Measurement Technique in Multiphase Flows
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Lecture – 08
Radioactive Particle Tracking

So, welcome back. What we are going to discuss today is the next to the non-invasive velocity measurement technique and the technique name is radioactive particle tracking technique. Now, as the name suggests that we are going to use a radioactive particle and we are going to track the motion of that radioactive particle to get the velocity field. Now, this technique is actually very versatile technique and has been implemented on many multi phase flow reactors.

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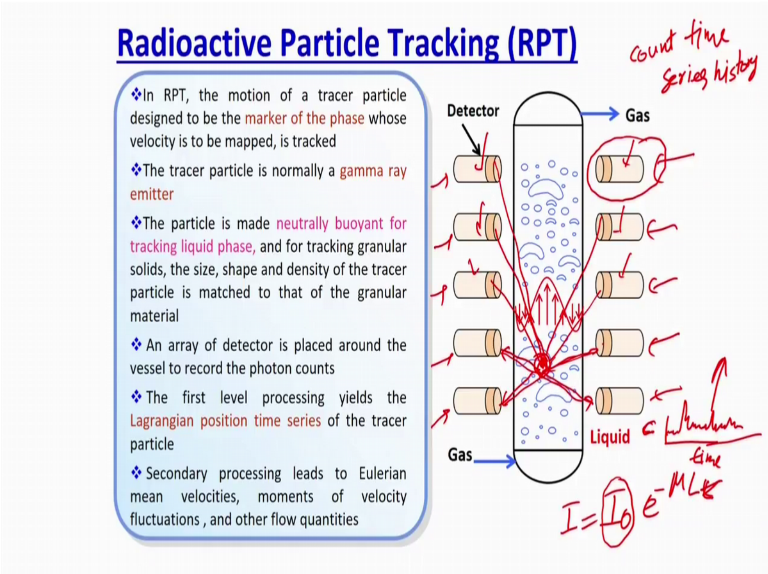

And the major advantage of this technique is the use of the gamma ray and unlike pepped positron emission particle tracking here we use actually the gamma ray source itself it means what it gives the luxury to use your source strength as well as source energy as per the application. So, if suppose I have this column, which the column diameter is very small, then I can use a source, which can have a very low activity. Now, activity as I said has been defined is the disintegration per second, so number of gamma rays disintegration per second.

So, suppose if I am talking about activity of one curie, it gives 3.7 into 10 to power 10 disintegration per second, it means it is three into 3.7 into 10 power 10 gamma rays will be emitted per second by the particle. So, I can unit kind of I can choose a source of different energy I can choose a source of different activity or strength, and therefore I can use this thing or this technique for any kind of system whether the system is transparent it is opaque, it is a smaller diameter, it is a bigger diameter. What you need to do, you need to prepare the tracer particle accordingly in that we will discuss.

So, what we do in this technique the major advantage as I said is the technique is there is a very versatile technique. It can be used for any system whether it is a gas-solid, it is a gas-liquid, any phase fraction does not matter that whether the discrete phase fraction is 5 percent, 10 percent, 30 percent, 40 percent, 50 percent any discrete phase fraction we can use this technique. We can use this technique for opaque system because I am using the gamma ray. So, it can penetrate almost anything. I can use it for the gas-solid system, because what I am doing I am just preparing a tracer particle which is going to track the motion of the phase of interest.

So, let me elaborate about this technique now with the advantages which I have discussed and I will also discuss the disadvantage at the end of this technique. So, what I said it is a radioactive particle tracking technique in which I will use a single radioactive particle. And this is very critical that we use a single radioactive particle as a marker of the phase whose velocity I need to map. So, suppose if I have to map a velocity of a solid present in a flow in a say gas-solid fluidize bed or liquid-solid fluidize bed, I will take the tracer particle this radioactive tracer particle exactly of the same shape, size and density. So, it means I am choosing one of the identical particle, one of the particle and making it radioactive by doping some radioactive element, and then after doping that I am keeping the density of the particle, shape of the particle, size of the particle exactly same as of the other particles project.

So, my tracer particle is none, but one of the billion of the particles of several particles which are present in the column of interest. Now, because these are radioactive particle, what it will be happen in the case of the movement. Suppose in the gas-solid fluidized bed, once the solid will move with the other solid this solid will also move because it has a exactly same property. Now, during it is path what it gamma ray does gamma resource does, it emits photons or gamma rays depending on its strength. So, we know that strength and if I know the strength I know that this much gamma emission it will do per second.

Now, we place some scintillation detectors and we will discuss about the functioning of the detector later on. But these are the scintillation detectors available which as specialise detectors to adsorb this photon counts which is emitted by the source. Now, suppose the particle is here, it will emit the gamma rays, and all the detective place detectors around the column of interest. And all the detectors acquires the gamma ray or the acquires the photons at the same time. So, it means all the detectors are fired at the same time. So, they are acquiring the gamma rays at the same time.

So, what will happen, we prepare a identical particle marker of the phase and that is why I am say marker of the phase; in case of the solid, the size shape and density of this tracer particle will be exactly same as of the solid present in the flow. In case, if you want to do the liquid tracking, the particle, which you present should be very small in size, and the density of the particle should be equal to the density of the fluid. It means you have to prepare a particle, which is neutrally buoyant. Now, if the particle is neutrally buoyant if their size is very less then what will happen it will actually follow the path of the fluid if the stokes number is less than one. So, in that case it will just keep on following the path of the fluid and you will track the motion of the fluid. So, this is the technique which gives you the advantage to track the motion of solid, motion of liquid everything.

Now, with the part, once the pressure particle will move inside, suppose in this case whatever I have drawn for the gas liquid; and this tracer particle is neutrally buoyant with the liquid whatever I have shown here. And once it will move, it will emit some gamma rays. Now, those gamma rays will be actually adsorbed by the detectors which are being placed around the column of interest all around at all the location to cover your phase of interest and zone of interest.

Now, what will happen, each detector will record a photon count time series history. So, I will just say that it is a count time series history. So, what does it mean say each detector what it will be happen, suppose I will get a graph where the y-axis will be count I am denoting it with the C, x-axis will be time. And you will see that how the counts emitted a photon counts when the once I say count photon count is changing with the time on each detector. So, you will get a photon count time series history for each detectors with the particle movement.

Now, I am using single particle, I want a whole velocity field. So, what I need to do, I need to perform the experiment for sufficiently long time, so that the particle covers approximately all the places inside the vessel of interest or column of interest; and not only one time it is a travel several time to the same location, so that I can also get the mean velocity. So, what will happen we will discuss all those things? So, what will happen you will get the photon count time series history on all detector with the time.

Now, we know that by using Beer-lamberts law that I equal to I naught e raise to the power minus mu into L, where mu is the attenuation coefficient of the medium, L is the distance between the source and the detector, so that will be there. So, what I need if I have some calibration position I naught values already existing, then what I can do I can find it out the distance from each detector. So, by using Beer-Lamberts law it says that the photon counts will be higher on those detectors where the distance is less it means this L is less. It means if suppose the particle is placed at this location the photon counts on these detectors will be higher, I will say even say let us include these detectors will be higher compared to these detectors compare to these detectors.

So, what will happen, I will get that what is the approximate location of the particle depending upon the photon count time series history. And by using the Beer-Lamberts law and we will discuss the reconstruction algorithm later on, but let us understand in a very simple language by using Beer-Lamberts law what I will get, I will get the distance if I know that attenuation distribution. And this is code that if I know that attenuation distribution, then I will know the distance from each of the detectors of this particle.

So, what will happen if I have four such lines or four such distances, then what will happen I will get this and I will get that what is the location of the particle. So, ideally what I need, I need the three detectors because each detector will give me a certain distance, wherever they will cut I will know that where is the location of the particle and because this is changing with the time I need the four detector to cover the time coordinate. So, three detector will cover the x, y, z coordinate; and four detector will cover the time coordinates. So, I need four detector to reconstruct the position of the tracer particle.

But what I have right now I have several detectors, so each detector is going to give me a distance that how far this particle is. And by solving all this distance or all these count time series together, I will get the exact location of the tracer particle. And when I am acquiring the photon counts with the time, with the time what I can do I can find it out how the tracer particle position is changing with the time. It means this I can convert in terms of the position, so I can get the Lagrangian position time series of the particle. And from their Lagrangian position times series once I have I can find it out the local velocity of the particle or local velocity of the tracer particle by using just simple delta x by delta t is equal to velocity. So, I am getting position with the time, I will get velocity with the time or I will say that Lagrangian velocity of the tracer particle because I am moving with the particle with the time.

So, I will have Lagrangian position of the particle, I will have Lagrangian velocity a local velocity of the particle. Now, as I said we are performing the experiment for sufficiently long time. What will happen the particle will move each location several times and then by doing the ensembled average of all those put point all those times was the particle comes to a fixed location, we can calculate the mean velocity of that position. And by subtracting the mean velocity to the instantaneous velocity, we can get the fluctuations.

And once you have a fluctuation, you can calculate many turbulent quantities like Reynolds stress, RMS, kinetic energy, we will discuss about all those, but you can calculate lot of turbulent quantities, so that is the beauty of the technique. And the principle of the technique which is very simple that we are tracking the motion of a single particle for sufficiently long time. These are the gamma rays particles, so which emits the photons with what you will happen is the particle will move with the time what will happen you will get that how the count photon count is changing on each detector with the time. From there if we solve all the detector’s photon count time series history simultaneously by using the suitable reconstruction algorithm, then we will get the position of the particle. So, what you will get is the position time series and from there you can get the velocity.

So, this is the basic principle of this technique. The technique basic looks very simple, but it has many challenges, and we will discuss some of those challenges in this course to understand that what is the benefit, how difficult or how easy it is to implement the technique. How it is how difficult or easy it is to reconstruct the particle position, and calculate the post process that data.

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So, as I said that what you are going to have we are going to suppose have a system, this is a typical liquid solid system diagram where these are the scintillation detectors, we call it scintillation detector which are placed around the column of interest. So, if you see that, I place the detectors all around the column; and then these detectors are connected actually to a data acquisition system which records how the photon count time series history will change on each detector with the time

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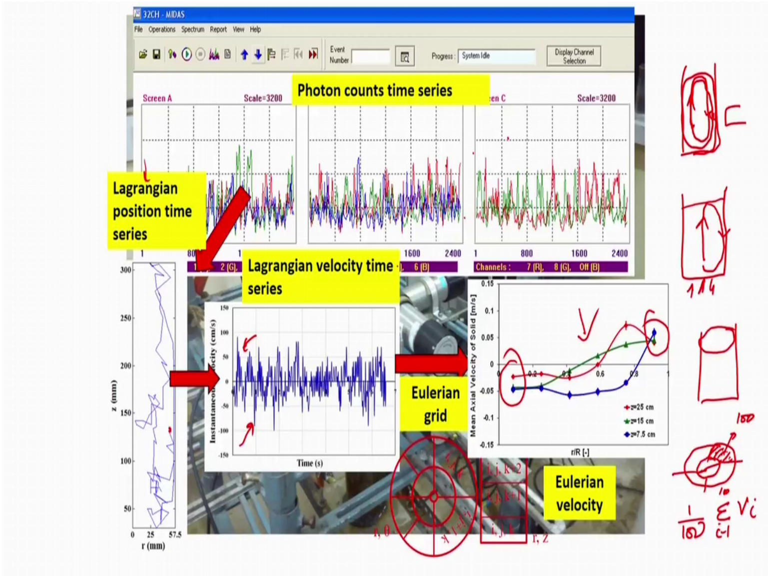

Like suppose this are the eight detectors I have placed around the vessel of interest then these if you see is the photon count time series history for each detectors. So, each graph shows actually the photon count time series history for the three detectors. So, if you see this is for detector number 1 - graph is red, two green and three is blue. Similarly, for all the three boxes, this is for 4, 5, 6, 7, 8. So, because I have eight detectors used in this experiment I am getting the photon count time series history with for all the eight detectors. Here x-axis is the number of event if you multiply it with the data acquisition time, you will get that time unit; and y-axis is the photon count.

Now, you can see that if I track any line whether the red color or green color, you see that how it is moving, it is increasing, then count is reducing, then again increasing, then reducing, then increasing, it means what the tracer particle is actually circulating inside the system. Suppose, this is the system this is the detector because in the liquid solid fluidise bed the solids are in batch then what will happen the tracer particle will be keep on the circulating, it will be keep on the circulating inside. So, what will happen once it will be far the detector count will be on the detector will be low; once it will come close the count on the detector will be increasing, so that is what we are seeing that increasing and decreasing count pattern for all the detectors.

So, what we have now we have a photon count time series history of the tracer particle. From there by using the suitable reconstruction algorithm, I calculate the position of the particle. We will discuss about the reconstruction algorithm. So, suppose this is the initial position of the particle and it is so that how the particle position is changing with the time so how my tracer particle is actually moving with the time. So, this is the photon count time series history which shows that how the tracer particle moving with the time. So, what you will get from this data, you will get that how the particle position is changing with the time. I have taken a very small time period, so that we can see the trajectory if you take for the complete experiment say for 8 hours, 10 hours or 20 hours depending upon the diameter of the column or volume of the column, you will see all where the this kind of a trajectories.

So, what we will get we will get the Lagrangian position time series history for the tracer particle. From there as I said by using delta x by delta t, I can calculate the velocity and that velocity will be nothing but the Lagrangian time series velocity of the tracer particle or Lagrangian velocity of the tracer particle. So, we will get how the tracer particle velocity is changing, it shows that how sometimes the velocity is higher, sometimes velocity is lower, sometime velocity is positive, sometime velocity is negative.

As this curve shows that this is positive, this is negative velocity, why it is like that because you are going to see again, I said that the solid is in batch. So, what will happen it will always remain inside the liquid is passing through the bottom, so it will move with the solid liquid up at the center say and then it will come down. So, what will happen once it will be going up, velocity will be positive; once it will be coming down, the velocity will be negative. So, you will get a Lagrangian velocity time series that how with the time Lagrangian velocity of the particle exchanging.

And then come to the Eulerian velocity or mean velocity or ensembled average mean velocity. So, what we do like CFD, we discretize the whole column in a small parts, small cells like I did here. So, suppose this is my column, and suppose this is the diameter of the column, so whole diameter a whole column we divide in a small grid say this way. And we see that during the course of the experiment, how many times the particle comes in each grid. As I said that as we perform the experiment for sufficiently long time, so that I have a sufficient statistic we weighed that for each cell the particle comes several time in each cell.

Now, if suppose in each cell say this cell if the particle has come say around 100 times, I can calculate the mean velocity of this cell by doing the ensembled average, it means I will do that one upon 100 summation I equal to 1 to 100 it is V i. So, I will get that ensembled average velocity of the tracer particle for each location. So, what I will get, I can get, if I plot that, I will get that the mean velocity and it shows that the tracer particle is moving up near the wall, and coming down at the center of the column. So, in this way we can calculate the mean velocity.

Once I have a mean velocity, I have the instantaneous velocity. I can calculate the whole fluctuation quantities by calculating the fluctuation velocity. So, we can calculate the Reynolds stress, we can calculate the RMS, we can calculate the kinetic energy of the turbulence in case of the solid phase, we can also calculate the granular temperature and so on. So, all the turbulent quantities you can calculate.

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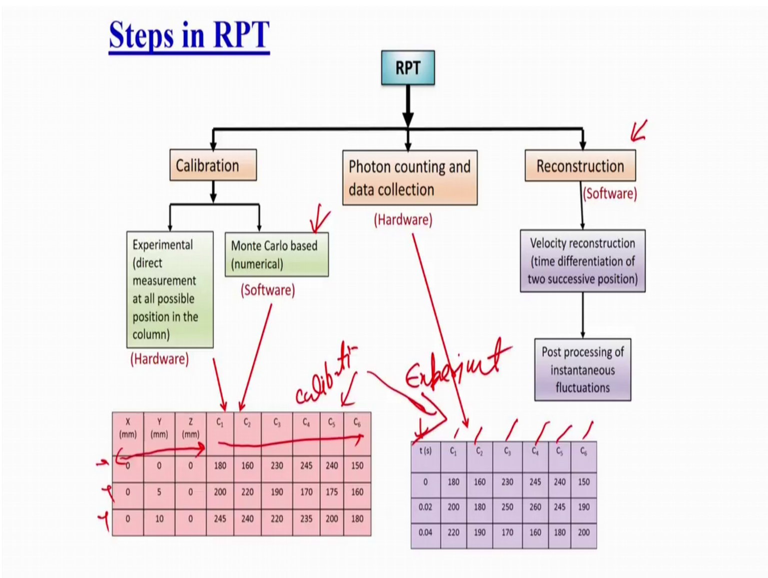

So, this was the flow chart. Though again as I said that the system looks very easy or the technique looks, very easy it is not that simple because RPT is a multi step process, it is not a single stage process. So, what is the stage involved in the RPT? The first stage is the experimental stage, I will not say it is a first stage, the one stage is the experimental stage where we keep the particle free inside the bed of interest and see that how the particle motion is changing with the time or hide the particle position is changing with the time.

So, what I will get I will get that how with the time the count on each detector is going to change because with the position the count on each detector will change. Because some detector say for particular detector some position can be close to that detector, some position can be far from that detector. If it is close, your count will be different; if you it is far, your count will be different. So, what you will get with the time how the count on each detectors is changing with the time, so that is what we get from the experiments as I shown in the comes of the graph.

Now, I have to reconstruct this thing in terms of the position as I said you by using the suitable reconstruction algorithm. Now, how to do that, to do that what I need I need a calibration I need to know that on the same location when the tracer particle was there under the controlled motion or no motion how much counts was recorded on each detective. Now, this is called calibration step. It means what we are trying to do we are trying to fix the position of the tracer particle, and we are going to measure the counts recorded on each detectors which are placed around the vessel of interest, so that is called calibration step.

The calibration step can be done in two ways; one is by experiments by using the hardware as I said and physically keeping the particle at several known location the way it means what we are going to do we are going to put the particle at a fixed location we are going to block the location of the particle. And for that particular location, we record that how all the detectors are recording time sorry recording count for all the detectors are for that position. And then once that is completed we actually move to the next position and then again calculate that how the photon count will be recorded on each detector for this next tracer particle position, so that is called experimental way of calibration.

However, if suppose you have a bigger column diameter or even a smaller column diameter of a little bit bigger size, what will happen you have to do the experimental calibration for very large number of points. Because you have the particle is moving continuously, you do not have that control that where the particle should go, where the particle should not go. So, it means what you have to actually do the calibration for entire range, entire column dimensions which is under the investigation. So, doing the experimental calibration is going to be very, very tedious and time consuming. And therefore, a software approach has been developed to do the calibration and that software approach we will discuss later on, but it has been developed to do the calibration. And software also do the same thing, it generates the count, recorded on each detector for a fixed position of the tracer particle.

So, now what we are doing in the calibration, we make a table and just like the real experiment we get the table in which x, y, z is fixed. And the count on the detector on each director is changing and that is with the time. So, this is the time how the tracer particle position and time m is changing, so that is called calibration where we change the tracer particle position, and we caught the count. In the experiments what we do we keep the particle free inside to move, and what we get we get that how with the time photon count on each detector is changing. So, I have two tables now; one from the experiments, one from the calibration, calibration and this is for the experiment.

Now, we compare these two tables. And once I compare these two tables, I will get what I will get the position of the tracer particle and that is called reconstruction. So, once I compare these two tables, I will know that how the tracer particle position is changing with the time and that is called the position reconstruction of the tracer particle. Once you reconstructed the position of the tracer particle, as I said we discretize the column we virtually divide the column in a small grid cells like CFD we see that how many times a particle is visiting each cell. And whatever the time the particle is visiting on each cell we take the ensembled average of that and that is called the mean velocity of the tracer particle for that cell. So, that feeds the way we can calculate the mean velocity; and from there we can calculate the fluctuation and other turbulent quantities. So, this is the steps in the RPT which is being used to process the data.

Now, like other technique PIV, LDA or pept are pretty is not an obsession technique it means you cannot just not a plug and play device and you have to fabricate it or you are installing from the basic nuclear spectroscopy hardware. So, we will get the individual hardware, but you will not get a unit name as a radioactive particle tracking technique that is one of the major problem with the technique that there is no readymade packages available. And one who wants to work with this technique have to understand the basic sciences, he has to understand how to assemble the nuclear spectroscopy hardware, and how to use that hardware for the reconstruction data reconstruction.

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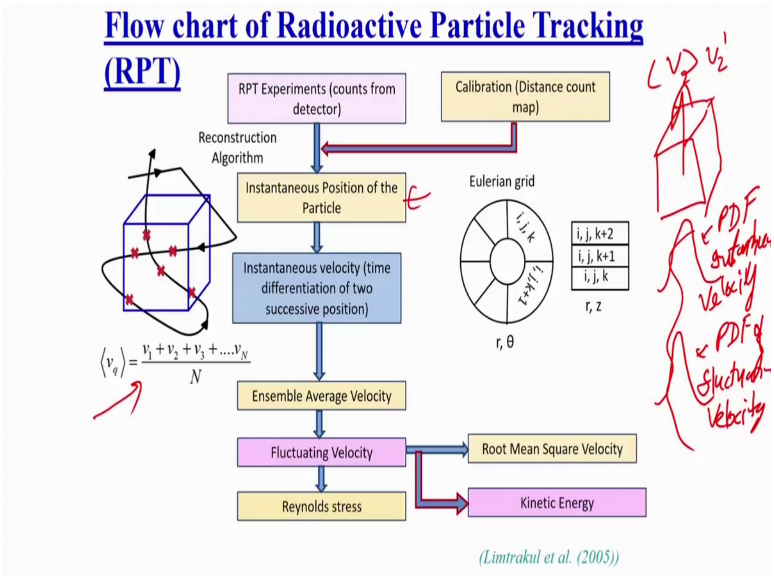

So, some of that hardware we are going to discuss. So, basically this is the flow chart of the RPT as I have already discussed before going to the hardware that how we do that, what we do we first do the detector calibration, we do the experiment we compare these two we get the instantaneous position of the tracer particle. We discretize the whole column virtually in like a grid in a small Eulerian cells. We note down that in each Eulerian cell how many this time the particle comes during all the experiments. So, we get that how many the particle position is of this the number of particle times the particle where which kind of visited the cell then we do the ensembled average. Suppose, it is visited n number time, I will just add those n number times the particle velocity divided by the total number of times the particle comes in that unit cell.

So, I will get that what is the ensembled average velocity of the particle. Once we know that ensembled average velocity of the particle, what we can do we can subtract the mean minus instantaneous, I will get the fluctuation velocity. Then the beauty of this technique as I said and if you try to understand is that suppose if I any grid cell if I am talking about. And I said that the particle actually visit the cell several times say n times the weight has been shown. So, what does it mean that you are going to have not only a single mean velocity for each cell, you are going to have not only the v z mean you, are going to have v z fluctuation and you are also going to have the value that this v z fluctuation we are going to have v z mean value. But you are also going to have the PDF of the instantaneous velocity is a PDF of instantaneous velocity and PDF of fluctuation velocity and these two are the major advantage of this technique.

So, what I am saying that I am not going to just tell you that what is the velocity or mean velocity at a particular location inside the column of interest. I am also going to tell that what is the velocity distribution for whole experiments for whole time for 8 to 10 hours, 20 hours how much velocity distribution you got for each location and then you can similarly use that velocity distribution local velocity distribution if you subtract it from the mean velocity what you are going to get you are going to get that the flow PDF of the fluctuation velocities.

So, what I am going to get, I am going to get the PDF of instantaneous, PDF of the fluctuation velocity it means you will not only get the mean you will get that what is the distribution of the velocity at a particular location, what is the distribution of the fluctuation at a particular location. And now if you are designing the system, you can design your system not based on the mean velocity only which is the traditional way of doing the designing, we can also consider the distribution in the velocity for each location. And that distribution in the each velocity which gives lot of flexibility to even do the post process the data for a higher order moments which we will discuss, so that is the flow chart of the RPT.

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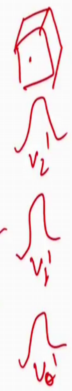
Quantities Calculated from RPT Experimental data

$v_r =$

$v_\theta =$

Instantaneous Velocity	$v_z = \dfrac{\Delta z}{\Delta t}$
Ensemble average velocity	$< v_q(i,j,k) >= \dfrac{1}{N(i,j,k)} \sum_{n=1}^{N(i,j,k)} v_{q,n}(i,j,k)$
Fluctuating velocity component	$v_q^{'}(i,j,k) = v_q(i,j,k) - < v_q(i,j,k) >$
RMS velocity	$< v_q >^{RMS} = \sqrt{< v_q^{'2} >}$
Stress	$\tau_{qs} = \rho_p < v_q^{'}(i,j,k) v_s^{'}(i,j,k) >$
Fluctuating kinetic energy per unit volume	$KE = \frac{1}{2}\rho_p [< v_r^{'2} > + < v_\theta^{'2} > + < v_z^{'2} >]$



$\rho v_r' v_z'$ $\rho v_\theta' v_z'$ $\rho \theta' \theta'$

$\rho v_z' v_z'$

This is the formula which is being used to calculate the velocities like if I say the instantaneous velocity, it is v z is nothing but delta z upon delta t. Similarly, we can calculate the v r and v theta, but you need to do certain trigonometry, we will discuss some of that I will at least I will show you the formula that how to calculate the v r theta. If you are solving in a polar coordinate, if you are solving in a rectangular coordinate, then v x, v y, v z all will be defined by delta z by delta t. You can calculate the ensembled average velocity as I already said that in each cell suppose the particle comes for hundred times, you add all those hundred velocities divided by the number of times particle comes it means hundred you will get the ensembled average velocity.

We can calculate the fluctuation velocity mean minus instantaneous within that cell for all the time the particle comes in that cell, you will get that what is the fluctuation velocity each time or you can say that you will get that the PDF of the fluctuation velocity in that cell. Then you can calculate the RMS velocity of that cell root mean square velocity by using this formula which is nothing but v prime square. So, if suppose I want that v prime square for this, so I will get say if I want the z direction of RMS velocity for each cell, whenever the particle comes there is a fluctuation velocity I will square them, and I will add them, I will get that what is RMS velocity of the particle at in that cell.

Similarly, I can calculate the Reynolds stress. Reynolds stress is nothing but rho v v prime Reynolds stress is rho v v prime. So, I can calculate all the nine component of the Reynolds stress. Suppose, if I am talking about or if this polar coordinate I can calculate v r, v z, rho v r v r, rho v z prime v z prime, rho theta prime theta prime and so on, I can calculate all the nine components of the Reynolds stress.

And we can also calculate the kinetic energy of fluctuations per unit volume of fluctuating kinetic energy of this per unit volume. And fluctuating kinetic energy has been defined for each cell. Suppose, if the particle is coming hundred times in each cell, what will happen you will see the hundred instantaneous velocity, you will get the mean velocity. You subtract it you will get the PDF of the this fluctuation velocities. Now, each velocity say v r, v theta, v z, you will get the PDF for v z prime, you will get the PDF for v r prime, you will get the PDF for v theta prime.

So, you will get the PDF of fluctuation velocity for all the three velocity components. And then we can do that averaging and half rho v x prime square plus v theta prime square plus v z prime square or you can right say v x of v r, it will be the nothing but the turbulent kinetic energy per unit volume of the tracer particle. Why per unit volume because instead of mass I am taking rho, because in case of the fluid we know the rho, but knowing the masses many times is very difficult, so that is the fluctuating kinetic energy per unit volume. We use this formula to calculate the quantities. We can also calculate diffusivity, we can also calculate autocorrelation and all other data we will discuss that later.

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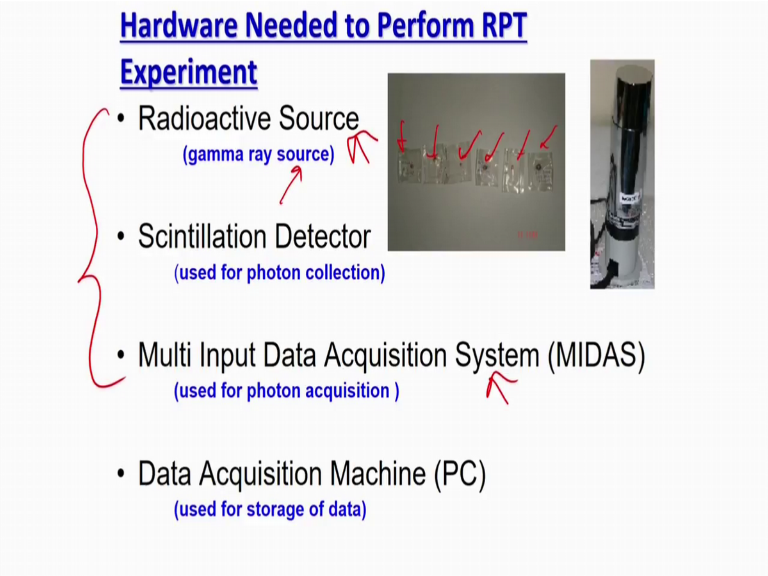

Now, as I said RPT is not an obsession technique, and you have to assemble it from the basic nuclear spectroscopy hardware. So, let us discuss that what are the hardware which is required for the RPT experiments. Now, as I said that the most typical part of the RPT experiment is the tracer particle, which we are using as a marker of the phase. So, the first hardware I will say is nothing but the radioactive particle which should be the gamma ray source. And the particle size if you are tracking again I am repeating, if you are tracking the solid phase, size, shape and density of the tracer particle should be exactly identical to the size, shape and density of the other particles which are presented the flow.

In case of liquid tracking, the particle size should be smaller and the density should be equal to the density of the liquid. In case of the gas tracking, I am sorry that is the major disadvantage of this technique you can track the gas by using the RPT technique. Why because it is very difficult to find a tracer particle, solid tracer particle which can match the density of any gas. And therefore, the gas tracking cannot be done, it can do either the liquid tracking or the solid tracking.

So, this the first hardware is your radioactive source, this is some typical photograph of the radioactive source. And you can see that depending upon the application the size, shape and density of the source is keep on changing. So, these are the typical sources which we use in our laboratory and that is what I have shown that it can be from very small to very big, and the tribes shape and density of this particles are kept exactly same to the solid present in the flow.

The second hardware and this scintillation detectors the job is to actually record the photon counts which is emitted by the tracer particle. The third is to multi input data acquisition system which also called it MIDAS if his job is to use a kind of acquire the data recorded or transferred from the detector. So, detector will absorb the count it will transfer that adsorb counts to the MIDAS or to the electronics and electronics job is to count that number of incidents of the gamma ray which has been detected by the scintillation detectors, so that is the job of the MIDAS. And then finally, you require a PC for the data acquisition as well as data processing. So, these are the typical hardware, actually this is the three main hardware which you require for the RPT experiments. This is a typical diagram of the scintillation detectors and we will discuss this diagram in later in more detail.

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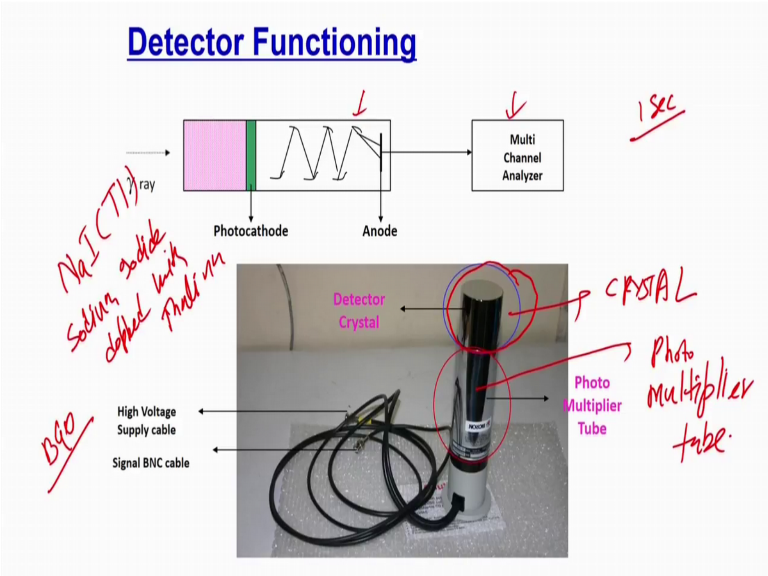

So, this is a typical diagram of a scintillation detectors which we use it. And if you see that this scintillation detector is divided in two parts. The first part is called crystal. And this part is called photomultiplier tube; so this part is called photo multiplier tube. So, the detector has been actually made of two parts, first part is the crystal which actually do the adsorption job, another part is the photomultiplier tube which is used generally for this for the supplying this voltage as well as to count the signal which is being generated during the adsorption of the photon counts.

So, how the scintillation detectors work to see that let us assume this is my scintillation detectors these are my photomultiplier tube and it is connected with a counter. Now, let us forget that what kind of counter it is, but let us assume that it is a counter which counts the signal. So, what will happen once this gamma ray is actually emitted on the crystal, what will happen the crystal will actually adsorb that gamma ray. Now, once the crystal will adsorb that gamma ray. So, suppose this is the time when the particle has incidented of the detectors, it will emits a photoelectrons.

So, what will happen we know that that once the gamma ray is adsorbed in any material or any crystal what happen that the crystal electrons goes to excited states because they got certain energy. Once they will come back from that excited state energy they actually emits a photon a photoelectron or so that photoelectron actually is covered to the photo cathode to generate a electron. And that electron passed through this multi photomultiplier tube which has actually several diodes placed to enhance the signal it actually passed through that. And once it passed through that it reached to the anode; once it reached to the anode like this way, it passes is generate a pulse a current signal. And that pulse or current signal is being actually counted by a counter which is being placed after the detectors.

So, each photon counts or each photon which is incidented on the detector adsorb by the detectors because only once the photon adsorb, it will emit a photoelectron, it will go to high-energy state, and then it will emit to follow to an electron. So, for each gamma ray which has been adsorb by the detector, each current pulse has been generated. So, it means if you just count the number of times the current pulse has been generated between the data acquisition system, so say if I am acquiring with one second data acquisition frequency, after every one second, I am acquiring the data, so I will see that how many times this current pulse have been generated within that one second and that is been called that it will be shown as the photon counts on that detector for that time period for that delta t. And you will get this kind of whatever we were discussing, you will get this kind of a map for each detector that how the photon count is changing on each detector with the time clear.

So, now if the detector is closed definitely number of intensity will be higher. more number of photons counts will be incidented. If the detector is very far, the cone angle, the view angle, the factor, the attenuation will be higher, so the number of photon counts emitted or incidented on the detector will be low and that is why the counts on that detector will be low, so that is the basic principle we use. And we get the photon count time series history.

So, this is the way the scintillation detectors work. And there is a crystal inside most of the time there are different type of crystal available in the market for different type of detectors, but most of the time we use Na I Tl which means sodium iodide dopped with thallium is used as a scintillation detectors. So, these are sodium iodide detectors. Why it is being used because it is very cheap compared to the other detectors like BGO or any other detectors this, this is very cheap and that is why for RPT application generally we use sodium iodide detector scintillation detectors which is dopped with the thallium.

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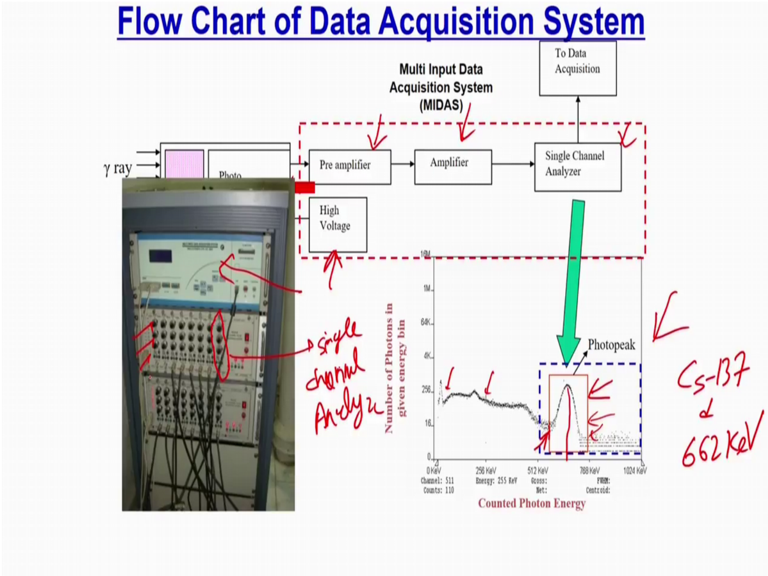

Now, the second hardware which is important is whatever is being put which I keep on telling till now is a counter which is being placed after the detectors. So, there several advancement is there in the RPT hardware. So, earlier this system used to be very huge, but with the modern development of the electronics or develop a modern electronics, now the system size has been reduced. So, what we need actually this detectors as I said have a photo diodes and those also need a energy.

So, what you require you require certain high voltage to maintain the particular potential within that detectors. So, you need a high voltage supply. Then the current pulse which is being generated by incidenting one a photon one gamma rays or photon count photon on the detector the intensity of that signal is very, very weak if density of that current pulse is very very weak. So, what we do we need amplifier or series of amplifier depending upon the intensity we can have a pre amplifier we can have amplifier which will actually amplify the signal. So, that I can see the signal and I can discriminate the signal from the noise.

So, I will get that amplifier then we use a single channel analyzer or multi channel analyzer now what that the job is as I said that single channel it means it has a single channel which records or which counts the number of photons incidented on each detectors. So, this is nothing but a counter, but it is also a single channel analyzer. So, it is also analyze that that the photon which has been incidented was of what energy because if the energy of the photons was very high then the probability of adsorption of those photons on the scintillation detector crystal is low and so the intensity will also be different.

So, we calculate that energy of the system or roughly energy of the system and we get that this kind of a photo peak curve. So, if you see that for each detector, each time you will get this kind of a curve for each detectors. Now, this is called photo peak we will discuss about the photo peak. Once we will do the tomography things, but what we get is actually you get that how the count energy is changing number of photon counts versus number of this count photon count energy. So, you see that this kind of a curve and then in this channel we put some discriminator of filters to record the count only which is coming directly from the source and those counts or those area is called photo peak.

So, what will happen now there is a question there is lot of things to discuss I am trying to cover in a little bit brief. If you have any problem please discuss me over the assignment, we can drop me the questions, I would love to answer those things. So, what we do actually that even our tube lights is also emitting photons. Now, hardware is not able to detect the difference between that photon and the photon which is coming from the gamma rays other than the energy that the energy of this tube light photons will be much lower compared to the photons which is coming from the gamma rays. So, and there will be some noise also. As you know that we will all the electronics generate some noise and that is why we put the preamplifier and amplifier, so that I can increase the signal to noise ratio, I can amplify my signal, so that I can reduce the noise.

Now, this is the ways, so all these things are incidenting they are actually contributing towards the count. So, to detect that which are the count which is coming from my source which is relevant to me what are the count which are not coming from my source or which is coming from the source, but has been got attenuated because of the several collision. It means which is not directly coming or straight coming from the source we have to neglect those counts.

So, we draw number of photon on y-axis and energy on the x-axis, and you will get this kind of a curve. In that curve you will get a prominent peak and that peak will actually represent the energy of this source. So, like in this case, we are using cesium 137 as a source which energy is 662 k e v and that is why we are getting a peak at 662 k e v and this is the sample where the red bracket you are seeing is called the photo peak. It means that is the peak or that is the peak which is directly coming from the source we are very sure about it.

So, we put a discriminator of filter which actually reduce the remove the counts which are below than this photo peak or below the energy which will below in this photo peak. It means any energy which is less than this, it will be discriminated it will not be kind of recorded any energy which is higher than this which also not be recorded. So, we record only the photo peak counts and that is what we call it as a photon count time series history and that is being done by the single channel analyzer or multi channel analyzer where we can have multiple channels or energy channels. So, this is the electronics part of it how the data has been recorded. So, the photon count which we record actually the time series history the graph which I have shown you is only for the photo peak it is not for these grounds which are actually noise. So, we record the photo peak counts.

Now in with the development of the electronics earlier we used to use this all these electronics separately and that is why the system used to be look very bulky. But now with the development in the electronics and coming with the modern electronics nowadays we actually can accommodate all this devices in a single device and that is called multi input data acquisition system or MIDAS. And this is the multiple data acquisition system and this one unit if you will see this one unit is called single channel analyzer, analyzer.

Now, these knobs you are seeing that knobs are actually to set the setting of the detectors. So, one knob is for high voltage supply that how much voltage you want to supply, one knob is for the discrimination putting the limits on this energy spectra, so that you can acquire the count only those counts which are directly coming from the source. So, this is another device we need to do the recording.

Now, there are several steps as I said in the RPT. In the RPT there are several steps as I said that first step is the photon counts, second step is calibration and third step is reconstruction. So, what we were discussing about the photon count till now, and the hardware which is needed for the photon count experiments. Now, as I said that for the reconstruction what you need you need to put the tracer particle at a various known location before performing the experiments.

And the challenge is to do that at in-situ condition, in-situ condition means suppose I want to perform the experiments for a particular solid circulation rate or particular amount of the solids say in the gas solar system particular gas velocity I have to do the experiments you calibration for exactly same condition. It means for that much amount of the solid and for that solid velocity for that gas velocity. So, you have to do that the calibration at in situ and during that in situ calibration now we put the tracer particle at several known location and you got the count on the detectors.

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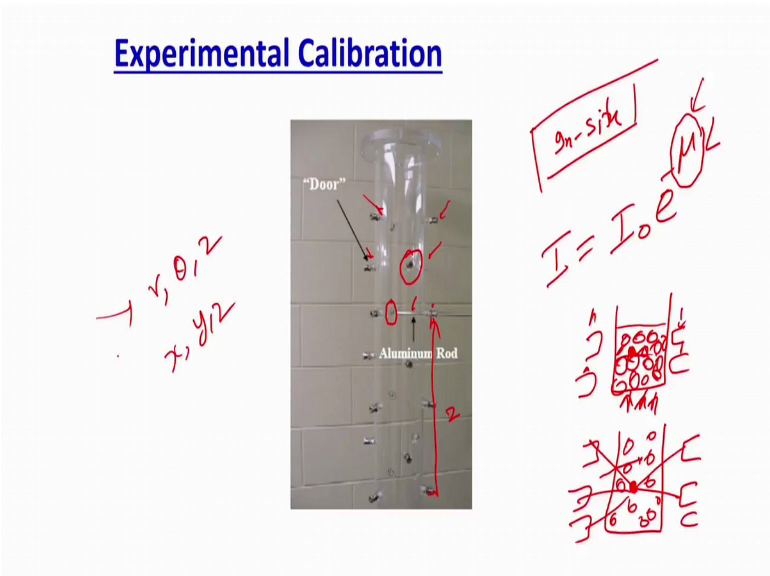

Now, how we can put the tracer particle. There are several ways to put the tracer particle. And if you go and see the literature on the radioactive particle tracking you will see that every one device derive of quantity or design or calibration device based on their column, operating condition, column geometry and column size. So, what we are going to discuss is one of the method which is very simple and we always use that in our laboratories.

So, now the first question is you can ask that why in situ calibration, because I said that we are if you are using I equal to I naught e raise to power minus mu L, what I need I need this attenuation coefficient for that location of the tracer particle. And this attenuation coefficient will be differ based on the operating condition. So, suppose if I am operating a gas solid fluidized bed say, this is my solid and this is the pad bed condition suppose and we know that if I pass the gas a velocity will come when the particle will start moving. So, in the pad bed condition, if suppose this is my tracer particle the red color and these are the detector placed, what will happen the attenuation will be more because all the solids are perfectly packed. So, attenuation it will see lot of solids.

Now, definitely depending on the density say gas have a very low attenuation; the materials which have a higher density is going to have a very high attenuation. So, you are going to see lot of solids your attenuation will be different. So, what will happen you will see the different count on all these detectors.

Now, if I fluidize suppose what will happen the similarly these are the detectors which will be placed say and now the particles has been fluidize. So, what will happen if they fluidize, the particles will move far from each other. And now if suppose this is my tracer particle now the counts recorded on these detectors will be different, because now it is seeing less number of the solids. So, if because it is seeing less number of the solids it is going to have less recognition. So, now, the count will improve, so that is the region that you need to have you have to take care of this mu distribution which is clearly the function of the operating condition and that is why we need to do the calibration at in situ condition.

So, what we need to do at in situ condition, at the same operating condition, we need to put the tracer particle at several known location. Now, there are several days as I said in literature everyone use a different method depending upon the operating conditions say what is my operating condition that I am operating at a very high pressure or very high temperature, whether it is a gas solid flow whether it is liquid solid flow. So, depending upon the type of the reactor, depending upon the size of the reactor, different calibration strategies has been developed by the different researcher, but idea is to place the particle at a known location.

So, generally what we do in our lab we put the pores several pores near at the wall. So, these are the pores. And I know the pores because we are designing the column I put the pores I know the r theta and z position of this pores. So, I can say that instead of r theta and z say if it is a rectangular I will say x, y, z position of the tracer particle. So, I will sorry of this pores. So, I know this pores now we take a rod and we put a tracer particle on the top; I do not know how much it is visible, but I will show the next figure where you can see clearly that there is a tracer particle which is on the top.

So, you can see that there is a small tracer particle here which is on the top. So, this is the tracer particle. And we put your instead of the threaded rod, so that you can move the thread and you can change the location of the r value. So, the z of the port is fixed; the theta of this port is fixed, and you are now changing the r value. So, you will prove the you will change the r theta and z position of the tracer particle, and you will record the counts, so that is the one way of doing the calibration, but that should be at in situ condition I have drawn taking the photograph at empty column, so that we can explain the facts.

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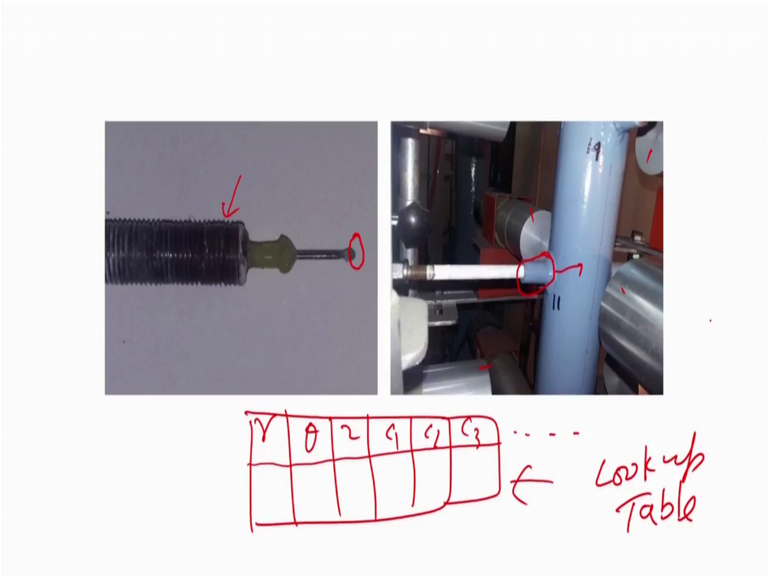

So, what we do suppose this is the opaque column. So, we take this kind of a threaded rod, if you see this figure. We put the tracer particle on the top this is my transfer particle. And at the in situ condition we place the transfer particle through these pores and they are detected placed which actually record the counts now definitely these detectors are going to record very high counts compared to the other detectors which are placed here. So, I will get for the calibration, if I put it here I will get that what is the count recorded on each detector for dislocation of the tracer particle it means I will have say r theta z. And I will have c 1, c 2, c 3 and so on all detector how the counts is changing for r theta and z.

Then what I will get do I will just move this thread further. So, the particle will move further inside. So, I will change the it means what I did I change the position of the r again I will record the count on each detector. So, what will happen I will have a lookup table we call it lookup table which says that how the particle trace; however, the detector counts are changing with the particle position. So, this is called calibration. Then we perform the experiments we get the time versus count, we compare both two, and we calculate that what is the position of the tracer particle.

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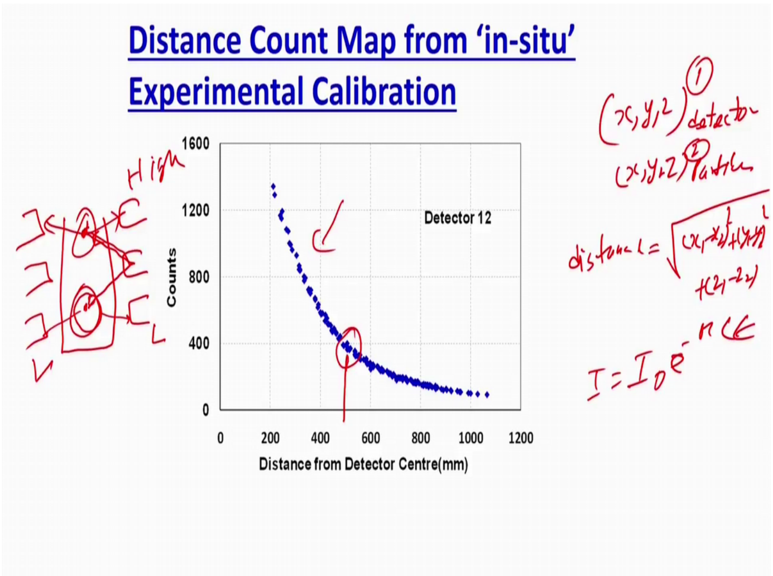

So, what you will get actually if you do the calibration experimentally you will get it that how the count is changing with the distance from the tracer particle. So, I know the position of the detector I know the position of the detector it means I know the x, y, z coordinate of the detector. I know the x a, I will write it as a detector I know x, y, z are power position of the particle I know this coordinates I can calculate the distance that will be nothing but under root x 1 minus x 2 square plus y 1 minus y 2 square plus z 1 minus z 2 square. So, I will add one to this say two to this I will get that distance.

So, what I will get how with the distance tracer particle position you can say or you can say distance from the detector a particular detector, the counts on that detector is changing. And as we know it is going to follow I equal to I naught is from minus mu L, you can do the calibration you can validate it whether it is following or not. And you can see that it is following that curve a bell kind of a curve or a Gaussian curve which is showing that it is following the Beer-Lamberts law.

So, it is the exponentially the counts recorded on the detector is changing with the distance. So, similar graph you can prepare for all the detectors. So, you will know that at what distance what count you are expecting on that detector. Now, why we need several detectors, because there can be a position when suppose what can get confusion one can ask the question suppose this is my column, I am using this two detector; if suppose the particle is moving vertically downward then the count on this location distance of this location in this location will be the same.

So, what will happen in that case in that case I will not have a unique picture, I will have I can either reconstruct this position of the particle or this position of the particle because if I will go to this lookup table they will give me the same counts this count if I mean distance of say 500. This is going to give me the same count and that is the reason why we place the several detectors to cover the entire area. So, yes it is true that this you will calculate with one detector we will not get the unique solution.

So, if I take the counts and that is the region that why while reconstructing we take the counts from all the detectors. Now, if suppose I have a two detectors here two detectors here. What will happen for this location for this location now these distances are low these detector distances are low. So, they are going to get high counts, they are going for this location they are going to get low counts and the vice versa will be true for this location. These two detectors will get higher count; and these two detectors will get lower count.

So, if I do the combine if I take the effect of all the counts all the detector counts to reconstruct the position of the particle, I will always get a unique solution and that is the major plus point of the RPT technique that you always get a unique solution because you have only one particle where the counts are coming. Compared to the other technique where the unique solution is also sometimes are difficult and that is the major added advantage of this technique.

So, what we do we generate the photon count time series history that how photon count time series is changing with the tracer particle location. So, distance and location is same you are moving far; distance is increasing we are coming close distance is reducing. But as I said it is impossible to do the calibration, experimental calibration for all the location inside the tracer inside the reactor or inside the column of interest. Why, because of the two position it is very difficult to put a pores at all the physical location because the pores require some physical area. So, you cannot put the tracer particle at all the location.

Second it will be very time consuming for each firing what you need to do it in situ condition you have to put the particle at several location, pull the particle out. Now, if you are pulling the particle out suppose it is a gas solid or liquid solid what you need to do you have to first set down the system neither the solids will start leaking from this pores or liquid will start leaking from this pores.

So, what you need to do you have to shut down the system, then you have to remove it then again you have to put it into the other pore, you have to close this pore, you have to put it in the other pores you have to again operate the system. You have to wait for a study state to achieve and then you have to do the same exercise that you change the location. So, these two major disadvantages of the experimental calibration; the first is it is almost impossible to do the calibration at all the location in sight and remember that the tracer particle is free to move anywhere inside. So, what you have to do you have to actually need the calibration at all the known location or you need to depend on the interpolation.

Now, we know that the interpolation had certain accuracy, we do not want to get involved in that. So, for the better accuracy, we want that I should have a calibration count for all the possible position inside the vessel of interest. So, for that purpose, as I said earlier that the calibration we cannot do only we cannot depends only on the experimental, we have to also do a software calibration which is actually based on the Monte-Carlo algorithm. Now, how to do that the software calibration we will discuss it later.

Thank you.