble regime you can find the power spectral density function; all these correlations can be done, you can find the volume fraction changes with the time and all.

So, it gives the enormous information; the only problem is you cannot say anything for concrete, it is all global it is not local information. So, it is good to get a first hand idea, but if you want to detail the characteristics of the flow; then it cannot be used for that purpose.

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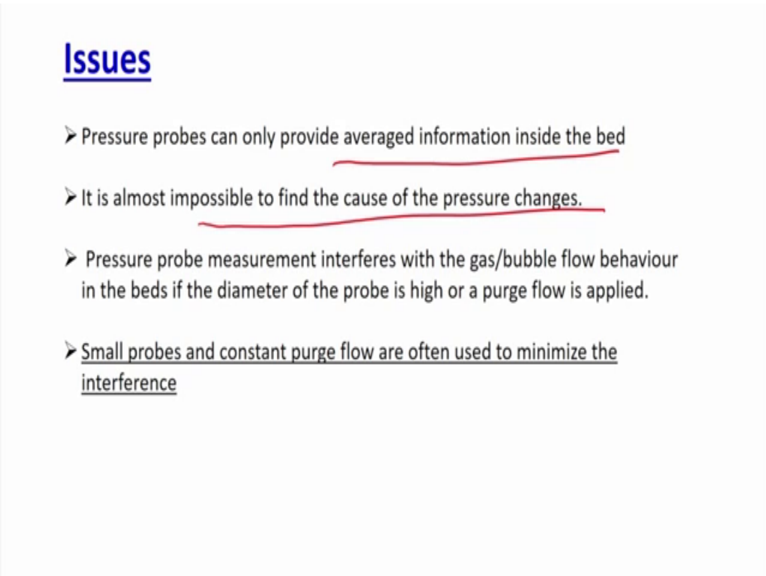

So, that is the major issue that it provide the average information inside the be; it do not provide a local information.

And as I have been discussed earlier; if the reaction is very fast then the local dynamics plays a major role compared to the overall dynamics. So, that is the major disadvantage of this; that is what I said that whatever you will record the changes that the pressure has changed, but almost impossible in multi phase flow to find a pinpoint the region; why the pressure had change. Say in a gas solid system; if the pressure have changed, it can be because of the coalescence of the two bubble; breakers of the two bubble, formation of some major scale metastable structures of the solids say solid agglomeration and all pinpointing any region is almost impossible to do that.

So, that is there; then there is another problem that the pressure probe measurement actually its interfere because again you are putting inside or at the wall at least; it is going to interfere with the gas and bubble flow behaviour in the bed. And sometimes it is being operated to reduce this we operated in the purge flow. Now if you operate the probe at the purge flow this influence is even more. So, what we can do? We can use either the smaller flow so, that the influence will be smaller or we can use a constant purge flow system to minimize the interference, but you cannot negate it; you are putting something inside it is going to change something; so, that is about the pressure probe measurement.

And with this, I would like to rest this course and we have covered almost all the measurement techniques which is widely used in the multi phase flow reactors or multi phase flow contactors to diagnosis, to analyze, to understand the flow dynamics.

Thank you.