Fundamentals of Fluid Mechanics for Chemical and Biomedical Engineers

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Lecture No. 2

Fluid Mechanics and Chemical Engineering

So, in this lecture we will be talking about role of Fluid Mechanics in Chemical Engineering discipline and we will take some different examples of chemical process equipment and discuss that how the role of fluid mechanics is important in the design and operation of these process equipment.

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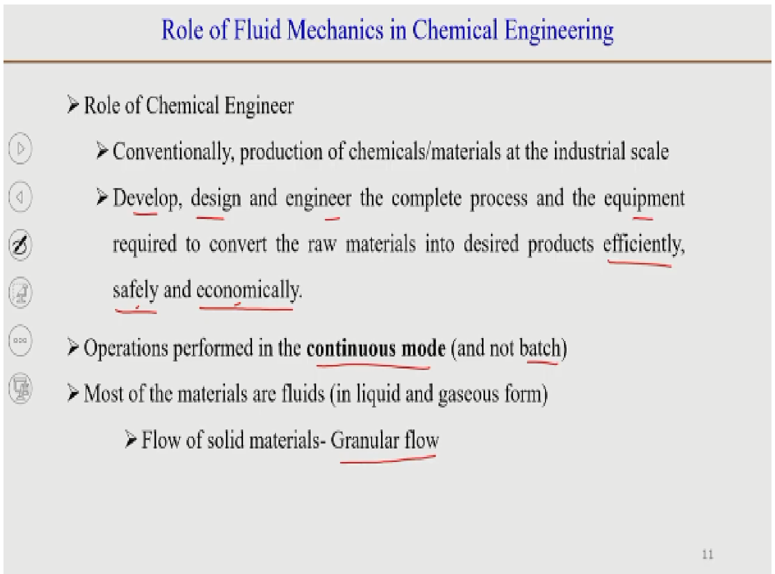

But before we do that, let us look at what is the role of a chemical engineer. So, when you studied or when you got admission into chemical engineering, if you are a chemical engineer, you would have been told or you now know that the chemical engineer is basically concerned with production of chemicals or materials at the industrial scale.

So, the role of chemical engineer is to scale up the production of a chemical, of a material or of petroleum products from a lab scale to industrial scale where it can be produced in bulk quantities, in large quantities and utilized. So, when this is done, we can see that during all the processes, the development of the process to develop, designed and engineered the complete process of manufacturing these chemicals as well as designing the individual process equipment, this can be, this equipment can be a heat exchanger, it can be a chemical reactor, it can be a separator, it can be a absorber or and so, on.

So, these equipments, they are required to convert the raw materials into desire products efficiently, safely and economically. So, the role of a chemical engineer is to develop the entire process as well as the process equipment. So, one need to understand all the processes, all the operations that occurred during this process, that taking these raw materials and making the desired product.

And as an engineer, one needs to of course, also take into account the money part so, it has to be done economically so, that maximize the profits, it needs to be done in the present context following all the environmental regulations. Of course, when this is required to be done, it should be done efficiently so, that all the parameters, all the requirements that the profit is highest, it is most safe, the pollutant emission is minimized.

So, developing these processes, designing these processes, engineering them is the role of a chemical engineer and then once this process is developed, the role of chemical engineer is also to make sure that this is done smoothly and troubleshoot any problems that occurred during this period. So, these operations in almost all chemical engineering processes, they are done in a continuous mode. So, just if somebody does not understand what is difference between batch and continuous.

So, batch is for example, when you do a chemistry experiment, you take two test tubes and mix the reactants in a beaker, in a flask or in a bigger test tube and then if required, you stir them and you get the desired product and then you can filter it. So, what you are basically doing, you are doing this in a batch manner and then if you want to produce it again, then you will do it again. Now, there is a lot of variability into it so, the product that you find first time, it may be slightly different from the product that you find second time. So, batch, in the batch manner there is variability.

Moreover, it is not an easy task to do production at a larger scale in a batch manner because one need to have very large vessels, one need to bring those materials to it so, what can be done is, it is done in a continuous manner, that the reactants or flow in the reactor in a continuous manner, they react and then they go out, product forms and then they go out and they are separated. So, this is done in a continuous manner. So, when it is done in a continuous manner, the reactants and products they flow and when it flows one need to understand fluid mechanics.

So, almost everything in a chemical plant flows through the pipelines etcetera. So, it is to be done in a continuous manner and it flows so one need to understand fluid mechanics it may be in a gaseous form, it may be in the liquid form, even the solid materials they also flow and for that the area of fluid mechanics or the area of chemical engineering what is called is granular flow.

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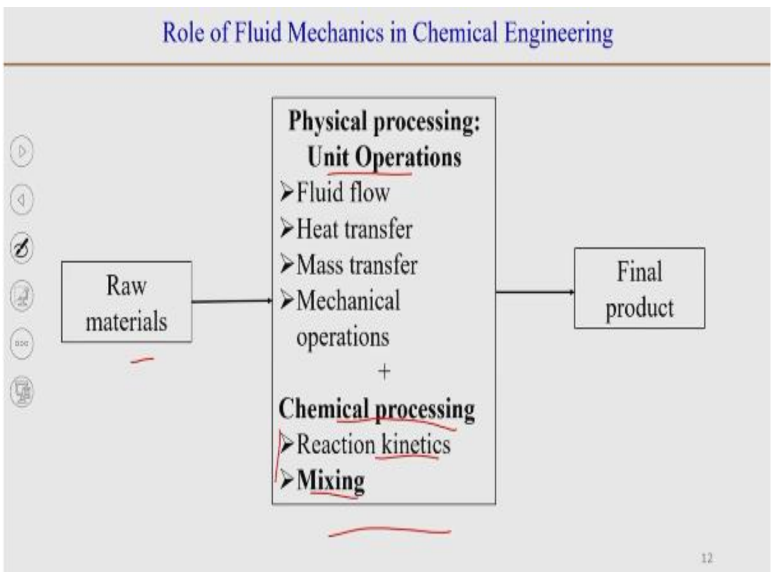

Now, if we represent this in a block diagram, that you take a raw material and then you process it and get the final product. So, if we list down all the processes that happens during this change, so, you can divide them into two type of processes, one is physical operations or what is called unit operations and another is chemical processing or what is called unit processes.

So, chemical processing is basically what you will study in chemical reaction engineering course, you will be concerned with the kinetics of the reaction as well as how the mixing between the fluids or between the reactants take place or the reactant and product take place or reactant and intermediate take place, all this will be in mixing. So, these are chemical operations, but apart from each chemical operations, there are a lot of physical operations that also happens, one is of course, the flow of these reactants and products, then the reactions will be done at a particular temperature at which the yield of desired product is maximum or the production of undesired product is minimum.

So, one need to maintain certain temperature inside the reactor or if the reaction is exothermic, then the heat that is being produced it needs to be removed, if the reaction is endothermic, then one need to give certain amount of heat. So, all this require the exchange of heat between the fluids. So, heat transfer come into picture. Then another area where is mass transfer so, mass transfer is, it can have absorption, it can be a diffusion etcetera. So, the mass transfer is again a physical process where you can have different operations leaching etcetera.

And then mechanical operations which can be grinding, crushing, filtration and so on. So, all these, when you look at the course curricula, you will have all these core courses of chemical engineering and fluid flow if you look at that in the heat transfer there are three modes of heat transfer, conduction, convection and radiation. And among all the three one of the most frequently used or frequently occurring mode of heat transfer is convection, which is by the bulk flow of fluid. So, convective heat transfer involves the flow of fluid.

So, to understand temperature field or the energy distribution or the heat distribution, one first need to understand the flow behavior of the fluid so, heat transfer is dependent on fluid flow. Similarly, mass transfer, the transport of his species, it will again depend on the bulk fluid. So, the fluid flow is important in mass transfer as well as and if we talk about chemical reaction engineering, the mixing will depend on the fluid flow behavior, that how the fluid flow is happening inside the reactor, what are the dead zones inside the reactor, where the fluid is mixing or what kind of mixing do we require, all that will be coming under chemical processing.

So, one of the very important topics in chemical reaction engineering is what we call residence time distribution, that defines the distribution of times or distribution of residence times of the fluid molecules that exit from the reactor. So, if you take the molecules that are coming out of the reactor and find out their exit times and plot it, then that distribution function is called residence time distribution. So, that will of course, again depend on the velocity of these different fluid particles. So, residence time distribution is again dependent on the velocity distribution inside the reactor.

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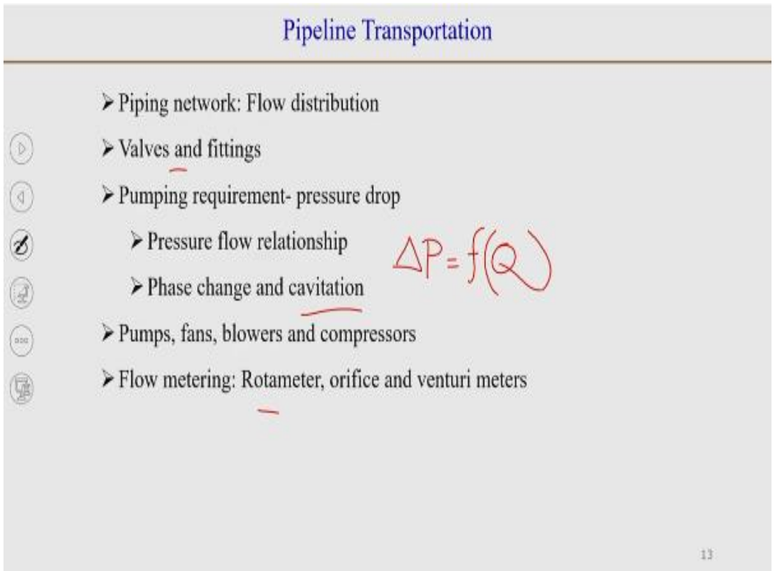

Now, if we look at some of the important operations in chemical engineering. So, for example, pipeline transportation, we have a piping network in chemical engineering plant where, if from one pipe the flow will be distributed into different pipes. So, how much flow is going or how much flows would go to different branches, that flow distribution one need to understand the conservation of mass at these junctions' etcetera.

Then, there will be valves and fittings so, one when one is designing these pipelines, the control of fluid or for different purposes we need control walls, we need fittings, what is the pressure loss during this and how much pressure will be required for the fluid to flow, how much pressure head will be required that will come under fluid mechanics.

So, the pumping requirement in a pipeline transportation and that will depend on what is the pressure drop in the piping network. So, one need to understand the relationship between pressure drop and the flow rate, volumetric flow rate or the mass flow rate. So, how the pressure drop and the flow rate are related and based on that one can choose the pumps that will be required in a piping system.

One also need to take care that the phase change does not place take place in the pipelines otherwise cavitation may occur. So, cavitation is the process, if you have a liquid flowing in a pipe the presser as we go along, the pressure drops and if the pressure at a certain point it becomes lower than the vapor pressure of a liquid, then the evaporation can take place.

So, if the evaporation can take place there is a phase change and there will be because that there is a large difference between the density of gas phase and the liquid phase so, there will be sudden change in density and there will be sudden change in the flow behavior, there will be oscillations etcetera, and that generally happens in say pumps, in centrifugal pumps where the flow velocity is very large and pressure can become very low.

So, one need to make sure that cavitation does not take place again this can happen especially in the liquids where the vapor pressure is high or the volatile liquids. So, that also need to be made sure in pipelines. Of course, the design of pumps, fans, blowers and compressors for the transportation of or generating the pressure head for the transportation of liquids and gases and the measurement of the fluid that has flown. So, one need to have some flow meters, Rotameter, orifice meter, venturi meter or to measure local velocity say pitot tube.

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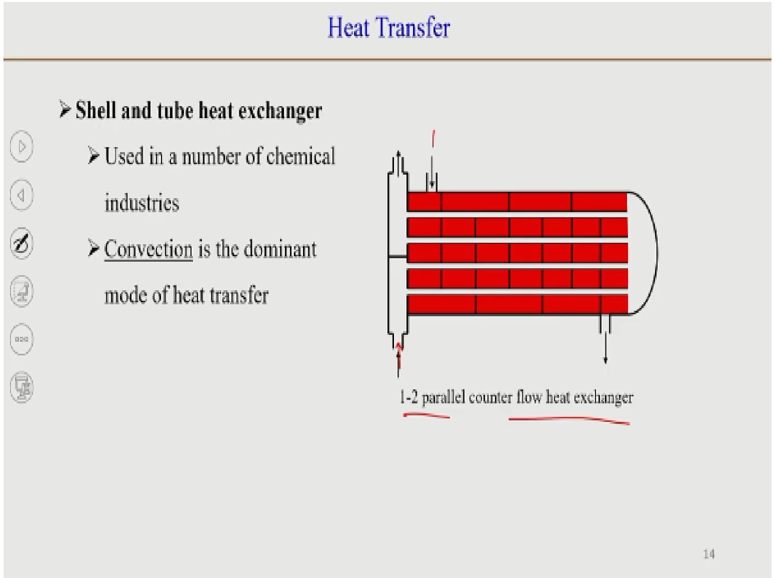

Then, so, heat transfer so as we said that there are different mode of heat exchange, mode of heat transfer so, we take a typical example of a shell and tube heat exchanger, which is commonly used in chemical engineering. So, what we have here is 1-2 parallel counter flow heat exchanger. So, the flow happens through these tubes and the flow happens through the shell side.

So, there are two fluids, one fluid it will be hot and another fluid will be cold and fluid one is let us say is flowing through the tubes and fluid two is flowing this through the shell. So, in this heat exchanger, the exchange of heat happening is happening because of the convective heat transfer. And so, to understand the heat transfer or to find out the rate of heat exchange between the two fluids, which is done generally in terms of heat transfer coefficient or in a non-dimensional form in terms of Nusselt number and this Nusselt number is a function of Reynolds number and Prandtl number where Reynolds number is a fluid flow phenomena.

So, that will depend, depending on the fluid velocity, the rate of heat transfer will change. So, one need to understand first the flow behavior inside the shell and inside the tubes, so, that one can find out the heat exchange between the two fluids.

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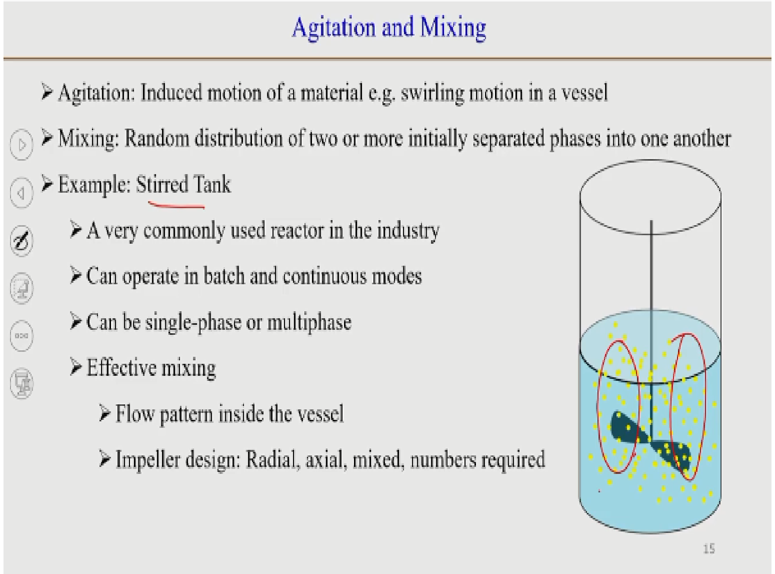

Another example is in Agitation and Mixing, so, agitation is basically that induced motion of a material or swirling motion in a vessel. So, you take a vessel and you agitate the liquid into it, this can be in a batch mode or it can be in a continuous mode. So, in a continuous mode the flow will be coming in and going out and this is what we call or this is how we have a CSTR, Continuously Stirred Tank Reactor.

And mixing is that random distribution of two or more initially separated phases into one another. So, for both agitation and mixing one can have a vessel and a stirrer into it. So, what kind of stirrer or what kind of this propeller one have that can give you efficient mixing, how we can reduce the circular motion so, one can have baffles around it, etcetera.

The stirred tank reactor or mixed tank reactor is one of the most commonly used reactors in the industry. So, design of this reactor and understanding of the flow behavior into it to find the yield of the product in this reactant, in this reactor is very important and this can operate in a batch mode, you put the reactants in it and then get the product out, which is done in generally in the pharmaceutical industry and in most of other chemical industries, it operate in a continuous mode, it is very simple design and one can use it for a single phase operations or multi-phase operations.

So, what you see here is that in the liquid one can have gas or another phase of liquid or another immiscible liquid or even solid phase or you can have gas, solid, liquid phase. So, one need to understand the interaction between the two phases, the drag that is being imparted on the different fluids and the energy that is required to drive this impeller all that will be based on fluid mechanics right. So, effective mixing, that how much mixing has taken place or characterizing the mixing that also will be based on the flow field inside this.

Now, if you have a two-phase flow or more than two phase flow, it will depending on the flow rate of gas and liquid phases and the impeller speed, there will be different flow patterns inside the reactor. So, different flow pattern means that sometimes you might have that at low gas flooded the gas will come and then it will just be concentrated around the impeller.

In another case, the impeller is speeded high or the gas flow rate is high and the gas will be distributed uniformly in small, in the form of small bubbles inside the entire reactor and in these two patterns or in these two flow regimes, the flow behavior will be entirely different, the gas liquid interfacial area which is an important parameter for the reaction to happen for gas, liquid reactions, then that will depend on the flow regime. So, it is important that what kind of flow regime one want to have inside the reactor. So, all that one need to have or one need to understand using principles of fluid mechanics.

Then, there can be different kinds of impellers. The impellers can be that they provide predominantly radial mixing for example, Rushton turbine which provides which is a radial mixer or a axial mixer, where the mixing is axially in this pattern. So, the vortices are formed in this manner or mixed mixer which provide both radial and axial mixing, as well as that how many impellers are required because if the vessel size is larger than one may require more than one impellers. So, all this needs to be decided based on the understanding of the fluid flow behavior in these reactors.

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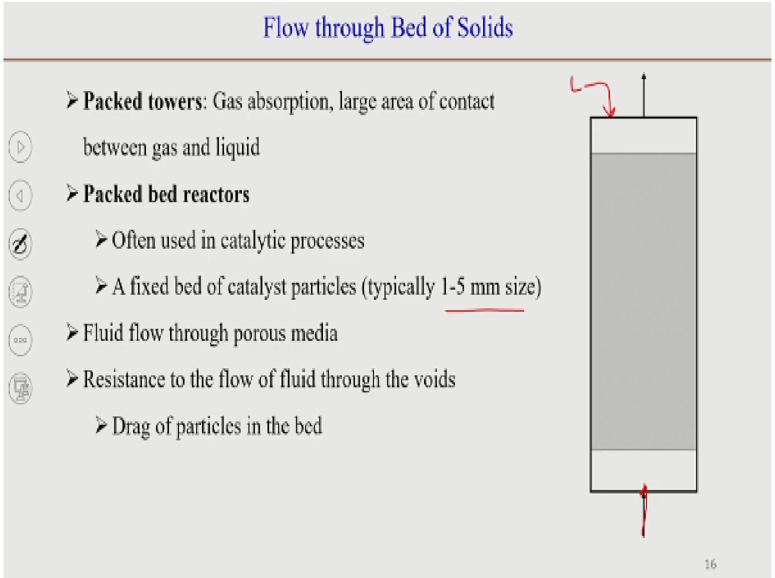

Now, another example, what we have here is what is called Packed Bed. So, packed bed is basically a bed of solids and the gas is flown at the bottom of it. Now, it can be used as a for gas- liquid absorption where we have packed tower and the purpose there is to increase the interfacial area between gas and liquids. So, in such case you will have a gas coming in from bottom and liquid being sprayed from top and then there will be one would like to have as much as contact possible between them. So, the liquid will flow from top to bottom and the gas will come from bottom to top and there will be contact between the two. So, that is one application of these packed beds which is as a packed tower.

Then we have packed bed reactors, which are generally used for catalytic processes and the packing in this, solid packing in this will be what will be a catalyst particles which will be typically in the size of one to five so, millimeter sized particles and the gas is transported which is generally the reactants. So, gas is transported in this case from the bottom and the gas flows through this and it comes into contact with the catalyst particle that is where the reaction happens.

So, one need to understand the flow through this porous beds because this is where one need to understand or need to find out the pressure drop through the bed, the flow rate required for the efficient reaction and so on what is the resistance of the flow of fluid through these voids that are formed in the packed bed reactor. So, that is again another very important reactor in chemical engineering applications.

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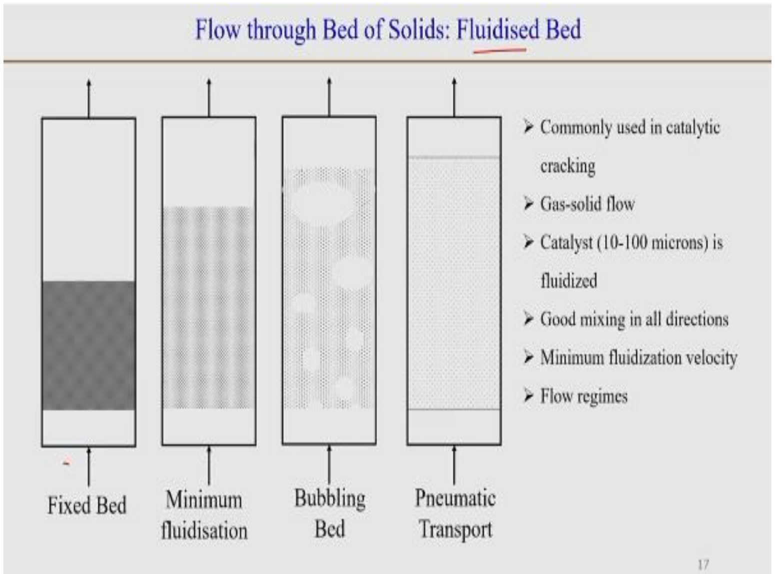

Then, if we increase the flow rate and allow this bed of solids to fluidize, then what we have is, is called fluidized bed. So, at low gas velocity, one will have a fixed bed that the bed of solids is fixed at low gas velocities, but if we keep increasing the velocity of the gas and allow this the bed to fluidized bed of solid particles to move then at a certain velocity, which is what we call minimum fluidization velocity the bed will start fluidizing and the particles, the distance between the particles will be large and the gas will fill the voids between them.

If you increase the gas velocity further, there will be large voids which we call bubbles so, this kind of bed will be called bubbling bed and at further very high velocities, one can use the gas for the pneumatic transport of solids. So, in chemical engineering such kind of system is used as a fluidized bed reactor, because it provides very good mixing, again these particles are catalyst particle and one of the very common application is catalytic cracking in refineries. So, if you have visited a refinery you might see their CCU Catalytic Cracking Unit or FCCU Fluidized Catalytic Cracking Unit where you will find such kind of reactors.

So, this is basically if you can see that the solid particles are flowing because of the drag on them imparted by the gas flowing so, it is an example of gas-solid flow. These particles are very small in size. So, if you remember when we talked about fixed bed, the particle size was about one to five mm whereas, in this case the particle sizes is a few microns to tens to hundreds of microns or at least one order of magnitude less than a size and these particles are fluidized.

So, it provides the advantage of fluidized bed is that it provides good mixing in all directions and again, as we talked about in a stirred tank reactor, again we have different flow regimes here, it can be a bubbling bed, it can be pneumatic transport or just a fluidized bed. So, depending on the flow regimes, the reactions etcetera, will be different. So, one need to understand the fluid flow behavior in this reactors and it is a lot of flow physics inside the reactor which is still not well understood and the design is most of the time is based on the empirical relations which have been developed from the experiments that have been conducted in these reactors.

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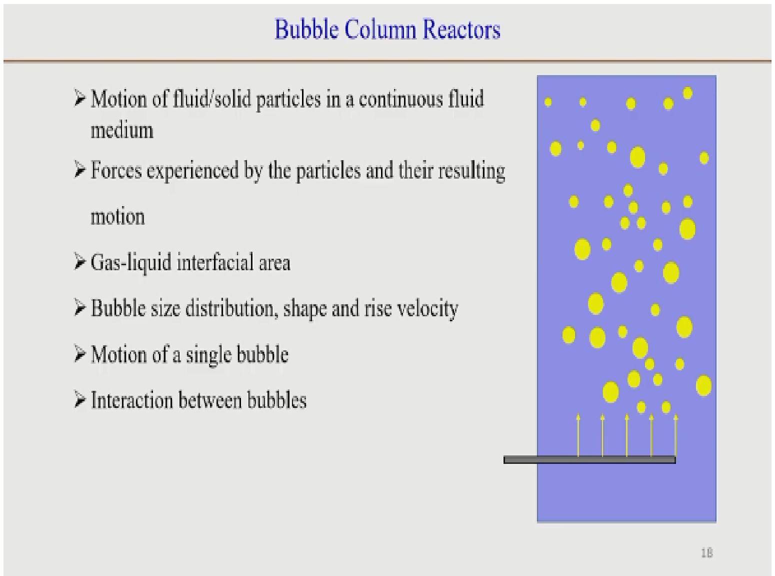

Another reactor is say Bubble Column Reactor. So, in this basically again you have two phases, but here you have a liquid which is represented by blue color here and gas bubbles which are shown in yellow. So, in a liquid column, the gas is introduced from the bottom and because of buoyancy, these gas bubbles go up. Now, depending on the gas flow rate, one will have a different kind of bubble sizes, different kind of flow patterns inside the bubbles again, because this is generally used for gas liquid reactions.

So, one will need to have or one would like to have as large interfacial area as possible so, as to maximize the yield and that will depend on the motion of these fluid particles. So, here you have two fluids, gas bubbles and the continuous liquid medium and the flow behavior of inside the bubble columns will depend on a number of factors. So, and it will depend on what is the force, drag force and the lift force experienced by which particles and their resulting motion, their interfacial area, the distribution of the sizes of the bubbles, their shape and their rise velocity etcetera.

So, before we understand anything first we need to understand what is the motion of a single bubble and what is the interaction between one bubble with the surrounding bubbles and how far the sphere of influence of a bubble can go. So, we have looked at a number of reactors, two or three different reactors for example, stirred tank reactor, we have looked at bubble column reactor, we have looked at fluidized and fixed bed reactors. So, they involve gas-liquid-solid, liquid-solid or gas-liquid flows in them.

Now, all of that all the reactors, they require an understanding of the flow behavior, flow regime inside them, so that one can design the reactor efficiently and get the maximum possible yield. So, another example we saw about heat exchangers, that to design a heat exchanger, one need to understand the fluid flow behavior.

So, what I have tried to demonstrate from this that in chemical engineering the design of process equipment requires a sound knowledge of fluid mechanics. So, the more you understand about the fluid flow behavior inside it, the more you will be able to or the better you will be able to design a reactor. So, with this we will stop here. Thank you.