Measurement Technique in Multiphase Flows

Dr. Rajesh Kumar Upadhyay
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

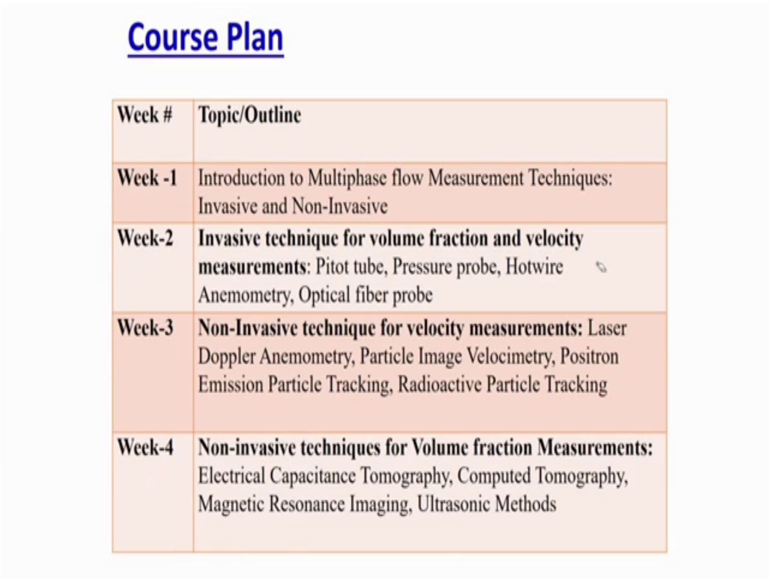
Lecture – 01
Introduction to Multiphase flow Measurement Techniques

Good afternoon to everyone. So, this course is about the measurement techniques in multi-phase flows. Now we are going to discuss in this course about the different techniques used to measure the flow behavior of multi-phase flow reactors, before that my brief introduction, I am Rajesh Kumar Upadhyay associate professor in Department of Chemical Engineering IIT Guwahati.

And my major research area is on multi-phase flow reactor diagnosis, and I am working on the different techniques and trying to implement those techniques to investigate the flow physics in multi-phase flow reactors. Now coming back to the course, as I said that the course has actually two things, one is the measurement techniques, and about the multi-phase flow reactors. I would expect that you should have a brief idea about the multi-phase flow reactors, but is still to bring everyone in the same platform.

Initially what I will do? I will introduce about the multi-phase flow reactors, and different terminology used to analyze the multi-phase flow reactors. And then I am going to divide the whole course in the following content.

(Refer Slide Time: 01:30)



Course Plan

Week #	Topic/Outline
Week -1	Introduction to Multiphase flow Measurement Techniques: Invasive and Non-Invasive
Week-2	**Invasive technique for volume fraction and velocity measurements**: Pitot tube, Pressure probe, Hotwire Anemometry, Optical fiber probe
Week-3	**Non-Invasive technique for velocity measurements:** Laser Doppler Anemometry, Particle Image Velocimetry, Positron Emission Particle Tracking, Radioactive Particle Tracking
Week-4	**Non-invasive techniques for Volume fraction Measurements:** Electrical Capacitance Tomography, Computed Tomography, Magnetic Resonance Imaging, Ultrasonic Methods

So, first week we are going to discuss about the multi-phase flow reactors, and multi-phase flow measurement techniques. So, here in this week I am going to tell mainly about the different terminology used to define the multi-phase flow, then what are the multi-phase flow techniques invasive.

And I am going to divide that multi-phase flow techniques in two parts one is invasive, and another one is non-invasive. And we will discuss, what is invasive and non-invasive techniques? So, this is the basics where we are going to bring everyone in the same platform, I am going to tell you about the basics, definitions and all.

Then the next week what we are going to do? We are going to again take the invasive techniques, and invasive techniques again actually we will divide into part velocity measurement technique, and volume fraction measurement techniques. Now what are these two we will discuss in the first week?

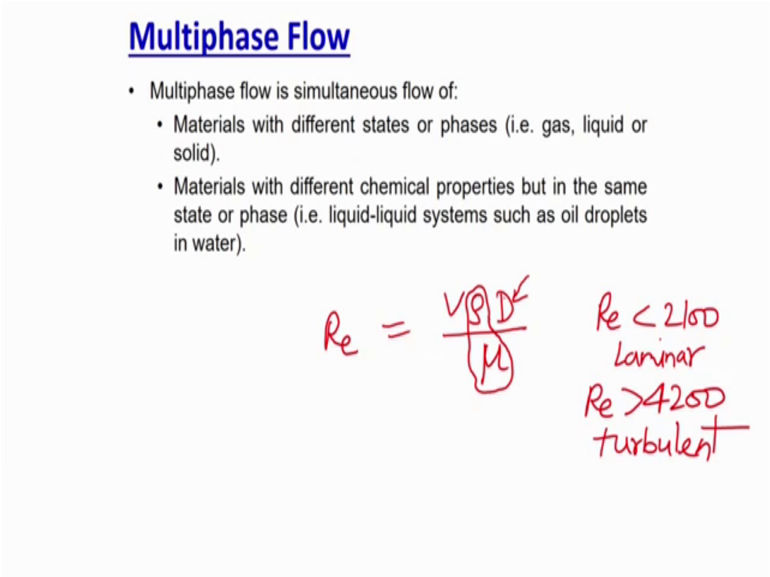
That is all that what is volume fraction, and what is the velocity measurement and when I say the volume fraction measurement or velocity of measurement what do I mean. So, under this in this week what we are going to do we are going to cover mainly 4 techniques, one is pitot tube then pressure probe hot wire anemometry, and optical fiber probes. So, we will discuss about the principle of these techniques advantage disadvantage and limitations if any, then in the next week I am going to focus on the non-invasive technique, and actually I am going to take 2 weeks to cover the non-invasive techniques, because this is the technique which is widely used in the modern era. And particularly if one is interested in the higher studies or research, this is a technique which are widely used to diagnosis the multi-phase flow reactors now. So, I am going to spend 2 weeks on this that is why, and the first week what I will do I will take the non-invasive techniques, and we will discuss about the non-invasive technique which is used for velocity measurements

So, here I will discuss the mainly again 4 techniques, one is the laser Doppler anemometry particle image, velocimetry positron emission particle tracking, and radioactive particle tracking technique. And I would spend more time on the radioactive particle tracking technique here, then next week what we are going to do we are going to take the non-invasive technique only for volume fraction measurements.

So, here what I am going to do that how to measure the volume fraction in multi-phase flow reactors by using the non-invasive measurement techniques, and again I am going to discuss the 4 techniques mainly, it is electrical capacitance tomography, computed tomography, while discussing the computed tomography I would also introduce something about the x ray tomography.

And we will see that why I have not put it in the same topic, as this as a different topic, then I am going to discuss about the magnetic resonance imaging, and ultrasonic methods which are used for medical as well as now it is been popular to use for the chemical reaction engineering, or reactor engineering also. So, this will be the overall course plan, and with this course plan we will start our course, and I will try to put a assignment for each section. And we can discuss whenever it is needed you can drop me up your questions, and we will try to answer whatever the queries we have.

(Refer Slide Time: 04:32)



Multiphase Flow

- Multiphase flow is simultaneous flow of:
  - Materials with different states or phases (i.e. gas, liquid or solid).
  - Materials with different chemical properties but in the same state or phase (i.e. liquid-liquid systems such as oil droplets in water).

$$Re = \frac{V\rho D}{\mu}$$

$Re < 2100$ Laminar

$Re > 4200$ turbulent

So, let us begin the course and as I said that I am first going to introduce about the multi-phase flow. That what is multi-phase flow.

Now, it is not like that measurement techniques are required only in the multi-phase flow, measurement techniques are required even for the single phase flow, and since the generation of the fluid mechanics I can say or any transport processes the measurement becomes a integral part of that. So, why it is important because if I want to understand about any system, I need to major the flow behavior or the process conditions of the system. So, let us take a very simple example.

Suppose I have there is a fluid which is flowing in a pipeline, and I want to major that what is the behavior of the flow. So, how we characterize the behavior of the flow in single phase, we say that if I want to find it out the flow behavior we want to calculate a number called Reynolds number, I hope everyone's knows, what is Reynolds number but to introduce that Reynolds number; Reynolds number is we wrote D upon mu.

So, this Reynolds number is a dimensionless number, and so Reynolds number Re is equal to V rho D upon mu. Now let us see that I know that what is the fluid which is flowing inside the pipe, and I know the diameter of the pipe. So, if I know the diameter of the pipe actually I know this. If I know the fluid, then I know both rho and mu of the fluid, but what I do not know is the velocity.

So, what I need to do I need to measure the velocity of the fluid, in the pipe line and if I (Refer Time: 06:12) to measure the velocity of the fluid in the pipe line, I will able to calculate the Reynolds number. And if I am able to calculate the Reynold number I will able to say that if Reynold number is less than 2100 my flow is laminar, and if Reynold number is greater than 4200 my flow is turbulent, and in between if I have something I am in the transition region. So, even if I want to characterize a fluid flow or single phase fluid flow in a pipe line, I need a measurement which is called velocity.

So, I need a velocity measurement and based on that I can calculate the Reynold number. So, since the origin of all these transport processes not only in the fluid Magnus, I have taken a typical example of the fluid mechanics, but even if it is a heat transfer I need to measure the temperature to find it out that, how much heat flux will be transferring by using the Fourier's law. Similarly in the mass transfer I need to measure the concentration.

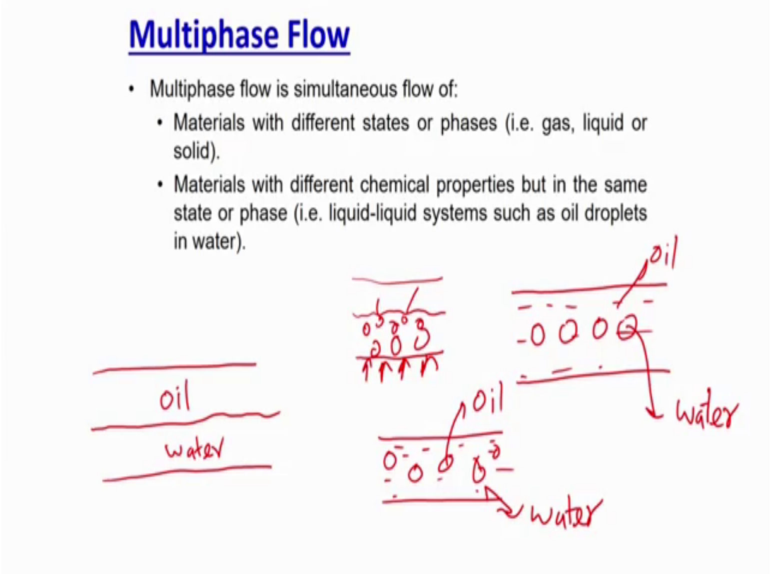
So, any transport processes you think about, if I want to understand about that transport process, I need to under measure something some variable to define my transport processes and to define the behavior of that transport processes. So, multi-phase flow reactors are no different in that also we have to measure something to find if we want to classify the (Refer Time: 07:33) the multi-phase flow reactor or understand the multi-phase flow reactors or vessels, we need to measure some parameters to understand that.

Now before going to that measurement part I would like to first discuss is that, what I need to measure. So, to do that before that I would like to introduce about the multi-phase flow that what is multi-phase flow. So, there is some confusion in the multi-phase flow always, and people generally believe that once I say multi-phase it means the state. So, actually multi-phase flow means the flow of either 2 different or 2 or more different states which are flowing together like gas liquid or solid.

These are the three states we know. So, if the flow of the two different states are taking place that is; obviously, as multi-phase flow reactors, it can also be defined that if the 2 species which are same in the phase wise their state wise, they are same like liquid the state wise either they are liquid or they are gas, but if their chemical properties are different they will still be considered as a multi-phase flow.

So, multi-phase flow reactors broadly or formally can be defined as the simultaneously, flow of materials which is having or different states or having a different chemical properties. Now once I say that state is different it means, 1 phase can be in gas, 1 phase can be in liquid, and 1 phase can be in solids. So, or a combination of all 3. So, like if suppose if I talk about a typical distillation column. So, what happened there is the 2 phases are available 1 phase is in the vapor, inside the distillation column and one phase can be in liquid. So, what happened in each tray, if you think about the tray there are some liquid holdup on the tray?

(Refer Slide Time: 09:15)



Multiphase Flow

- Multiphase flow is simultaneous flow of:
  - Materials with different states or phases (i.e. gas, liquid or solid).
  - Materials with different chemical properties but in the same state or phase (i.e. liquid-liquid systems such as oil droplets in water).

And so, if I think about the each tray what happened there are some liquid hold up inside the tray and vapor of the another phase or the same phase is actually pass through this tray. So, what happened they form a small bubbles and then they go to the next strip? So, if you think about the each tray on the distillation column it is a flow of a gas, and liquid system and that is become some multi-phase flow reactors, and or multi-phase flow contactors and the behavior of the distillation column.

We all know that is going to depend on the plate efficiency and plate efficiency is going to depend on the interaction between the liquid and this bubbles that all vapour bubbles, which is passing through this. So, that is we can make the multi-phase flow systems very complicated and interesting, because they are different states are involved and the behavior of the multi-phase flow reactors or performance of the multi-phase flow reactors or contractors depends on the interaction how these 2 phases are being interacted.

Similarly we can if the 2 similar phases (Refer Time: 10:16) states are moving together, they can still be a multi-phase flow like a typical example is oil water flow in any petroleum industry. So, oil and water both are in the same states both are in the liquid phase, but still if they are flowing together there can be a multi-phase. So, what happens that if the oil and gas flow together, then depending upon the properties the oil can be in continuous and we can see the droplet of the water? So, this is oil which is in continuous and we can see the droplet of water.

So, first the water is being in the suspended phase or in dispersed phase in the oil, or oil is in the dispersed phase in the water depending again on the properties I am telling then again the same thing that, if suppose this is oil phase and this is the water continuous. So, this can be oil, and this can be water. So, depending on their property the oil can disperse in water or water can disperse in oil both are in the same state in the liquid phase, but still this is a typical multi-phase flow example.

Even for the matter of the fact if suppose both are in the they both are not dispersed, and they are separated with layers. So, suppose this bottom part is water because of having higher density and top part is oil because of having lower density, if they are flowing together they are still considered as a multi-phase flow, because of the interface they are going to interact with each other. So, the multi-phase flow I hope it might be clear, now that the multi-phase flow is the simultaneous flow of either two different states or same state, but their chemical properties would be different. So, these are classified as a multi-phase flow. Now multi-phase flow can take place, in reactors, can be in contactors, actually if you go and analyze any industry this multi-phase flow can see it can be considered as heart of any industry.

So, you think about any contactors which you have studied in your under graduate studies, all you think about most of the reactors you will see that everywhere there is a multi-phase. Now what is the region that multi-phase flow is being used so widely, now if I come to the reactor purpose I will just take you back to the basic CRE courses chemical reaction engineering courses, which you have done is that we say that to increase the reaction rate, what I need to do there is two kind of resistance one is mass transfer resistance one is kinetic resistance.

Now most of the time even if I have a very good candidate I am not able to do the reaction at that rate which is desired, and that is mainly region is without the surface area. Now to increase the surface area what we can do I can try to do the reaction, in presence of some solids.

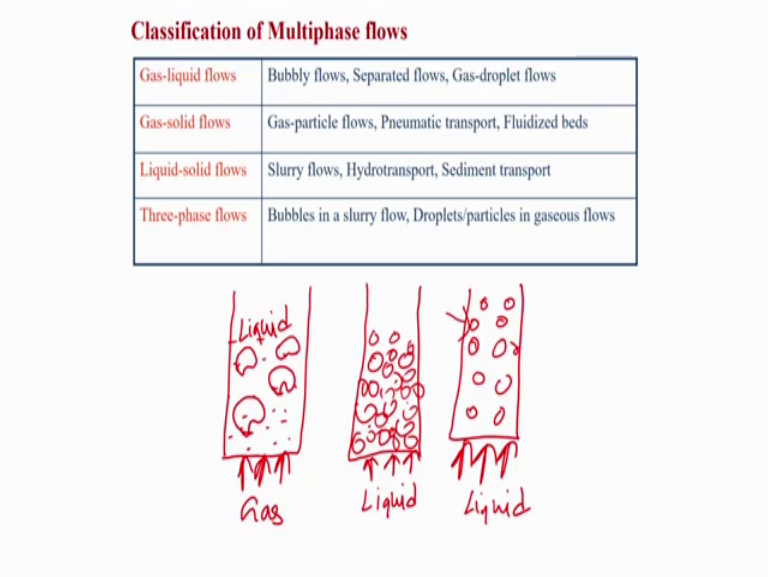
Now, if suppose there is 2 fluid which are doing the reaction say gas and liquid or say liquid, and liquid in the same state and they are not multi-phase, if they are going trying to do the reaction. The reaction will take place only at the interface if they are mixed, if they are not mix there at the interface if there mix then maybe in the bulk, but still the surface area will be very low.

Now how can I increase the surface area, if I make a solid if I suspend some of the solids there, and let allow the reaction to happen on the surface of the solids, then what will happen the surface area will increase drastically, because now I have a small fine particles on which the reaction is taking place. Then the rate of reaction will be actually I can enhance by enhancing the mass transfer. So, that is the region that what we want we want to have increase the rate of reaction, or we want to increase the production rate. So, we want to increase the surface area and therefore, generally we use solid as a catalyst to enhance the reaction surface area as well as the selectivity.

As we know that most of the reactions also produce the by products to minimize the byproducts production, or increase the selectivity of the desired product, we use some catalyst and most of this catalysts are actually in the solid form to increase the life of the catalyst, as well as to increase the surface area to reduce the mass transfer limitations.

So, this is the basics that why the multi-phase flows are becoming the heart of any industry, and is the need of the day to maximize the rate of production.

(Refer Slide Time: 14:45)



Classification of Multiphase flows

Gas-liquid flows	Bubbly flows, Separated flows, Gas-droplet flows
Gas-solid flows	Gas-particle flows, Pneumatic transport, Fluidized beds
Liquid-solid flows	Slurry flows, Hydrotransport, Sediment transport
Three-phase flows	Bubbles in a slurry flow, Droplets/particles in gaseous flows

So, what we can do we can classify the multi-phase flow, in the different form as I have discussed some of this, but the major classification of the multi-phase flow, is actually can be divided in 4 part, one is the gas liquid flows, the gas liquid flows is like a simple example is bubble column or distillation column which I have discussed. Now what do you mean by an if I mean by the gas liquid flow, it means if the liquid say I can fill in a column in a batch which is not moving, and I can is parse the gas from the bottom of the column. So, this is my gas and this is my liquid.

Now, what will happen if I parse the gas from the bottom of the column, the gas will form a bubble and why I am drawing the shape of this bubble in the mushroom shape, there is a reason behind this, and you can go and see the danckwerts theory or surface renewal theory or other theories which are available for the bubbles, you will see that there is a region of being forming this kind of bubbles. So, what will happen the bubbles will form, now these bubbles will actually do the mass transfer with the liquid and based on that if it is a reactor, and we want a gas liquid reaction?

The reaction will take place if it is a contactors some mass transfer will take place with from the gas to liquid or liquid to the gas. So, in that way this is the typical flow is being used which is called bubble column and it is widely used in many industries for the contacting purpose as well as for the reaction.

One of the very important reaction which is known as a fisher trops reaction is also occur in the bubble column. So, it is a very important reaction class, where the bubble and gas and liquid actually contact with each other, and flows together or they actually do some reaction together or mass transfer. So, this is called gas liquid flow, then there is another class which is called the gas solid flows.

Now this class is again very popular and widely used in most of the industries, but we in petroleum bulk chemical, chemical pharmaceutical industries because most of our catalysts as in the solid phase. As I discussed and the cracking pro process of the crude oil is actually take place in gas solid reactors. So, what happen in the gas solid depending on the type of the reactor there is a huge classification here, and the gas solid flows I am not going in that classification.

But consider a simple case that of a packed bed that the solids are being packed in the reactor, and gas is being passed through the bottom of the column. Now if this there will be some interaction some mass transfer or some reaction will take place, and this clean kind of flow is classify as a gas solid flows. The most of our absorber or of this kind of a flow where the solids are being packed, which is used as a absorbent and the gases is being passed to purify that. So, suppose I have a mixture of hydrogen CO CO 2, I can pass the gases through this kind of adjournment which is very selective for a particular component. So, they may absorb the CO CO 2 and H 2 depending on the adsorbent properties.

So, this is a typical gas solid flows or we can also do that I can make the flow at a little I cannot pass the gas at a little bit higher velocity, and suspend the solids. This is called flutized bed reactors and being again widely used in many industries, mainly because of their better heat and mass transfer characteristics, and why there is a bit and heat and mass transfer because the solids are suspended so, your surface area has increased compared to the packed bed reactors.

So, that is why these reactors for the reaction purpose is preferred, because you have enhanced mass transfer and heat transfer, but this is also a classification of gas solid multi-phase flow reactors, there are certain things which is called pneumatic transport which is being also used in many industry to transfer the solid from one place to another place.

So, there is two ways you can use a belt conveyor or you can use the truck or any other transportation system to transfer the solid from one place to another place, but if you are using a belt conveyor it is very costly, transporting it through the vehicles within the industry it is sometimes very difficult, because of the space requirement. So, generally we use the pneumatic conveying where we use the air pressure to transfer the solid from one location to another location. So, that is also considered as a gas solid flows, and widely used in many industries.

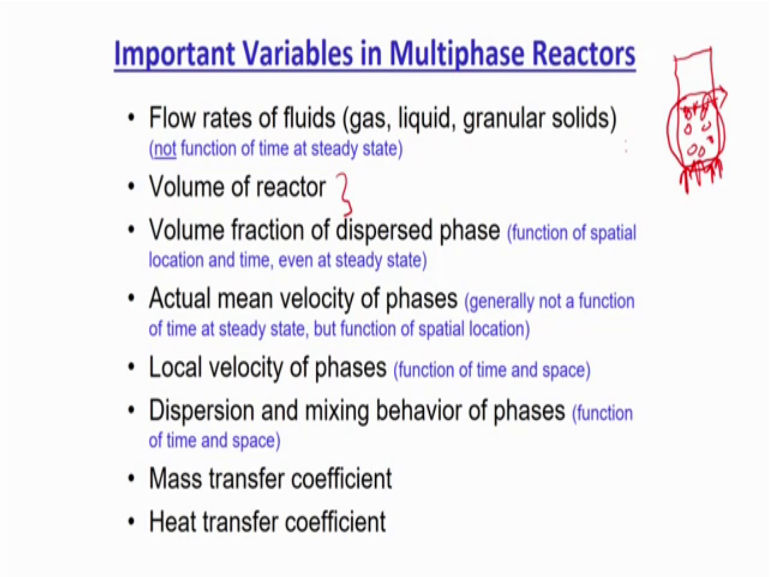
Now, why I am emphasizing about this because I want to just give you an idea, that what kind of applications we are going to target. And depending on the application what are the parameters will we want to study. So, those things will discuss later on, but let us first discuss about the classification of the multi-phase flow, then comes to the liquid solid flows just like a packed bed and fluidized bed reactor, I can say that the similar condition where the solid is being packed with the and instead of the gas liquid is being passed, so the bottom of the column, or liquid is being used to slutice the solid, and this is also used in many industries presently the sedimentation industries, slurry transport industries, mining industries, where we have we mine the ores, and you want to separate the useful ore come from the non-useful ore or unused utilized ores. So, you use the all those separation process by using the liquid solid flow. So, that is also a class, and then another class is where all the 3 phases are flowing together gas liquid and solids.

So, this is called slurry column or 3 phase fluidized bed reactors where all the 3 phases are flowing together, the application of these kind of reactors is also very huge. And again I will go to the fisher trops, now with the development of the new catalyst the Fischer trops reactions are actually is being done. In the slurry bed, in the slurry bubble column in which the solids are being used as a catalyst gaseous phase is being used and is as a product, and gas phase is used as a reactant and liquid is as a product.

So, that is called Fischer trops reaction and which is typically used now in a 3 phase flow. So, this is the classification of multi-phase flow reactors. Now moving to the next what I would like to discuss is that once we are saying about the multi-phase reactors, and I am trying to give that what are those reactors or different type of the reactors, the important parameter that why we want to study about this course.

And what we want to study and what is the critical need of this. So, mainly as I have discussed that if you want to understand about any reactor, or any contactors, or any flow through system you need to measure something. Now what are the measurements needed particularly in terms of the multi-phase flow reactors.

(Refer Slide Time: 21:36)



Important Variables in Multiphase Reactors

- Flow rates of fluids (gas, liquid, granular solids) (not function of time at steady state)
- Volume of reactor
- Volume fraction of dispersed phase (function of spatial location and time, even at steady state)
- Actual mean velocity of phases (generally not a function of time at steady state, but function of spatial location)
- Local velocity of phases (function of time and space)
- Dispersion and mixing behavior of phases (function of time and space)
- Mass transfer coefficient
- Heat transfer coefficient

So, as of single phase flow, I want to definitely understand that what is my flow rate of different fluids, now I am telling it fluids, but I will say that different phases. So, it means what is my flow rates of either gas liquid or solids, if they are flowing together or if only one phase is flowing then also, I want to understand that. What is the flow rate? So, I want to definitely measure this quantity to understand that. What is the flow rate requirement?

So, that as of the basic single phase flow I can calculate the Reynolds number if needed. Now what is the issue in that one can always say that, if you want to measure the flow rate you always have some measurement devices, which is used in the single phase flow like Rota meter venturi meter, or orifice meter or pitot tube, or any other meters mass flow meters to measure the flow rates, what is the problem.

Now the problem here is that how this sometimes the phases are not separated, they are exactly mixed. So, like if I talk about the crude oil, then the crude oil once we are exploring the crude oil from the well or from the reservoir, then what happened to explore those crude oil.

We actually inject the steam of water to push the oil up, now during that injection some of the water is mixed with the oil. And whatever we get is actually not only the oil, but a mixture of oil and water, and that makes the measurement of those things is very difficult because whatever the understanding of venturi meter, orifice meter, or Rota meter, we have is for single phase flow which is based on either the pressure drop or on the some calibration method for the case of Rota meter.

So, all those things is based on the single phase, but now I already have a fluid which is in the multi-phase. Now if one good parameter in this case is that if I able to maintain a steady state, then this parameter actually is not a function of time; so though if the phases are already mixed, then it is difficult to measure the flow rates. And we will try to discuss that if the phases are already mixed how to measure the flow rate of the fluid, but if they are suppose for a very simple case.

If I assume that there is a pipeline in which I am injecting oil separately water separately, and if these are not mixed already they are the pure species, when I am injecting into the reactor or into the pipeline, then yes measurement can be done and at the steady state condition they will not be the function of time too. So, then it will be easier, but in case if they are already mixed it will be little bit difficult to understand the how to measure the flow, and that case we will try to discuss during the course.

Then the second thing is volume of the reactor now this is interesting, because one can always find that say that why the volume of the reactor can be a parameter, which I need to measure. So, I can always fabricate a reactor, if I am fabricating a reactor I already know the volume of the reactor, but the most of the time the problem is it is true actually for many of the cases, but most of the time the problem is that suppose a case of fluidized bed, in which there is solids which are actually suspended in the fluid, they are not going out let us assume they are not going out.

They have just suspended in the fluid. So, what happened because of the air velocity some of the solids actually try to go up? So, if I make the reactor volume up to this level till the label solids are suspended, then what will happen because of some fluctuations local fluctuations in the flow conditions, and why that local fluctuation will take place will discuss later on, but let us assume there are some local fluctuations, then what will happen the label of this bed a label of these things can change. And because of that the moment the label will change, and if I make the reactor up to the same size as the solids are suspended this particles will go outside. So, what will happen I will lost my solids?

And if I lost my solids if suppose they are catalysts I will lost the amount of the solids or weight of the solids. So, what will happen my conversion or the rate of reaction will change. So, to minimize that losses what we do we add some extra length here. So, that I can make sure that even if there is some local fluctuations, the solids will not go outside of my reactor, but though this solves a problem it is also create adding this extra length solves the problem, but it also creates the problem.

Now how it create the problem, now I have added the extra length I have solved the problem that my particle will not go outside of the system and magnate of the catalyst will remain intact or remain same, but I missed the information about the size of the reactor that what is the reactor size. So, can I take this reactor size the complete size the answer is no, because my reaction or my mass transfer is going on only in this volume.

So, I need to find it out what is this volume. So, that is also a challenging for multi-phase flow reactors. Now thereafter it comes to the volume fraction, now this is the main thing which we are going to discuss mainly in this course that how to measure the volume fraction. So, that is again a problem, now once I say volume fraction it can be of dispersed phase though I have written about the dispersed phase, but it can be the volume fraction of the continuous phase 2, I have written only dispersed assuming that they are 2 phases only, and if I know the volume fraction of the one phase, I will be knowing the volume fraction of the other phase also.

Because the overall mass continuity will be there so, epsilon one it means volume fraction of the phase one plus volume fraction of phase 2 should be equal to 1. So, if I know the volume fraction of phase 1, I can calculate the volume fraction of the phase 2. Now there is a problem in that. So, what is volume fraction? I will discuss later on I am just trying to introduce the course. So, be a with me and will introduce this volume fraction later on, but what is a problem in measuring the volume fraction. So, it means suppose there is a gas and there is a liquid inside the pipeline, I want to understand how much fraction of is of the gas is present inside, and how much fraction of the liquid is present inside. Now why this is a problem? Now I do not I want a global value for sure that also I want to calculate even calculating that is a problem, but I also want a local variable, it means how this stages are distributed inside.

Now, why this distribution is important, because as I said that if suppose I have a 2 phase flow reaction which is the liquid is reacting with the gas, the reaction will occur only at those locations where the gas is present. If the gas itself is not present there is no chance of any reaction. So, therefore, for a better design operation and scalar it is important to understand that how this gas phase is distributed inside, to do that what I need a functional a spatial distribution of the phases.

So, I need that how this phases are spatially distributed inside second is this phases are changing with the time is this, distribution itself is changing with the time, if yes then how this distribution is changing with the time. And even if I maintain a steady state flow condition at the inlet, it is being observed that these phases the spatial distribution of this phases locally keep on changing, and that makes my life even more complicated.

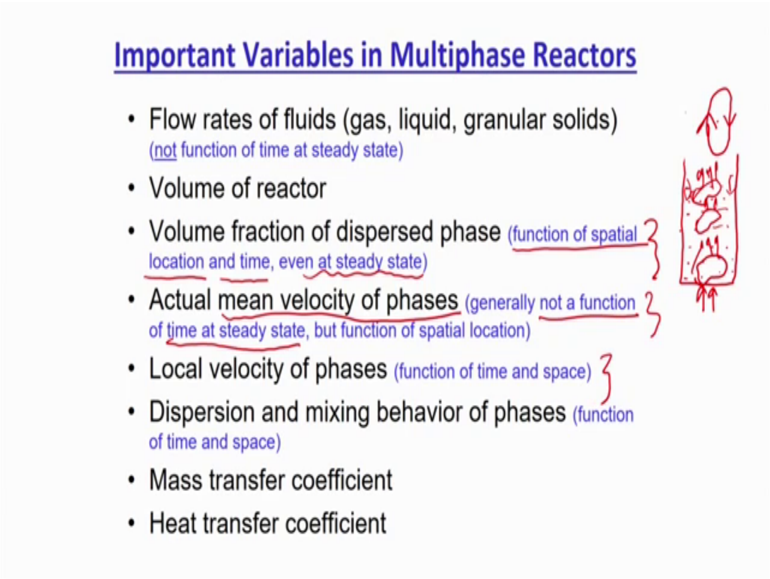
So, it means what I need temporal resolution, I need a spatial resolution, in my technique temporal resolution means my technique should be very fast it should capture it, all the possible instances all the possible changes with the time. A spatial resolution means even at a small distance, if I move from say center to a very close distance to the center say 2 mm 4 mm, 5 mm I should able to understand how my fractions are changes.

So, that is going to be very critical, and we are going to see that how to do that and which are the techniques which are capable of doing this or is there is any technique, which can do both. So, we will discuss all those things, but that is the reason that we are going to follow the volume fraction, because this is a very critical quantity, and the mass transfer rate, or the reaction rate, or extent of the mass transfer, or instant of the reaction is going to depend, that how these phases are distributed, they are interacting how their distribution is changing with the location and with the time so, that is what is the one of the critical parameter, we want to find it out, and the problem I have already discussed that even at a steady state condition, they are a function of time locally and they definitely change with the space.

Now again I want to measure another quantity is called mean velocity of the phases. So, whether it is a gas liquid or solid, I want to understand the mean velocity. Now once I say the mean velocity, it can be the time average mean velocity, it can be ensembled average mean velocity, we will discuss about these 2 mean velocities, I hope some of you might have idea about that, but still I will try to introduce this in later on this course.

So, what happened that mean velocity, because as I said that it is a mean velocity is I am talking about time average mean velocity definitely it is not going to be the function of time at a steady state condition. So, once it is the steady state will achieve it will not be the function of time. So, it will not be a function of time, but still it will be a spatial dist location. So, even if it is ensembled average or time average it will be the function of location. Now why it will be the function of location the mean velocity let us discuss, let us try to understand.

(Refer Slide Time: 31:07)



Important Variables in Multiphase Reactors

- Flow rates of fluids (gas, liquid, granular solids) (not function of time at steady state)
- Volume of reactor
- Volume fraction of dispersed phase (function of spatial location and time, even at steady state)
- Actual mean velocity of phases (generally not a function of time at steady state, but function of spatial location)
- Local velocity of phases (function of time and space)
- Dispersion and mixing behavior of phases (function of time and space)
- Mass transfer coefficient
- Heat transfer coefficient

So, suppose I have a column and I will take again a case of the gas liquid system where the liquid is in the batch the most simplest case, and I am injecting a gas from the bottom let us assume I am injecting a single bubble. So, I am injecting a single bubble, and then or 1 1 bubble after a periodic interval.

So, suppose if the single bubble I am injecting what will happen along this bubble, the liquid will move up either on the top of the bubble or on because of the weight formation of the back of the bubble, it will move up and with the time what will happen the bubbles will move upward. Now again if I inject the second bubble after some time is the same profile will follow. So, what will happen liquid at the center will actually move up in the time average, since as well as in the ensembled average sense, but liquid near the wall will actually move down because gases will erupt from the at the top and go to the atmosphere.

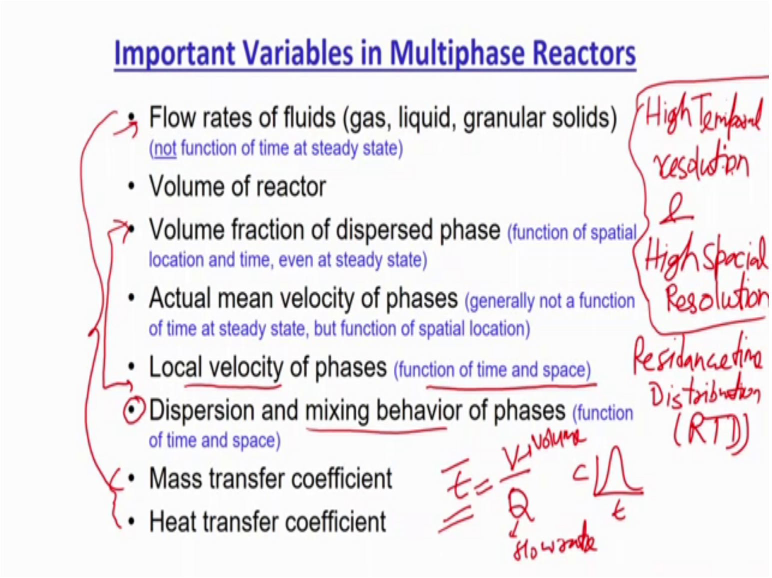
But liquid cannot pass through the column. So, they have no other option the liquid element which is moving up they have to come down towards the wall to fill the volume. So, because of that I will see a proper flow pattern, in which liquid will be moving up from the top going down from the bottom, and in between somewhere the velocity may be 0. So, it means what even in the steady state condition, even at a time average condition, I am getting this picture, but it is changing with the locations. So, I need to measure the mean velocity at steady state condition it may not be the functional it will not be the function of time, but still it will be the function of a spatial location.

So, I need to measure the mean velocity first, and then I need to see that how the mean velocity is changing with the location. So, that put a extra challenge, now another parameter which I need to do just like the volume fraction is the local velocity of the phases. Now this is very again very critical and important now why it is important, because we know that for most of the fast reactions the kinetics of the reaction actually depends on the local hydrodynamics compared to the global hydrodynamics so, time averaged hydrodynamics.

Now what does it mean that it means that I need I should have a global information of mean velocity information, but I should also have a formation about the local velocity. Now how to find the local velocity information, and whether it is a function of time or a phase if this is a local velocity I am talking then definitely it is going to be the function of time, because suppose I discuss the same case in which liquid was filled in the column and a bubble was injected. So, what will happen with time this bubble will move up? So, if I see the velocity at this location say, what will happen initially the velocity here was 0, but when the here the velocity was 0, but when the bubble will reach here the well you will see some velocity .

So, because of that so as I was discussing that the local velocity of the phases is important, and why it is important that as we already know that in our reaction engineering that once the reaction is very fast, then the local hydrodynamics actually plays more important role compared to the global hydrodynamics.

(Refer Slide Time: 34:29)



Important Variables in Multiphase Reactors

- Flow rates of fluids (gas, liquid, granular solids) (not function of time at steady state)
- Volume of reactor
- Volume fraction of dispersed phase (function of spatial location and time, even at steady state)
- Actual mean velocity of phases (generally not a function of time at steady state, but function of spatial location)
- Local velocity of phases (function of time and space)
- Dispersion and mixing behavior of phases (function of time and space)
- Mass transfer coefficient
- Heat transfer coefficient

High Temporal resolution & High Spacial Resolution

Residance time Distribution (RTD)

$\bar{t} = \frac{V}{Q}$

So, it means if suppose my fluid is flowing inside, if my bubble is flowing inside of the same example that liquid is filled, and I am passing the gas from the bottom of the column in form of it will form a bubble, then what will happen if I see in the time everywhere, since then initially at time t equal to 0 at the top the velocity of the liquid will be 0, because there will be no movement or very small movement will be there, and the bubble is moving from the bottom of the column. Now once the time passes the bubble will move up, and then what will happen the velocity at the bottom will actually goes to 0 there will be no bubble here left. So, there will be no bubble. So, bubble is now here the liquid is still at the bottom.

So, what will happen now the velocity of the liquid here is very low, and the velocity at the middle section will be higher. After some times the bubble will reach till the top of the column, and at that condition what will happen the velocity of the gaseous or liquid will be very low near the bot near the bottom of the column, and it will be higher near the top.

So, what is going to happen the local phase velocity is again going to be the function of time as well as the space? So, space why it will be the function of a phase the region becomes same that the bubble is moving only at the center of the column. So, liquid will move up at the center down near the ball. So, it means even the local velocity of the fluid will change with the space, and because the bubble is moving with the time up the velocity of the fluid, local velocity of the fluid will also change with the time.

So, that makes this column this local velocity is a function of both time, and space and again it makes the problem more complicated, and we will discuss some of the techniques for the velocity measurement both through invasive and non-invasive methods, and we will try to see that which technique can give me ideally a very good spatial as well as temporal resolution.

So, the technique which we called both can provide both will be the ideal technique to use in the multi-phase flow reactors, if I want to understand the reactor in detail even at the local scale, then comes the dispersion, and mixing behavior of the phases now, from your undergraduate studies you might have been knowing that the one of the important parameter to analyze the reactor is mean residence time or residence time distribution, we also called it RTD.

Now this is a quantity which is very important and can be easily calculated or relatively easily calculated, I will say not easily calculated and gives the global picture about the behavior, and that is why this is very popular in many industries people do the RTD studies to do the troubleshooting as well as to understand that design or behavior of the column or reactor.

Now what happened in the single phase flow how we perform the RTD studies, we inject some of the tracer a mass transfer which can change either the PH or any quantity in the flow, and we measure the concentration of that mass traces are at the outlet. Now depending upon whether what type of the reactor it is behaving I will get as some concentration versus time diagram of that mass tracer.

And based on that this concentration versus time graph our diagram, I can predict the behavior of this reactor, and I calculate the dispersion number through which I can calculate the mixing. So, I can define the mixing now this is very straightforward or is relatively is easier in single phase flow, but once it comes to multi-phase flow this, becomes a problem. The first problem is the tagging the individual phase itself is a problem. Now suppose I have a gas liquid again same reaction and I want to find it out the residence time of the gases.

So, what I need to do, I need to find a tracer which can go inside the bubble and then I can see that how these bubbles are moving. So, I will inject that tracer in here, but that tracer should able to go inside the bubble, and I should then able to calculate their concentration in form of the bubble at the exit, because once they will go ahead and exit they will disperse.

So, I should able to find the concentration of the bubble. So, doing that tagging a special phase itself is a problem other than that the many things which we use in the basic RTD. The first thing which we use we cannot calculate in the multi-phase. Now the first thing which we use in the basic RTD is called mean residence time, which can be which is calculated by V upon Q where V is the volume of the reactor or the column, and Q is the flow rate. Now in multi-phase flow actually I cannot calculate this t bar.

So, in single phase flow the good thing is, if I know the volume of the reactor, if I know the column dimensions, I know the volume of the reactor, I can measure the flow rate easily by using any of the measurement devices like, venturi meter, orphis meter, or Rota meter. So, ideally I can calculate the t mean, and then whatever the graph I have said I can calculate that whether the t mean of this graph, and this theoretical value is matching or not.

If it is not matching there sometimes rules through, which I can find it out whether there is a recirculation, whether there is some dead zone, or something whatever is happening inside. So, I can do that by calculating the t mean from this place to the ideal t mean, the problem with the multi-phase flow I cannot calculate it. Now why we cannot calculate it the first thing I have already told you that volume of reactor itself, is a questionable that what should be the volume of the reactor, as the height of the liquid may change depending upon the velocity of the gases in this case, or height of the solids may change depending on the velocity of the gas or liquid for which the column is being used. So, I will not able to calculate the exact volume that is the first problem. Second problem is with the flow rate. Now why we have used the flow rate which is outside assuming that the velocity inside will remain same, because the superficial velocity the column is empty.

Now in this case the one phase is going to disperse inside. So, actually you cannot take a empty column area. The area will be actually whatever the area is being occupied by that phase, now that is going to change, and that may change with the time, with the location.

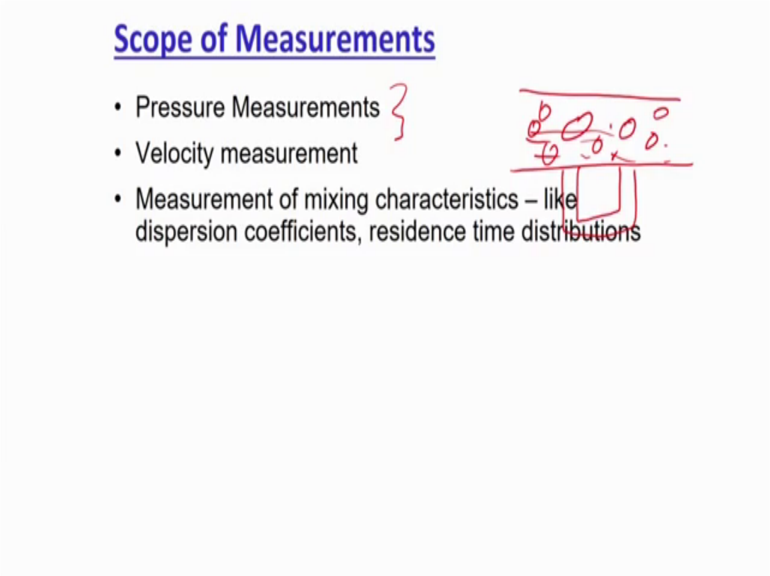
So, that makes the problem more complicated to analyze the RTD curve, still the RTD is a very popular technique and many people are using, and we will also try to discuss that how to perform RTD in multi-phase flows, and how I will also try to discuss some of the case studies.

So, this is the another an issue and this again, I told you that it is going to be the function of time and space, and then they are 2 derived quantity which have mass transfer coefficient, and heat transfer coefficient ideally I need to measure all this if I want to design the reactor. So, that I can find it out what is the limitation, or what is the resistance offered because of the mass transfer, and resistance offered due to the heat transfer.

So, that I can predict the temperature profile, and concentration profile inside the reactor. So, these are the quantities which ideally we want to measure, and we will try in this course to focus mainly on these 3 quantities, and we will briefly discuss about this and once will discuss 4 we will already come to know about the flow rates measurement that how to do that. So, that is the thing which we are going to cover in this course, why it is important, what are the problem, and how to encounter that we will see it later on, but I have tried to keep till now, of basics that how to measure these things, what are the problems whether it is going to be the function of time or not.

Whether it is going to be the space or not, and it means ideally what I want the as a technique. So, I will say my wish list should be high temporal resolution, and high spatial resolution. So, what I want from all this is high temporal resolution, and high spatial resolution, it means what I want my technique to be very fast. So, that it can see all the changes inside. So, it be very accurate with the space it means the scale it should be as low as possible. So, that I can see that with the location how the things are moving. So, this is the two parameters, which we are going to discuss when I will discussing the techniques.

(Refer Slide Time: 43:03)



Scope of Measurements

- Pressure Measurements
- Velocity measurement
- Measurement of mixing characteristics – like dispersion coefficients, residence time distributions

Now what we are going to see the scope of measurement? I trade that the parameters which we want to measure, but one of the most things which we are going to say is that the pressure measurements. So, we are going to discuss about the pressure measurements, as we all know that if I am talking about the flow, the flow always occurs because of the delta P.

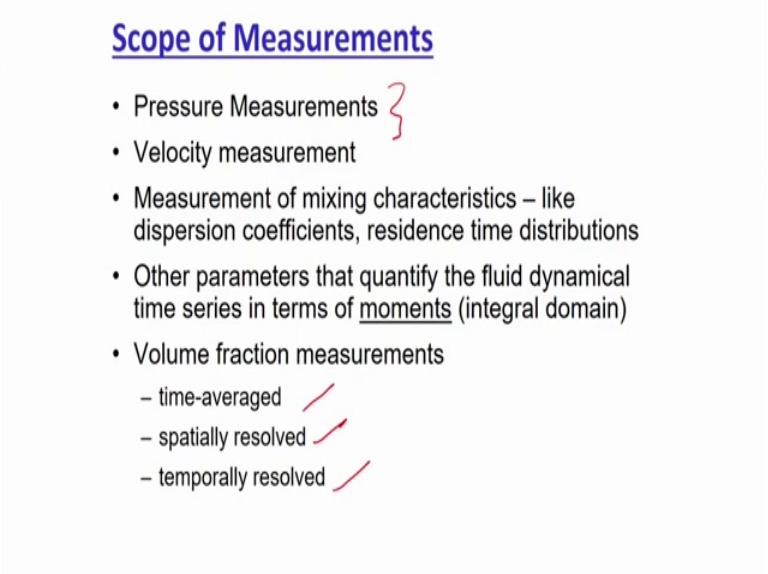
So, if I want to do a flow in multi-phase condition also if the 2 fluid are flowing, a still the delta P requirement is there. So, I would like to calculate that how to measure the delta P in a multi-phase flow reactors in single phase it is easy, because you can just use a Nano meter, but in multi-phase flow, this is difficult because suppose if I am using a pipeline. How to suppose this is a condition in which the flow is separator water is down oil is up, and if I am measuring the flow here, in this line with the manometer the delta P how what whether I will even to see the complete effects ok.

So, that is the question we need to answer, and more problem comes once the flow is dispersed. So, suppose if the oil is dispersed in the water, and seeing the bubbles or droplet sorry of the oils, and then it is passing through the water is there. So, what will happen whenever they there is oil you will see a fluctuation? So, it will pass through you keep on seeing the fluctuations in your mano meter reading.

So, the moment oil will come you will see some fluctuations. So, getting a steady state value a constant reading of delta H in the manometer is very difficult, similar problem will comes even if you use a pressure gauge. So, how to calculate the delta P or how to measure the delta P, and then how to analyze that delta data itself is a issue in multi-phase flow reactor, and we will try to discuss that in the pressure measurements, then we will do the velocity measurement and already discussed that what we want to measure local velocity, as well as the mean velocity once I say mean velocity, I am interested in both time average velocity, as well as ensembled average velocity, and we want to measure actually all 3.

Then we want to measure the mixing characteristics as I said that if I measure the RTD or, if I measure the volume fraction as well as the velocity, I can ideally major mixing characteristics. So, I would like to measure the mixing characteristics dispersion number residence time distribution, all these things we want to measure, and will try to see that. Then we want to measure not only the mean velocity or the local velocity we also want to measure the moments of that.

(Refer Slide Time: 45:28)



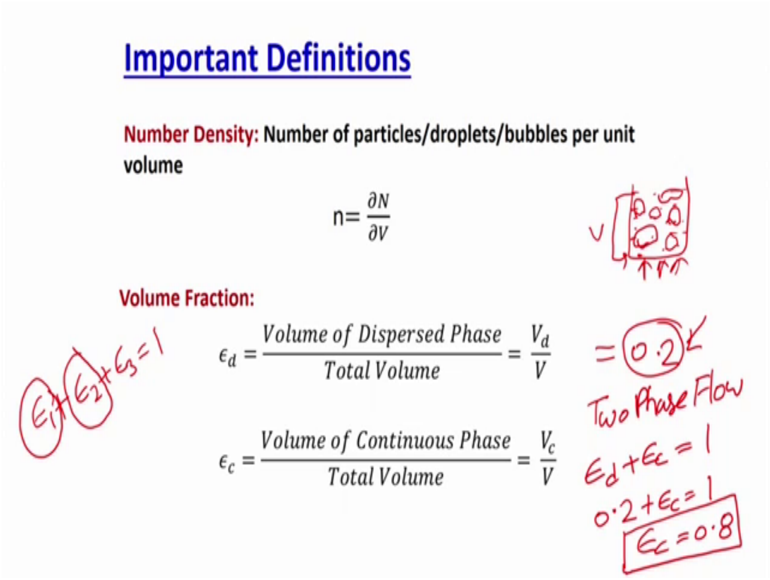
Scope of Measurements

- Pressure Measurements
- Velocity measurement
- Measurement of mixing characteristics – like dispersion coefficients, residence time distributions
- Other parameters that quantify the fluid dynamical time series in terms of <u>moments</u> (integral domain)
- Volume fraction measurements
  - time-averaged
  - spatially resolved
  - temporally resolved

Now what does I would mean my moments. So, I just do not want to measure the mean velocity I will also like to measure the fluctuation velocity. So, I will say it as the first order moment of the velocity. I would also like to measure the RMS velocities, I would also like to measure diffusion coefficient from the RMS velocity, I would also like to do some time series analysis of the velocity data. So, to find some chaos analysis. So, we will see that can we do that, can we do all these things because more the detailed information we have better the understanding we will able to generate.

Then I would like to measure the volume fraction, as we have already discussed that how the phases are being distributed. And as I said I would like to measure the time average, picture, the spatial picture, and temporal resort picture. So, I want to see all these 3 how these quantities are wearing, in the time average sense, in the spatial sense, and in the temporal sense. So, all these things we would like to see in the scope of measurement and will try to discuss all these methods all these measurement this methods, the techniques which can measure all these parameters. So, we will discuss some of the techniques to measure the pressure, when you discuss some of the technique invasive, and non-invasive to measure the velocity, and we will discuss some of the technique to measure the volume fractions.

(Refer Slide Time: 46:50)



Important Definitions

Number Density: Number of particles/droplets/bubbles per unit volume

$$n = \frac{\partial N}{\partial V}$$

Volume Fraction:

$$\epsilon_d = \frac{Volume\ of\ Dispersed\ Phase}{Total\ Volume} = \frac{V_d}{V} = 0.2$$

$$\epsilon_c = \frac{Volume\ of\ Continuous\ Phase}{Total\ Volume} = \frac{V_c}{V}$$

$\epsilon_1 + \epsilon_2 + \epsilon_3 = 1$

Two Phase Flow

$\epsilon_d + \epsilon_c = 1$

$0.2 + \epsilon_c = 1$

$\boxed{\epsilon_c = 0.8}$

So, now before going to the main course starting the measurement techniques, I would like to briefly introduce about, some of the definitions, or some of the numbers of quantity, which we are going to use widely in the course I would highly recommend that you should do some multi-phase courses. And if you have done the multi levels courses maybe these things are repeated, and you might have seen these numbers or this values, but still to make everyone on the same platform, I am going to tell the same thing.

The first thing in the multi-phase flow we define is number density. Now what does the number density means, the number of particle droplet or bubbles per unit volume? So, now, I have a reactor and as I said that there are 2 phases. So, suppose the dispersed phase is suppose bubble, in a liquid gas liquid system again I am taking the same example, and suppose I am is purging the gas from the bottom, what will happen I will see some bubbles. So, number density is that what is the number of your droplet, your particle, in this case what is the number of bubbles per unit volume that is called the number density ok.

So, this is one of the very important parameters which we need to understand that what is the fractions have the density available of the stage number density, then the volume fraction which we I was using, since long that this is the volume fraction measurement we want to do. Now I would like to formally introduce the volume fraction. So, what does volume fraction means; volume fraction means, the volume of dispersed phase divided by the total volume.

So, again I will go to the same. So, if I know the number density of the phases which is say in the same system gas liquid, if I know the number density if I know the volume of each particle, I will know the total volume of the dispersed stage. So, either if I know the say number density of the particle, and volume of the each bubble.

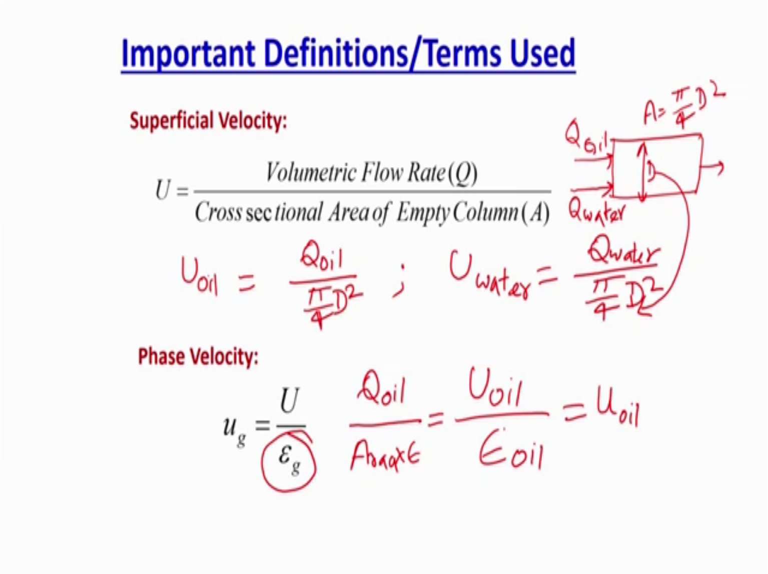
Then if I multiply them then I will find the total volume fact volume of the dispersed phase to the volume of the reactor, and volume of the reactor is this till what the liquid is being fed the height, after the bubble injection. So, that is the volume of the reactor. So, if I know this the ratio of this to volume, or I can say the dispersed phase volume to the total volume is called volume fraction.

It means that much fraction out of the total volume is being filled by the gas. So, if I say that the volume fraction say this is equal to 0.2 it means 20 percent of my total volume is being filled by the gases. Similarly for the continuous phase I can say the volume of the continuous phase divided by the total volume, it will be the volume of VC is the volume of the continuous phase total volume of the reactor is V.

So, if I say that the same example if the 20 percent is my dispersed phase volume, if for the 2 phase flow I am writing this 2 phase flow that is important, I can say that epsilon d plus epsilon c will be equal to 1. So, if I know that the volume of dispersed phase is 0.2 I can say that this plus epsilon c is going to be 1, it means epsilon c is going to be 0.8. So, if I know the volume fraction of one phase for the 2 phase, flow system I can easily calculate the volume fraction of the second phase. Now for 3 phase flow this becomes little bit typical, because if the 3 phase flow is there will be 3 phases epsilon, 1 epsilon, 2 epsilon 3, this 3 will be equal to 1 it means, if the flow is 3 phase your problem is more complicated in 2 phase flow you just need to measure the 1 volume fraction. If you measure 1 volume fraction your job is done, in 2 phase 3 phase flow you have to measure at least 2 fractions, if you measure the 2 fractions, then only will able to find the fraction of the 3rd.

And then only you will able to see that if this measurement is correct. So, in that way the 3 phase mixture systems is becomes little bit more complicated. So, that is the reason, but the volume fraction definition itself is defined as the volume of the phase, divided by the total volume of the reactor. So that is called or the total volume not the reactor total volume or both the phases. So, that is called the volume fraction.

(Refer Slide Time: 51:09)



Important Definitions/Terms Used

Superficial Velocity:

$$U = \frac{Volumetric\ Flow\ Rate(Q)}{Cross\ sectional\ Area\ of\ Empty\ Column(A)}$$

$$U_{oil} = \frac{Q_{oil}}{\frac{\pi}{4} D^2} \; ; \; U_{water} = \frac{Q_{water}}{\frac{\pi}{4} D^2}$$

Phase Velocity:

$$u_g = \frac{U}{\varepsilon_g} \quad \frac{Q_{oil}}{A_{area} \times \epsilon} = \frac{U_{oil}}{\epsilon_{oil}} = u_{oil}$$

Now, another definition I hope this everyone knows, but it still for the sake of again bringing everyone on the same page, we introduced the term superficial velocity you all might be knowing superficial velocity is nothing, but the volumetric flow rate, divided by in the (Refer Time: 51:25) cross section area of the empty column.

Now for the single phase flow it is very simple that the say liquid is passing through a column, or in the pipeline then what we say that if I know the volumetric flow rate, which I can measure through pitot tube, I can measure through a venturi I can measure through orifice or rotameter, I know the area of the column if I know the diameter I know the area of this pipe. So, area of this pipe will be pi by 4 D square.

So, I can do the Q by A I will find it out the superficial velocities. So, the superficial velocity is the concept is being widely used in industries, in chemical industries mechanical many people have used, this in the engineering to find that what is the velocities. Now once we see in the multi-phase flow we will use the superficial velocity of the continuous phase, and dispersed phase.

So, I say that if suppose the case where oil and water is being fed separately both of threads of pure assuming. So, I can measure the what oil flow rate, and I can also measure the water flow rate by using the techniques, which I have already said pitot tube, orifice meter, ventury meter, Rota meter, then if I divide individually by area of the (Refer Time: 52:41) the column or area of the pipe, I can get find the superficial velocity of the water or superficial velocity of the oil. So, in this case suppose if I want to find superficial velocity of oil that will be Q of oil divided by pi by 4 D square.

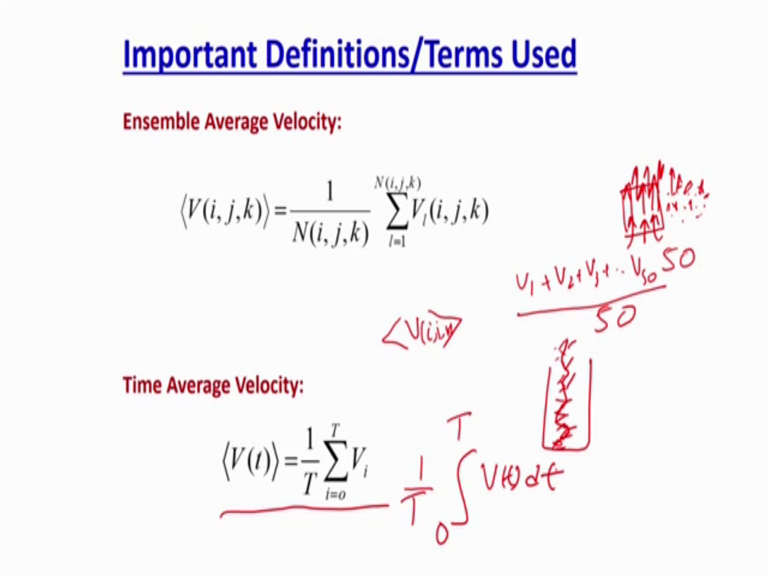
So, now, I am not worried that how the oil is whether dispersed or not how much fraction is have being covered by oil, or how much fraction is being covered by the water I am not worried about that, I am defining that this is the my oil flow rate let us assume only oil is flowing inside the pipe, and based on that I will define the superficial velocity.

So, in the term of during the course once I say that superficial velocity of this, phase it means only that we are assuming only that phase is flowing inside the column or reactor. Similarly U of water will be, but equal to Q of water and divided by pi by 4 t square, again I am telling you that this D and this D is actually equal it means, you are using the diameter of the column you are not worried about that whether how much fractions is being covered. So, that is called superficial velocity. Now once the superficial velocity concept is there we have to now define a term which is called phase velocity, the phase velocity means the velocity of that phase inside the column. So, ideally superficial velocity is really superficial they never exist actually inside, but the phase velocity can be calculated if I know the superficial velocity, and how the phase velocity can be calculated. So, the phase velocity will be nothing, but the superficial velocity divided by the epsilon g it means, what I am saying that I have calculated the say for the same condition oil.

If I know the superficial velocity of the oil if I know the epsilon of oil, it means the fraction of the pipeline which is being covered by the oil, then I can find it I had oil phase velocity inside the pipeline. And the concept remains same if you go with the concept what I will say the superficial velocity this is nothing, but Q of oil upon area, and this area is if multiplied by epsilon, I will say that this is the area cross sectional area which is being covered with oil.

So, now, I am going in the actual area which is being covered with the oil. So, then if I calculate the velocity I will get the phase velocity. So, it means if I need the phase velocity I need fraction, that what is the fraction of that. So, that is the another term which we are going to use widely that is called phase velocity, which is being defined as superficial velocity divided by the fraction that phase has been covered of volume fraction of that phase.

(Refer Slide Time: 55:33)



Important Definitions/Terms Used

Ensemble Average Velocity:

$$\langle V(i,j,k)\rangle = \frac{1}{N(i,j,k)} \sum_{l=1}^{N(i,j,k)} V_l(i,j,k)$$

$$\frac{V_1 + V_2 + V_3 + \cdots V_{50}}{50} \quad 50$$

$$\langle V(i,j)\rangle$$

Time Average Velocity:

$$\langle V(t)\rangle = \frac{1}{T}\sum_{i=0}^{T} V_i \qquad \frac{1}{T}\int_0^T V(t)\,dt$$

Now I was introducing about the ensembled average velocity, and time average velocities what is ensembled average velocity. So, ensembled average velocity is the velocity at a particular location if I see, I do not think about the time, I just think about that location how many times the particle is coming.

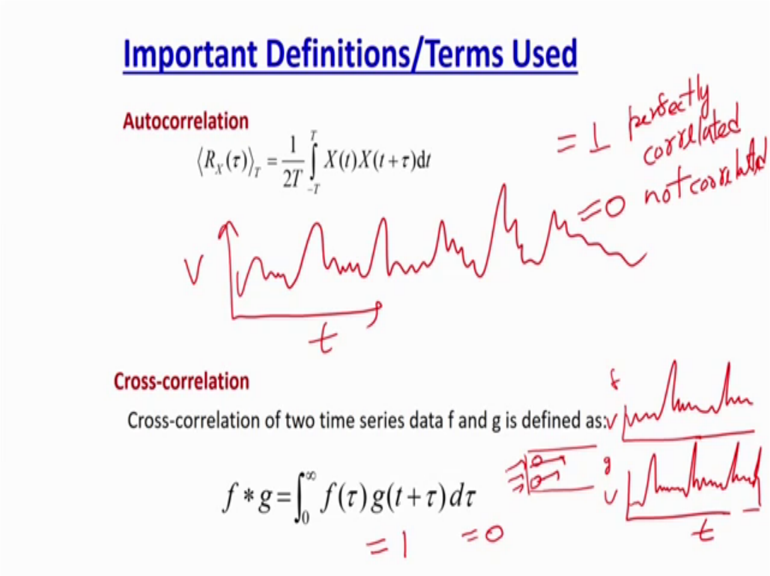
So, the ensembled average means suppose if I have a small section a fluid is moving here, several times. So, say several instances the fluid are moving. So, for all instances there is say these are instances and for each instance fluid has certain velocity. So, once I say ensembled average velocity, what I will do say I have a 50 instances for which the fluid comes within that element.

I will and each 50 instances the fluid had certain velocity I will add all those velocities say V 1 plus V 2 plus v 3 and so on to V 50, and then divided by the 50, that is called the ensembled average velocity, and why I write i j k, i j k are the indices which is showing that this is for a particular location. So, this will be the superficial velocity at a particular location it is called ensembled average velocity, in which I am using actually the number density, I am talking about the number of instances it came to that place, and each instances once it came to that place of when whenever we measure the velocities or whenever the particle come or that tracer come, then what was the velocity of that fit that tracer at that location. If I take the long time in ensembled average of or if I do the experiment for the longer time several time, the particle of this fluid will come at a particular location, we can measure the velocity there if I take the ensembled average, that velocity is called ensembled average velocity.

The second term is called time average velocity, now this is the notion of the velocity is continuous. So, it means if suppose I have to inject some tracer, inside the flow where the fluid is moving what will happen the tracer will also move with that time. If I each time it suppose I major the velocity, say V 1, V 2, V 3 which is changing with the time, and if I take the summation of that and divide it by the total time I will the time average velocity.

It means suppose the particle is moving with the time, what you are doing you are meeting the time at a certain intervals, and then you are just doing the one upon T 0 to T some books follow minus T to T, then it will be one upon 2 t this will be the t dt. So, this is called time average velocity. So, what we are interested, in we are interested in both ensembled average velocity as well as the time average velocities, and we will see that how to measure both the particles later on.

(Refer Slide Time: 58:26)



Important Definitions/Terms Used

Autocorrelation

$$\langle R_X(\tau)\rangle_T = \frac{1}{2T}\int_{-T}^{T} X(t)X(t+\tau)\mathrm{d}t$$

= 1 perfectly correlated

= 0 not correlated

V

t

Cross-correlation

Cross-correlation of two time series data f and g is defined as:

$$f*g=\int_0^\infty f(\tau)g(t+\tau)d\tau$$

= 1 = 0

f V

g V

t

Then we are also interested in the autocorrelation and cross correlation, and some of you might be knowing this, but is still for the sake of everyone and to make everyone in the same platform, I will try to repeat it. Now the autocorrelation is what autocorrelation is suppose I have a time series. So, suppose some tracer is moving or a fluid is moving inside.

And I have a time series say this is how volume velocity, let us say velocity is changing with the time, it can be even the volume fraction, it can be any quantity, it is a pressure how it is changing with the time. So, is there is any correlation, in the time series or in the tres suppose the tracer movement, is there is any correlation in the tracer movement with the time. So, to find that we find the autocorrelation function which says that use to the time interval it is from minus t to t or you can say 0 to t x t that function too, which is correlated with the function at a certain interval t plus tau a tau is of interval.

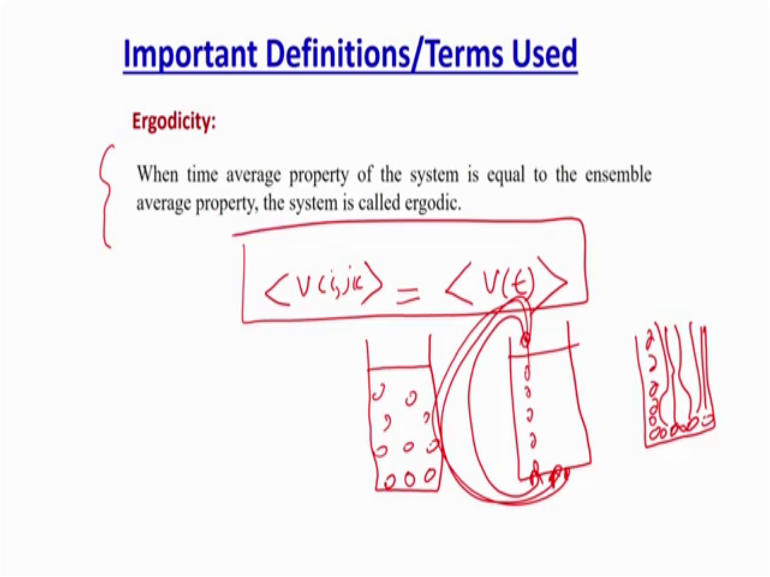
So, if the autocorrelation function is equal to 1 it means the flow is perfectly correlated, and if this is 0 it is not correlated at all and if it is between 0 to 1, we can say that extent till which it is being correlated. So, this is widely used to analyze the time series to do the time series analysis and to understand about the system, that whether the system is repeating himself or not whether it is a periodic or not and will discuss try to cover some of these points on during the course of our discussion of measurement techniques, and the post processing of the measurement techniques. Now there is another term which is cross correlation is used in some of the techniques to actually get the data, or to get the information what the cross correlation technique says, suppose I have a 2 time series analysis 1 is for function f and 1 is for variable g.

So, 1 is from variable f 1 is variable g or I will say that the same variable, but 2 different time series or 2 different particle time series if there is any correlation between them. So, that is called cross correlation. So, this is the time series of the first correlation first parameter or first series, and is it correlated with the second series. So, what does it mean suppose if I inject say 2 particles in a flow, now these 2 particles are flowing together ok

Now each particle suppose if I measure the velocity of each particle I will see some (Refer Time: 61:02) the times region analysis. So, this is say f and this is g for the second particle also I will see the time series that how the velocity is changing with the time. So, can I find that these 2 particle motions are correlated, if the value is equal to 1, again the motions are correlated if the value is equal to 0, then motions are not correlated in between they are partially correlated.

So, these information is needed to analyze the data, and will see in the measurement techniques that we will calculate this either to do the post processing to get some more information, or we will use these information to reconstruct or to get the parameters from measurement techniques. The same cross correlation, then this is a term which we are also going to use widely which is called a ergodicity.

(Refer Slide Time: 61:54)



Important Definitions/Terms Used

Ergodicity:

When time average property of the system is equal to the ensemble average property, the system is called ergodic.

$\langle v(i,j,k) \rangle = \langle v(t) \rangle$

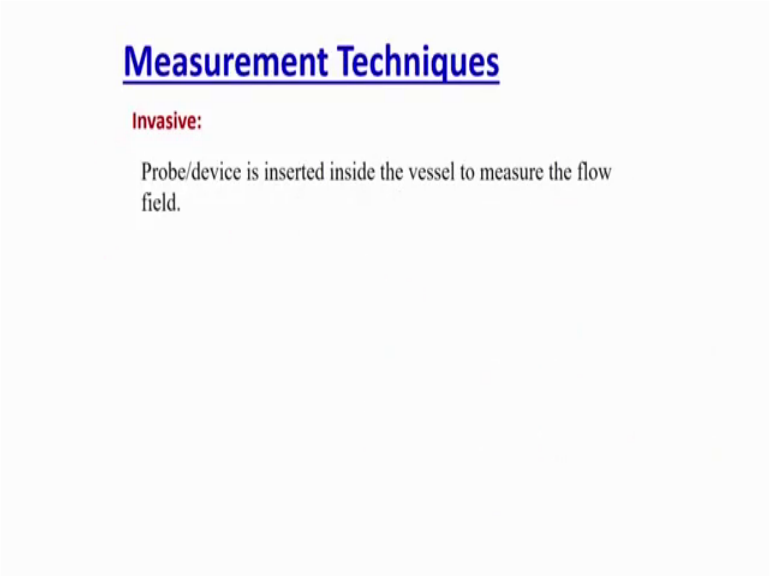
Now what is ergodicity when the time average, and ensemble average of this property of any a property is equal that is called the ergodic. It means if I am talking about the velocity then the V i j k, which is ensembled average velocity, is once it becomes equal to the time average velocity, the system is called ergodic in nature. Now what does it mean and this is very important in the measurement techniques particularly. So, suppose there is a this column in which a particle is being flowing.

So, if many particles are being flowing or say fluid, is flowing forget about the particle even let us make it single phase flow there is no 2 phase flow. So, if suppose there is a fluid is flowing and I want to track the motion of the fluid. So, for that what I can do I can inject some of the neutrally buoyant particle, and all our stream line potential flow all those fundamentals is being developed with the tracking of the particle path line stream line and all, and if you revise your undergraduate fluid mechanics courses you will see that.

So, what I can do I can either track the motion of this fluid with a single particle, where the single particle is moving and I can keep on tracking putting repeating the same particle. So, it means the single particle I have left once, the single particle will go up once it went on the top I actually have collected the particle, again I have re injected it, again I have re injected it, again I have re injected it. So, either I tracked the motion of a single particle for n number of time, or n number of the particle together all this n number of particle together.

And I track the motion of all this n number of particle that how they are moving. So, in one case I will get the ensembled average, one case I will get only the time averaged I will get that the motion of all the particles together, if both are giving me the same thing that is called ergodicity, and we will use the ergodicity concept very commonly particularly in the measurement techniques mainly once we talk about velocity measurement technique. So, this is called a ergodicity.

(Refer Slide Time: 64:07)



Measurement Techniques

Invasive:

Probe/device is inserted inside the vessel to measure the flow field.

So, with this the introduction on multi-phase flow, basic multi-phase flow, and the definitions or terminology which is needed to understand multi-phase flow, and multi-phase flow reactors, and measurement techniques I have covered. Now next I will start about the measurement techniques and we will classify the measurement techniques as I discussed in two part, one is invasive, and one is non-invasive.