Fundamentals Of Particle And Fluid Solid Processing
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Lecture – 38
Centrifugal Separation (Contd.)

Hello everyone and welcome back to the another class of Fundamentals of Particle and Fluid Solid Processing. We were in a Centrifugal Separation topic.

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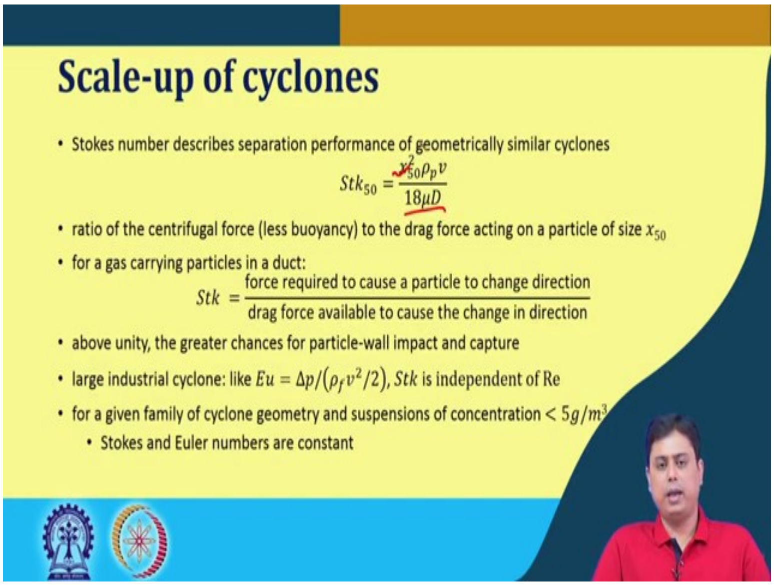

Now, there the last class we discussed about the cyclone separator, its total efficiency its grade efficiency. Now, we have also seen that what is the size distributions that can happen if we have say the feed size distribution. And say one of the outlet distributions say course product size distributions or say the fine particles that are escaping with the gas that size distribution. If we have, so either of these two anyone if we have this information along with the feed we can calculate the other size distribution, so this one we have seen in the last class.

Now, the question is that how to scale up or what are the consideration we have to do during the scale up of this cyclone or the gas cyclones or in general cyclone separators. So, one of the parameters we have already started is the Euler number ok, that remains typically constant for a given family of cyclone separator; that means, when I say family of cyclone separator. That means, it has a proportionate dimension with respect to the cyclone diameter; if those are fixed then this Euler number does not change with the flow rate.

Now, the other number that is important, the one another dimensionless number that is important in the scale up operations. Or the scale up design of the cyclone separators is the Stokes number which describes the separation performance of geometrically similar cyclones which is again the same phrase.

If I say in a different way is the same given family of cyclones that has proportionately equal dimensions with respect to the cyclone diameter. Now, this Stokes number has been defined as

$$Stk_{50} = \frac{x_{50}^2 \rho_p v}{18 \mu D}$$

where D is the cyclone diameter and μ is the viscosity of the gas phase.

Now, this Stokes number similar to the Euler number is also constant within a certain range. Now, this Stokes number physically what it tells this number says that

$$Stk = \frac{\text{force required to cause a particle to change direction}}{\text{drag force available to cause the change in direction}}$$

it is the ratio of centrifugal force minus the buoyancy force divided by the drag force that is acting on a particle of size x_{50}. So, it is the net force of centrifugal and the buoyancy divided by the drag force that is acting on a particle of size of this cut value or the cut size that is x_{50}.

So, for in generic; as a general information, when a gas carries some particles and flows in a duct then this Stokes number is basically the ratio of force that is required to cause a particle to change it is direction. And it is divided by the drag force available to cause that change in direction, so which means the force that is required to cause this particle to change it is direction when it is suspended in the gas phase and it is in the motion in a duct.

And the drag force that is actually available in that suspension flow or the particle laden flow to cause that change whether if that is sufficient. Then this particle will change it is direction which means if this Stokes number is above unity or more than one then there are chances of particle wall impact and consequentially it can be captured.

So, that is why this Stokes number is important in describing characteristics of a certain cyclone separator. Now, like Euler number, this Stokes number is also independent of Reynolds number and for a given family of cyclone geometry and say the suspension concentrations are less than 5 g/m^3 these Stokes number and Euler numbers are constant values.

Now, if you remember the expression of Euler number which we will now see when we solve couple of problems we will see that frequently. So, that involves the pressure drop information and the characteristic velocity.

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

Here, Stokes numbers is involved with the information of cut size, the cyclone diameter and the characteristic velocity.

So, if these two numbers; these Euler's number and the Stokes numbers if these two numbers are known ok. And these are typically fixed or constant values irrespective of the size of the cyclone separator provided it is increasing in proportionate manner. That means, the scale up is happening this number would be same for a given family or a given set of cyclone separators which are geometrically similar. Now, this greatly helps in scaling up of the laboratory scale cyclone separator to the industry scale.

So, once again the Stokes number describes the separation performance of geometrically similar cyclones that is defined as a ratio of centrifugal force and the drag force that is acting on a particle of equiprobable cut size that is x_{50}. If this number is higher or more than unity then there are chances of the particle wall collision or the impact and the particle can be captured.

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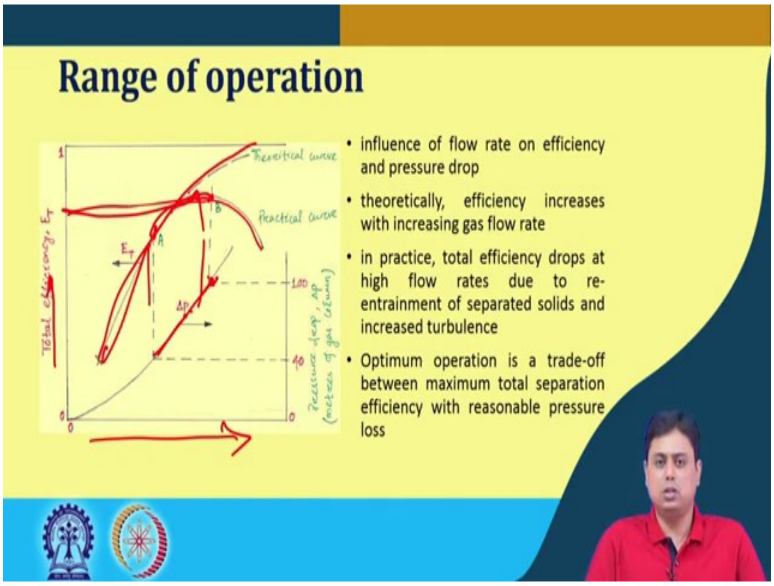

So, with this information let us see the range of it is operation now, range of operation is that where it can appropriately work or efficiently work in which scenario, and that mostly influenced by the available pressure drop that is there in a given condition. So, let us say you can afford a certain pressure drop you have that mechanical energy that you can supply.

In that range whether a cyclone separator will work or not this schematic will tell you that information. So, this plot basically is the total efficiency on the y axis, total efficiency and this is the flow rate in the x axis. Now, this influence of flow rate on the efficiency and pressure drop is one of the vital characteristics of a cyclone separator.

Now, theoretically the efficiency increases as the gas flow rate increases, but in reality or in practical case that does not happen. So, this is the ideal scenario that the theoretical case that it will go on increasing with the increasing gas flow rate. But practically it has been seen that it deviates after a certain point it falls the efficiency drops at high flow rate.

The reason is that the re entrainment of the separated solids and increased turbulence inside the cyclone. So, which means the particles that were dropping at the bottom of the that cyclone in the conical sections this high velocity will take them again with them and this efficiency will decrease. Because those solid particles cannot be further captured, because it increases turbulence with the increasing flow rate, the turbulence is introduced and the turbulence creates more chaotic or random flow pattern inside the cyclone uncontrolled flow pattern.

And that basically takes those coats particles again with them and then starts circulating inside the bed or the circulate this separator vessel. So, that is why there is a tradeoff between the optimum operations and the available pressure drop or the pressure loss that can be afforded and there we can have a certain efficiency. So, for this example from point A to point B, and the corresponding pressure drop line, ok. This is the window where this cyclone separator should be working or it should be utilized in that operating condition.

And now, you can choose any one point in between that much pressure drop you can afford and accordingly you get it is efficiency. At most you can go to this point B on this Δp line, because that would be the maximum efficiency you can achieve from this cyclone separator whose total efficiency versus flow rate curve is given like this.

Beyond this limit the efficiency is dropped due to the reason that I mentioned that increased turbulence and the re entrainment of the solids that were separated earlier in the low flow rate case. If we operate say below this region at a low flow rate, then this cyclone separator will basically works as of kind of a gravity settler, there would be no as such enhanced separation.

Because the velocity is not sufficient to create the stable vortex that was required to have the enhanced separations by impacting the solid particles are pushing the solid particles towards the wall which on collision on impact then collected at the bottom of the vessel. So, basically this A to B this zone is our operating window in this case.

So, which means the optimum operation is a tradeoff between the maximum total separation and the reasonable pressure loss that can be afforded, because pressure loss is related with the mechanical energy that is supplied to the system. So, this curve also shows the pressure drop with increasing gas flow rate.

So, the pressure drop versus the gas flow rate this is also given here, and we can see as the increase gas flow rate pressure drop also increases. So, we have to find an optimum scenario and that would be the range of it is operation. So, based on these ideas let us see a problem which implements this points and we can further simplify our derived expressions or see it is utility.

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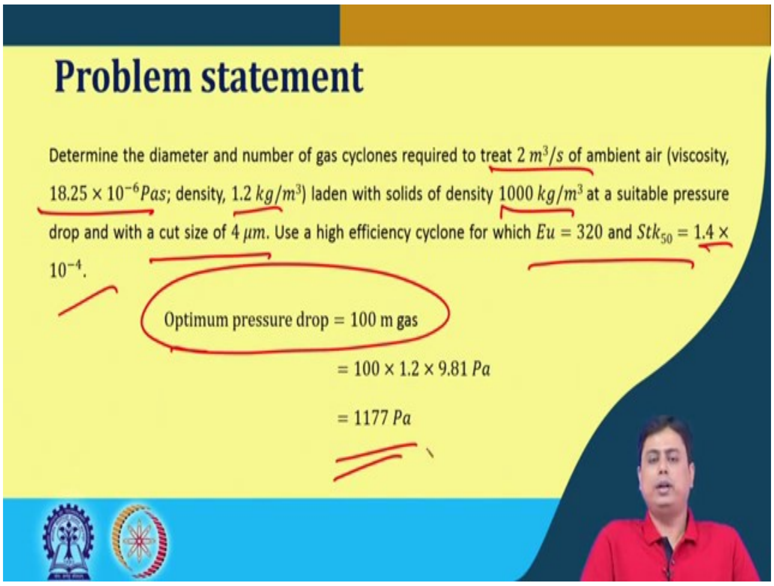

So, say a problem says that determine the diameter and number of gas cyclones that are required to treat 2 m^3/s of ambient air whose viscosity and density are known. This ambient air is laden with solids of density 1000 kg/m^3 at a suitable pressure drop with a cut size of 4 μm.

Use a high efficiency cyclone for which Euler number and Stokes number are given and the appropriate pressure drop or the optimum pressure drop that is mentioned it is 100 m of the gas. So, if typically this information is given which means we can calculate the optimum pressure drop in terms of Pa. Because this 100 m gas means, 100 m multiplied by its density multiplied by the g, the ρg is the head is the optimum pressure drop.

So, which means here the question is we have to use a certain numbers of gas cyclones to treat 2 m^3/s this much flow rate of certain particle mixed air, this is the feed flow rate. Now, there we know it is viscosity the physical properties are given viscosity and density of this particle laden gas is given.

The density of the particles are provided, the pressure drop is also mentioned, the required cut size that this much say 4 μm of the particle and bigger than that we have to separate from this mixture or this suspension of the particle laden gas phase this is the requirement. For that cyclone separator that we will be using that has the characteristics numbers that is the $Eu=320$ and $Stk_{50}=1.4\times10^{-4}$.

So, the question is what would be the diameter of our cyclone separator and how many of them having this Euler number and Stokes number we will be using or utilizing to separate this or to clean this 2 m^3/s of particle laden gas of cut size 4 μm. So, this is the problem statement, and let us see how we solve such problem.

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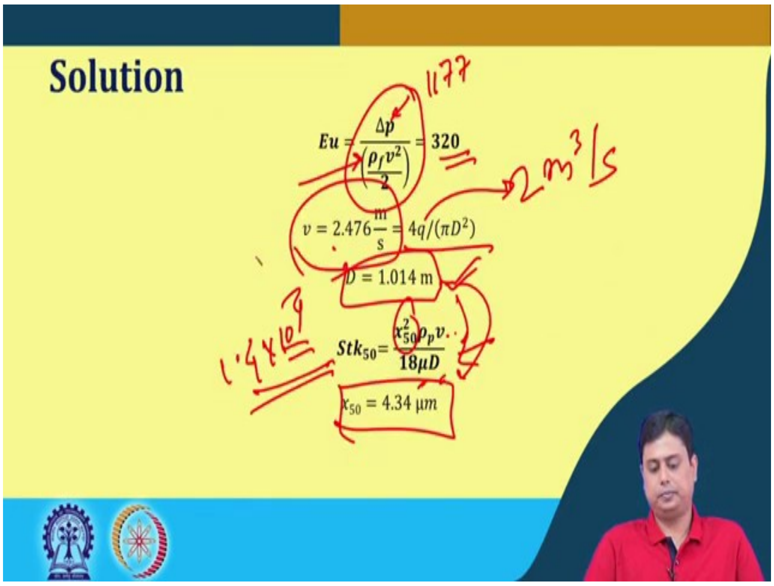

So, here the Euler number is mentioned, Euler number, is

$$Eu=\frac{\Delta p}{\left(\frac{\rho_f v^2}{2}\right)}$$

Now, here Δp is mentioned, ρ_f is given, characteristics velocity we have to calculate because Euler number is mentioned here, $Eu=320$. So, this should be the characteristics velocity if I replace here this Δp value of 1177 Pa, ρ_f is mentioned here 1.2 kg/m^3 which is equals to 320. So, we get the characteristic velocity as 2.476 m/s.

Now, again the characteristic velocity is

$$v=4q/\left(\pi D^2\right)=2.476\frac{m}{s}$$

Now, in this case the desired flow rate is also mentioned the q value is given which is 2 m^3/s which means we can find out what is the diameter that is required. Now, if we can calculate this or we have calculated now this diameter of the desired cyclone separator.

$D = 1.014\,m$

Now, if we put that into the Stokes number definition, we can check that what would be our cut size, with this diameter and with this definition where Stokes number is mentioned for that system which is 1.4×10^{-4}. We can find what is x_{50} in this system because ρ_p is mentioned which is 1000 kg/m^3 density of the particle, v is the characteristic velocity.

$$Stk_{50} = \frac{x_{50}^2 \rho_p v}{18\,\mu D}$$

We have just calculated μ is mentioned, D is just we have calculated. So, we find that for this Stokes number the cut size is 4.34 μm. Now, that is not what we require, we require 4 μm per size as the our cut size. So, which means this diameter that we have calculated is not going to have asked this result or our desired result having a cut size of 4 μm. So, what we did, once again step by step if I go through, we know the Euler number, we know ρ_f. So, we have calculated what could be the characteristic velocity of this cyclone separator.

With this flow rate; the given flow rate that is given as 2 m^3/s and the characteristic velocity that we have calculated we can find out what is the diameter of the cyclone separator.

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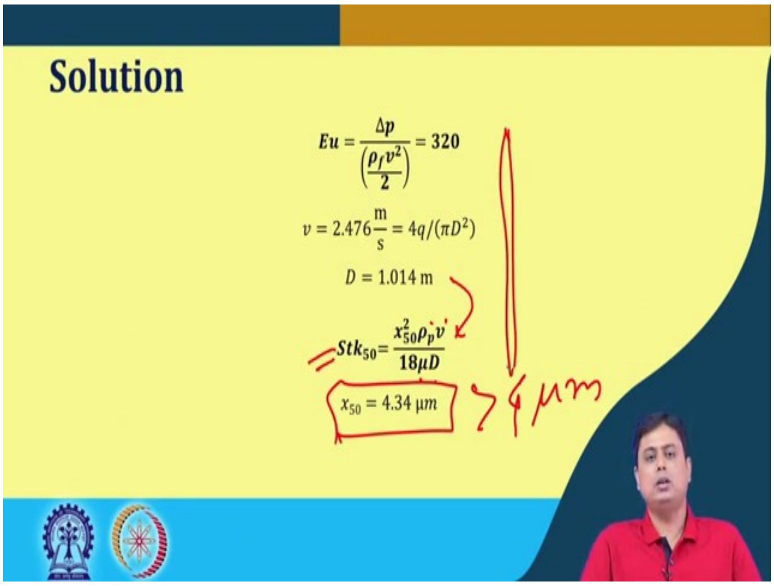

With this diameter and the given Stokes number where all the other parameters are physical parameters are given, we can find that what could be the cut size whether that is sufficient for our operation or not. Which shows that the cut size is more than what is desired, we require 4 μm of the particle as a cut size. So, which means this diameter is not sufficient, and this diameter is calculated as if there is only one cyclone separator is being used. Because this whole calculation stands for only one cyclone separator single in number, so which means we need multiple cyclone separator.

So, say we need n numbers of cyclone separators, and the flow rates are evenly distributed that are going in parallel to these cyclone separators. So, which means now the revised flow rate to each of the cyclone separator having say diameter D is here it is q is 2 m^3/s that is $2/n$.

$$q = 2/n$$

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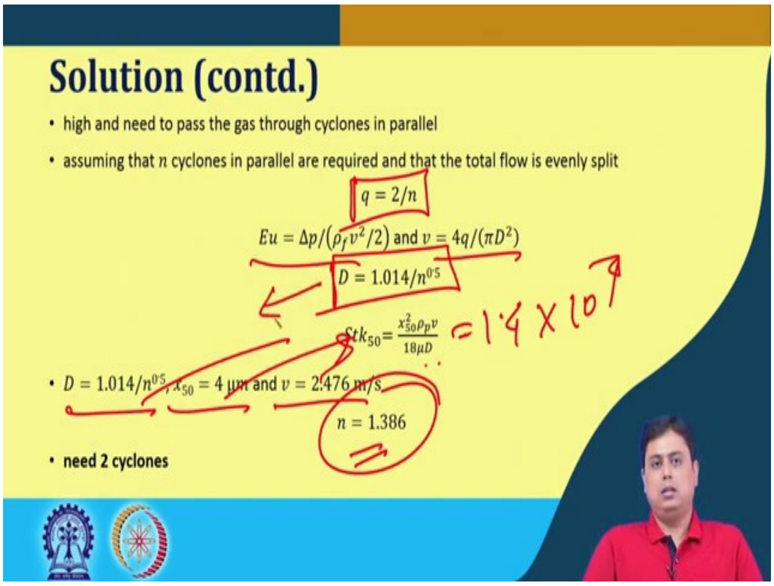

So, this n number of cyclones that are connected in parallel that would be required and in that case the total flow say is evenly splitted in between all these separators, and naturally the flow rate the revised flow rate is now to each of those multiple separators is small q which is $2/n$.

So, with this revised flow rate, the same Euler number and the characteristic velocity, because that would remain same. Because that is, that comes from the pressure drop calculations which is the affordable pressure drop which is the provided pressure drop. So, the Euler number remains same, so from these two expressions which remains same as of the previous calculation we find that the revised diameter is

$$D = 1.014/n^{0.5}$$

Now, with this revised diameter we again check or we again assure that matches the given Stokes number because this is a fixed constant number. So, which means we have D as this value where n is unknown, we have cut size of 4 μm that is desired and this $v=2.476\,m/s$ that comes from the Euler number which will not change since the Euler number is not changing,. accordingly we adjust our diameter.

We use these three values in this expression that is the Stokes number again which is 1.4×10^{-4} all other parameters are known. The unknown quantity is n which is calculated as 1.386, which means we need at least two cyclones to have this separation. By having two cyclones we can reduce the diameter and we can eventually go to the cut size of 4 μm. So, with these two cyclones what would be now the actual cut size, because this is not it cannot be fraction values 1.386 or 1.4 it cannot be the number. We have to use two numbers, if we use 2; that means, the D will be a different value that is 1.04 divided by 1.414 which is the square root of 2.

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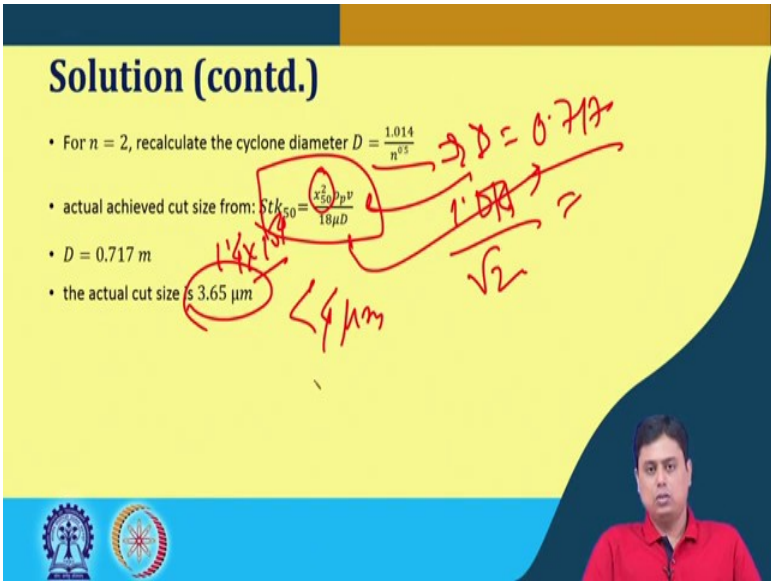

Once we find this μD the value of D we again use it in this Stokes law; Stokes number expression.

$$Stk_{50}=\frac{x_{50}^2\rho_p v}{18\,\mu D}$$

And we can find what is our x_{50}, here this D is 0.717 that is 1.014 divided by root 2 is equals to 0.1 or 0.717.

Using this D in the Stokes number ρ_p is 100 kg/m^3, v the value that we have calculated as 2.476, μ is 1.2 sorry $18.25 \times 10^{-6}\,Pa.s$. And D is what we have calculated that is 0.717 and Stokes number is 1.4×10^{-4} we use this we find what is x_{50}.

And we see that the x_{50}value is 3.65 μm which is below the desired one which means this suffices our requirement below the cut size required 4 μm; which means, if we use two cyclones having Euler number of 320 and Stokes numbers of 1.4×10^{-4} with a pressure drop of 1177 Pa, we can have a cut size of 3.65 μm; which means we can clean the gas from the particles having diameter of 4 μm and above.

I hope this problem helps you to understand that the utility or what are the utility of Euler number, and the Stokes number. And how we calculated, what is the desired cut size or what is the number of cyclones that are required to be connected in parallel. In the next class we will see couple of more problems to clearly understand this theory, till then.

Thank you for your attention.