Fundamentals Of Particle And Fluid Solid Processing
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Lecture - 36
Centrifugal Separation

Hello everyone and welcome back to the another class of Fundamentals Of Particle And Fluid Solid Processing. So, today we will start with a new section that is the Centrifugal Operation.

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Now, before going into that details let us think that why centrifugal separation or why centrifugal field is important in this course of study.

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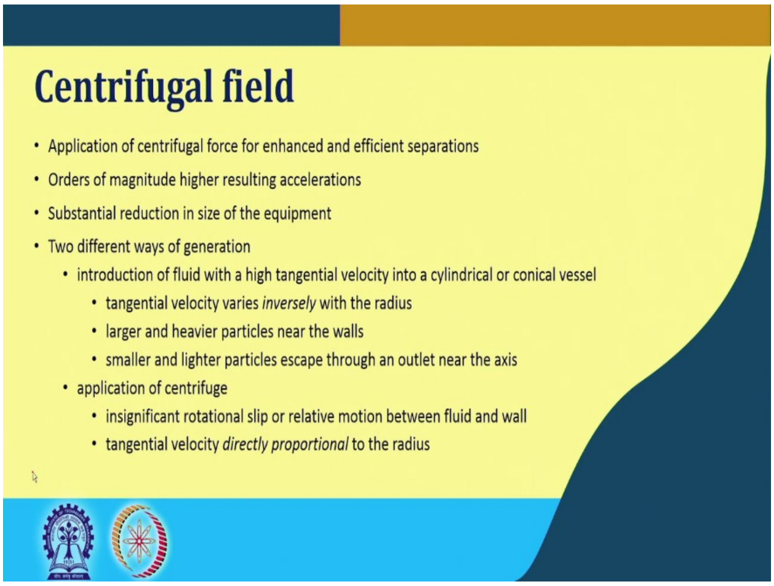

Now this there are several scenarios that when you have very fine particles in a suspension or in a fluid that has to be removed. Now by traditional gravity settling or by gravitational force sometimes such removal of the particles are usually impossible or practically impossible or sometimes it is very difficult to achieve the required degree of efficiency by the gravitational settling the conventional gravitational separation. Now application of centrifugal force actually enhances in the orders of magnitude higher than this gravitational settling cases or the separation cases.

So, it actually results in a very high resulting accelerations in the field that leads to efficient and enhanced separations of particles. It is not only like the separation in case of drying in case of breaking of colloidal particles or destabilizing an emulsion such kind of applications of this centrifugal field is of immense importance. Now what it does along with this enhancement of resulting accelerations, it actually substantially reduces the size of the equipment.

Now such scenario or whenever such thing happens that we are increasing the efficiency enhancing the efficiency as well as we are having miniaturized version of the equipment or at least a reduction in the size of the equipment such scenario is called the process intensification. A process and its energy efficiency is being intensified.

Now say application of centrifugal field leads to process intensification. Nowadays several studies are going on where for the conventional reactors conventional systems several types of process intensified mechanism are being incorporated to achieve the higher or the maximum yield of say maximum efficiency etcetera.

Now this centrifugal field can be achieved in 2 way or it can be generated in 2 ways. One way is that you introduce a fluid with a very high tangential velocity into a cylindrical or conical vessel. Now what it does it creates a vortex and then what happens this if we do some mathematics on this fluid dynamics or the flow pattern studies we see that the tangential velocity in this case varies inversely with the radius of the vessel.

Now by introduction of this tangential velocity at a sufficiently high rate to this conical or a cylindrical vessel what happens is that the coarser particle or say that the larger or the heavier particle goes near the wall and it is collected and the smaller or the finer particles or the lighter particles escape through an outlet that is near the axis of the vessel.

When we will see the flow pattern study on this particular aspect that is when the flow is injected in a tangential manner to a conical or the cylindrical vessel at a high rate. We will see how this flow pattern and why it is mentioned that the larger or the heavier particles are basically collected and near the wall and the finer particles escapes through the cleaner gas the same exit.

The other way of introduction of this centrifugal field is to use centrifuge; that means, here the equipment is itself is rotating at a sufficient speed that this fluid and the solid wall there is insignificant rotational speed or slip or the relative motion between these two. So, it is assumed or that would be the I mean a ideal point where basically the fluid sticks to the solid wall and it is moves along with the impermeable wall. So, in this case it has been seen the tangential velocity is directly proportional to the radius.

So, introduction or the incorporation of centrifugal field can happen in two ways. In one cases say you have a vessel you are injecting the fluid to the top of it with a tangential velocity at a higher rate and the other option is that you take somehow the liquid in that vessel and then you rotate the vessel at a certain speed at which that there would be insignificant rotational slip or relative motion between the fluid and the solid surface.

Now such kind of operations as I mentioned earlier it helps in separating this larger particles from the smaller particles based on their size, density. So, particle separation based on their size and densities are enhanced by centrifugal operation. If there are 2 immiscible liquids separation of that is also enhanced by introduction of centrifugal fluid centrifugal field. There can be the drying operation because you have seen in domestic washing machines or any washing machine when the drying component it rotates, it incorporates the centrifugal field and the waters are water drains rather quickly than the conventional process.

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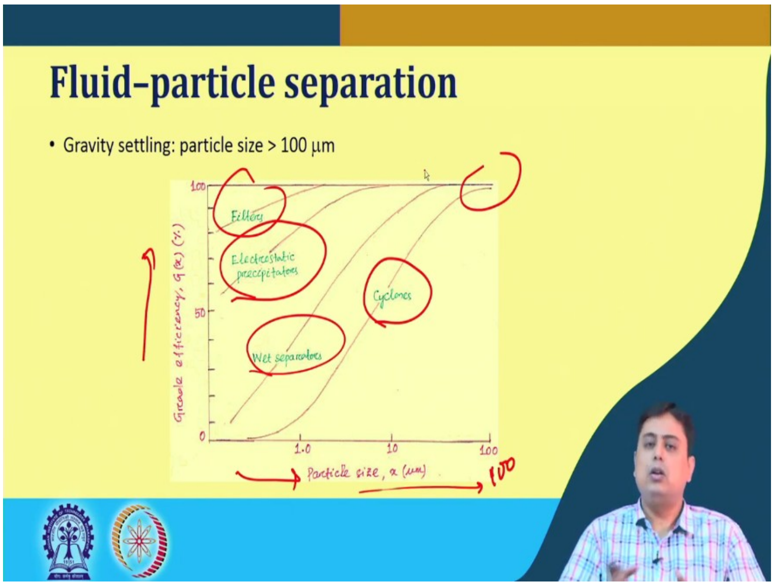

So, now in this section we basically will focus on both the aspects and we will start with the first option that say we have a fixed vessel and we have a high tangential velocity of fluid that is entering typical is such operation we call the cyclone separator. Now if the fluid is the gas phase we call the gas cyclone, if the fluid is liquid phase we called the hydro cyclone. So, the purpose of the cyclone operators are to separate the particles from the gas or the liquid phase.

Now typically any effective separation process or appropriate separation process depends on or the desired separation process depends on what type of the separating process of the separating equipment that has been chosen. So, for example, the particle size is larger than 100 μm in that case it has been seen that gravity settling operations can work sufficiently and also in an economic manner but if the particle size is are lesser than that then there are some typical methods that are used which are shown in this schematic of this graph is that the cyclone separator.

There can be the wet scrubber wet scrubbing option electrostatic precipitators, filters. Now here x axis is the particle size and y axis is the efficiency. The word says grade efficiency we will come to that that what is grade efficiency but you can at the moment consider that this is the efficiency of the equipment.

So, we see that as the particle size increases, the separation grade efficiency of cyclone separator increases but the limit here is the 100 µm because beyond this we achieve 100 % efficiency near about 100 % efficiency but the point is that above that a since we have to introduce this cyclone or the vortex inside the cyclone it requires higher tangential velocity which means requires higher pumping pressure.

So, the energy cost compared to the gravity settling is higher and that is why it is recommended that when the size goes below 100 µm then we can use any of these operation or separation process. The filter is one of the extreme one and in this diagram the cyclone is the other extreme equipment. So, which means if there are coarser particles in the range of 100 µm maximum size cyclone separator is used as the coarse material separation. It is not the final stage of the separation.

Another interesting point from this schematic you can recognize that see at 10 µm the separation efficiency is somewhat more than 60 % or 70 % say but below that there is it is not that much efficient. So, which means the cyclone separator also works well above 10 µm of the particle size and below 100 µm say. So, below 10 µm particle it is typically not suitable ok. It can, but the point is that the chances are it may escape through the cleaner gas if the concentration of such particles or the size the number distribution of that. 10 µm size particles are higher. So, based on this idea we have to choose appropriate separation process to separate our desired product.

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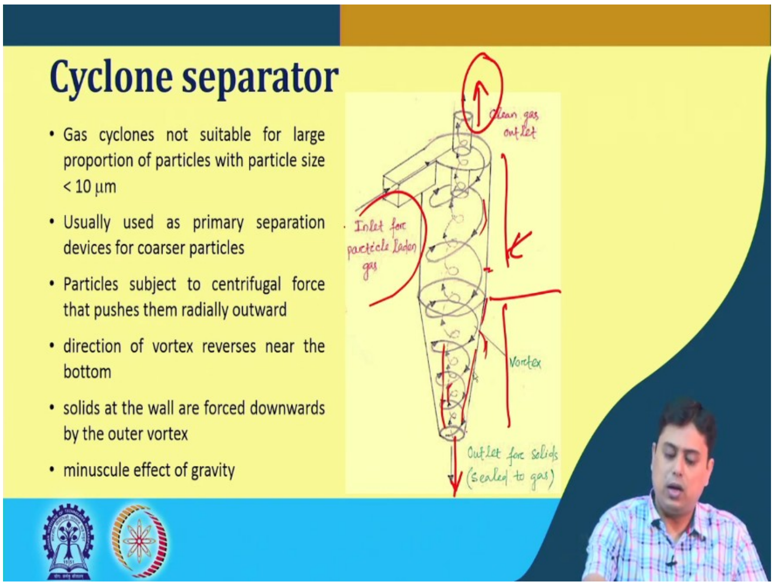

Now, as I mentioned this gas cyclone typically is not suitable for a large proportion of particles with particle size less than 10 μm because its efficiency goes down. So, that is why it typically used as a primary separation device for coarser particles and this is this one is the schematic of such cyclone separator where there is a cylindrical portion, there is a conical portion now by design this heights are fixed or the lengths are fixed of these sections, there is a inlet for the particle laden gas at very high tangential velocity.

It creates a free vortex inside the vessel and the particles are basically subjected to centrifugal force which pushes them radially outward and this direction of the vortex as it goes down it changes its direction from downward to upward at near the bottom of the vessel and what happens, the particles that impacts on the wall slides down and is collected through the outlet that is open for only solids, but sealed to the gas from that outlet.

So, solids at the wall are forced downward by the outer vortex and we have seen in cyclone separator there is a very insignificant influence of gravity in such operation and the clean gas escapes from the top and since practically there is no 100 % efficient cyclone some finer particles escape through this clean outlet clean gas outlet.

So, this is basically overview of the cyclone separator that we have particle laden gas for gas cyclone operation comes in at a very high velocity due to tangential input it creates free vortex inside that cylindrical section then it moves toward the conical section, there it changes its direction, it loses its strength and it creates a inner vortex which escapes the gas phase escapes through this gas outlet and the solids are pushed towards the wall and also forced downward by this downward movement of the free vortex and then the coarser particles are collected at the bottom. Usually cleaned gas or cleaner gas with very fine particles are collected from the top.

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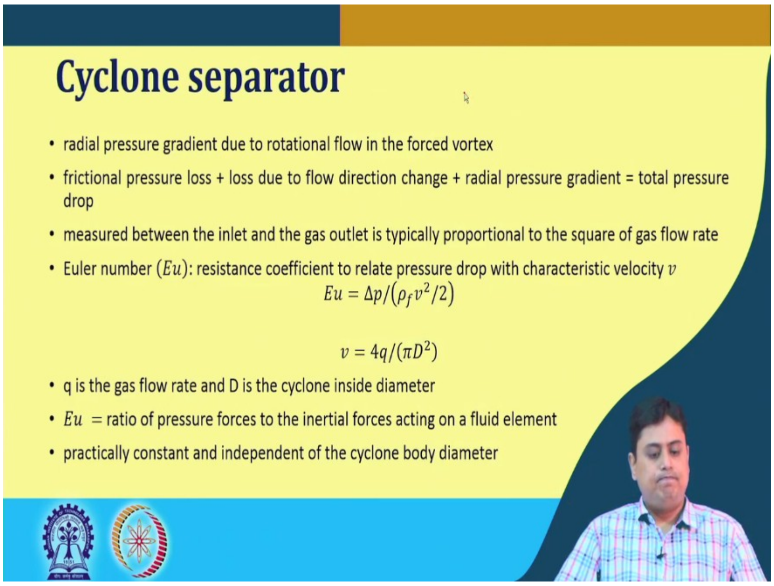

Now in this cyclone separator or such cyclone separator which means there is radial pressure gradient due to this rotational flow of the free forced vortex. Now the total pressure drop that is the inlet and the gas outlet it is measured between the inlet and the gas outlet. This total pressure drop it is a frictional pressure drop plus the loss that happens due to the flow direction change of this vortex plus this radial pressure gradient.

So, all these combines to provide us the total pressure drop which is measured between the inlet and the gas outlet and it has been seen that it is typically proportional to the square of the gas flow rate; that means, as the gas flow rate increases the pressure drop increases rapidly. Now to quantify this resistance dimensionless number called Euler number has been proposed.

It is basically the resistance coefficient that relates pressure drop with the characteristic velocity v. So, the Euler number is basically,

$$Eu = \Delta p/\left(\rho_f v^2/2\right)$$

where ρ_f is the density of the fluid and v is the characteristics velocity and that characteristics velocity can be measured in several way but one of the conventional way is to have for say that cylindrical or the conical section inlet it is

$$v = 4q/(\pi D^2)$$

that means, flow rate which is q is the gas flow and D is the cyclone inside diameter.

So, flow rate divided by the cross sectional area in case of a circular cross section. So, this is the characteristic velocity of a cyclone separator and the Euler number is basically I mean if you look at this expression [$Eu = \Delta p/(\rho_f v^2/2)$] the physical meaning is that it is the ratio of pressure forces to the inertial forces acting on a fluid element.

Now for a family of the cyclone separator or the similar cyclone separator this value is practically constant and it is independent of the cyclone body diameter that in; that means, the similar or that family of this cyclone separator means when those lengths that I mentioned; that means, the conical section length, cylindrical section length, the position of the gas inlet from the top such things are say we have a proportion with respect to the vessel diameter or the cylindrical section diameter.

If this those proportions are maintained this dimensional number where actually the value is basically constant and this helps in scale up operation or scaling up operation of this cyclone separator.

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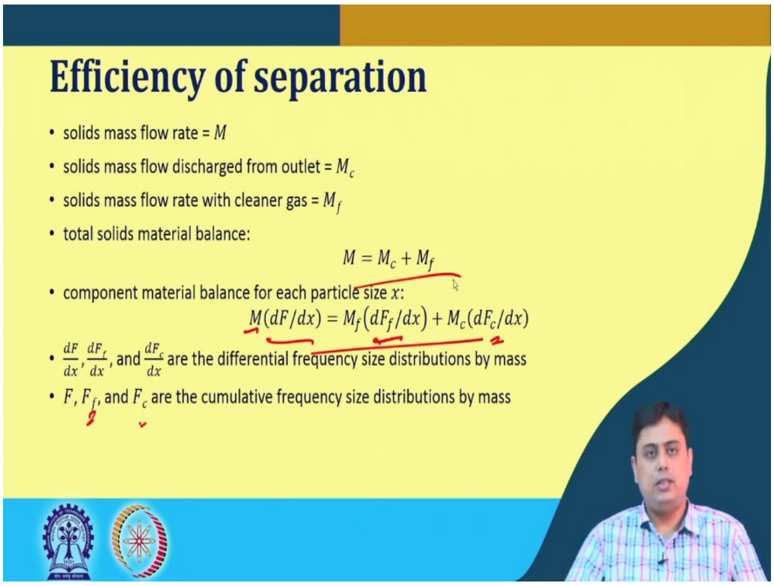

Now, if we look at the efficiency of separation. So, say we define the solids mass flow rate as M solids mass flow discharge that from outlet say M_c, c stands for the coarse particle because from the outlet the solid mass discharge it is the coarse particle that are being collected and solids mass flow rate with the cleaner gas say that is M_f that is f stands for the finer particles. So, the total solids material balance is basically

$$M = M_c + M_f$$

and the component material balance for each particle of size x is basically,

$$M(dF/dx) = M_f(dF_f/dx) + M_c(dF_c/dx)$$

where dF/dx is the differential size frequency distribution by mass of the total mass flow rate.

Similarly this expression with the sub superscript and the subscripts are here for the respective outlets that is for the fine particle outlet and the coarser particle outlet and if we consider only F that that becomes the cumulative frequency size distribution by mass. This we covered at the very beginning the relation between the cumulative frequency size distribution and the differential size distribution. So, f here small f and small c these subscripts stands for the coarse particle outlet and fine particle outlet.

$\frac{dF}{dx}$, $\frac{dF_f}{dx}$, and $\frac{dF_c}{dx}$ are the differential frequency size distributions by mass

F, F_f, and F_c are the cumulative frequency size distributions by mass

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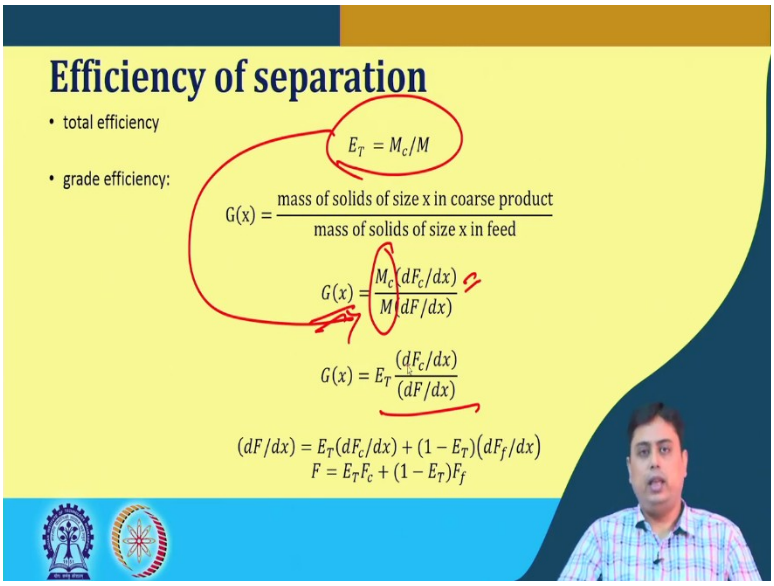

Now,. So, if these are the component material balance and this if this is the total solids material balance then the total efficiency of the equipment or the cyclone separator is defined as the mass fraction of the coarse particle that is collected during the whole operation that is,

$$E_T = M_c / M$$

the mass fraction of coarse particle that is collected in the operation. The grade efficiency that we have a spoken a briefly during the elaboration of this schematic. Total efficiency:

Now this grade efficiency is defined as the mass of solids of say certain size x in the coarse product and the mass of solids of size x in the feed. So, what does this mean basically.

$$G(x) = \frac{mass\ of\ solids\ of\ ¿¿\ coarse\ product}{mass\ of\ solids\ of\ ¿¿\ feed}$$

It means that say if you fixed a particular diameter of the particle size that I need say 15 µm size particles and above to be removed from this gas stream. So, your grade efficiency for that particular size it has to be maximum even if the total efficiency of the system is not near about to whatever is desired. So, the grade efficiency is that certain grade that you want to achieve for a particular size of the particle in the size range.

So, that is why it is explicitly mentioned that the mass of solids of size or say certain grade x here the grade is written in terms of size in coarse product and the mass of solids of size x in the feed. By this definition this $G(x)$ the grade efficiency can be written in this form

$$G(x)=\frac{M_c(dF_c/dx)}{M(dF/dx)}$$

and again we have seen this M_c/M is basically the total efficiency. We replace it we get the grade efficiency as

$$G(x)=E_T\frac{(dF_c/dx)}{(dF/dx)}$$

Now this means that we can write this expression because we have here the component material balance

$$(dF/dx)=E_T(dF_c/dx)+(1-E_T)(dF_f/dx)$$

and we get the value F in terms of total efficiency, the size cumulative size distribution in the coarse outlet and the cumulative size distribution at the fine particle outlet.

$$F=E_TF_c+(1-E_T)F_f$$

So, this is one of the important expression for the case of cyclone separator and what we have seen that how to determine the grade efficiency and the overall efficiency. We will see the flow pattern and other details in the next class but before that let us understand that what we have covered today is that we have seen the basic very; very basic overview of how cyclone separator works, how do we define a total efficiency of a cyclone separator, how do we define grade efficiency, when it works based, in which scenario it is; it will give us the desired result and in the next class we will see how the flow pattern evolves inside this cyclone separator and what is the critical particle size or how do we determine a critical particle size for a particular cyclone separator design.

Till then I thank you for your attention and we will see you in the next class.