Basic Environment Engineering and Pollution Abatement
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Lecture 21
Air Pollution Control 1

Hello everyone. Now, we will start discussion on the topic Air Pollution Control part 1. So, far we have discussed that our first strategy should be to prevent pollution in spite of that, there might be some possibilities to create pollution, we cannot prevent 100 % pollution creation, although we take sufficient care. So, in that case, what pollution is generated that has to be controlled and this can be done by using different equipment and instrument and different methods. So, that part we will discuss in this module.

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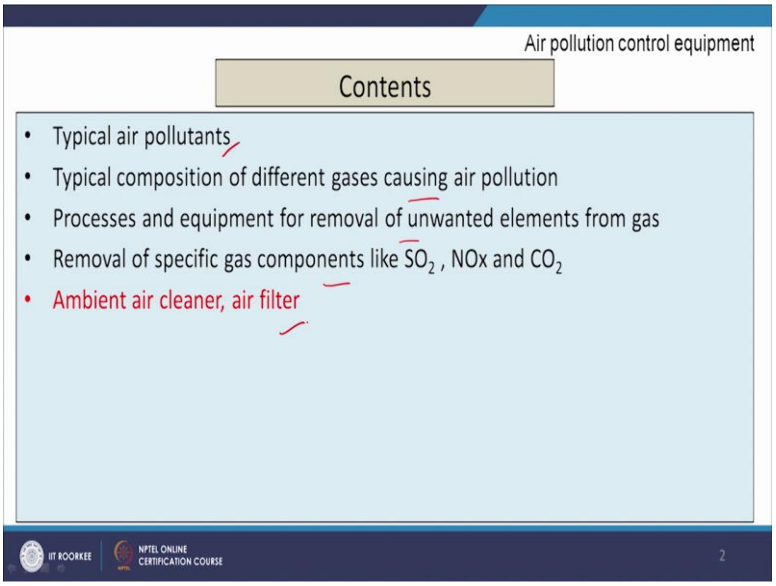

And the contents are typical air pollutants, typical composition of different gases causing air pollution, processes and equipment for removal of unwanted elements from gas, removal of specific gas components like SO_2, NO_X and carbon dioxide and ambient air cleaner and air filter. So, this content we will cover in four classes. Now, we will see typical air pollutants, already we have discussed that there are a number of criteria pollutants, which are very very important for the quantification of air quality. Those are particulate matters, SO_X, NO_X, ozone, lead.

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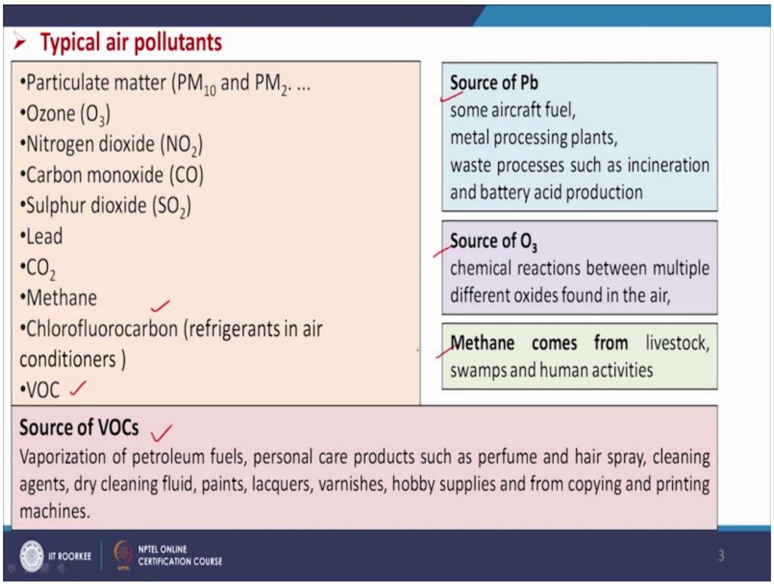

And apart from these, we have VOC, CFC, chlorofluorocarbon and NO_2 nitrogen dioxide and ozone. The sources of these pollutants we have already discussed, it can enter into the environment through natural sources as well as manmade sources, and some sources are also mentioned here that is source of lead, source of ozone and methane and volatile organic carbons.

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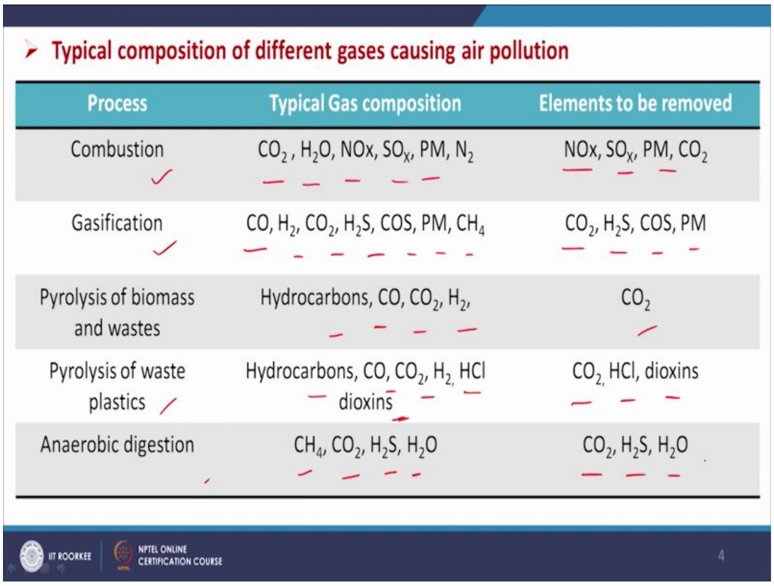

Now, we will see different types of gases which are responsible for the generation of pollutions in the air, examples are say combustion gases, so when some fuel or carbonaceous material is combusted, then we get a flue gas which mainly contains carbon dioxide, NO_X, SO_X, H_2O that is in vapor and particulate matter and nitrogen.

And in this case, we need to develop some methodology to remove the components like NO_X, SO_X particulate matter and carbon dioxide. So, similarly through a gasification process, we can get different gas in the produced gas stream like carbon monoxide, hydrogen, CO_2, H_2S, COS, PM and CH_4 these are the major components and we need to remove these also carbon dioxide H_2S, COS and PM.

Pyrolysis of biomass and waste through this route also the gas comes out to the environment which contains carbon monoxide, carbon dioxide, hydrogen and hydrocarbons, we need to remove carbon dioxide from this. And pyrolysis of waste plastics also gives us different gases that also contains hydrocarbons, carbon monoxide, carbon dioxide, hydrogen, HCl and dioxins.

So, this dioxin is very very toxic and we need to remove carbon dioxide, HCl and dioxins from these gas streams also and anaerobic digestion through this process, we get the gas which contains methane, carbon dioxide, H_2S and H_2O that is moisture or vapor and removal of CO_2, H_2S, H_2O are very very important. So, this removal normally takes place in the premise where the gases are produced in industrial scale.

Apart from that, so vehicular emissions that is very difficult to control basically and it contributes to the ambient air quality. So, to make the environment clean, we need to control the emission of these gas components when it get entry into the atmosphere. Here we have not mentioned regarding hydrocarbons, hydrocarbons mostly is available in terms of unconverted hydrocarbons in terms of suits or it may be as volatile compounds, so, those are also needed to be removed.

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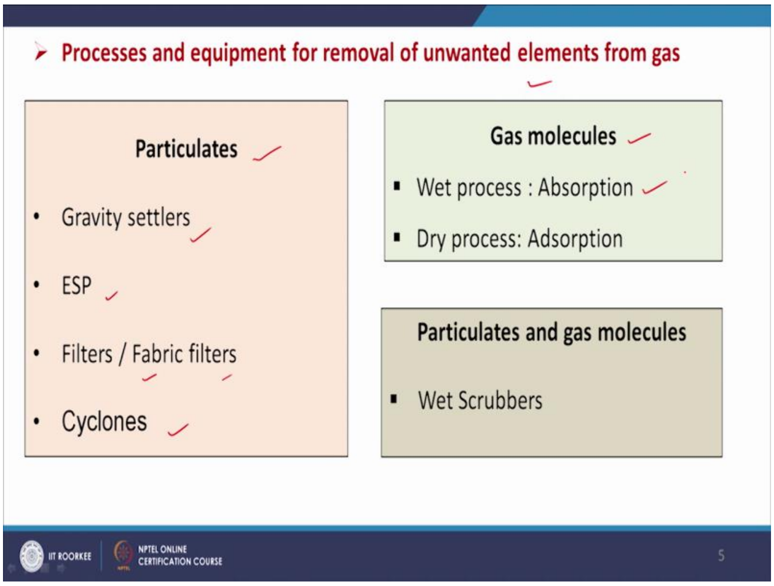

Now, we will see processes and equipment for removal of unwanted elements from gas. So, in the gas, one is particulate matter and another is other gas components we need to remove which are not desirable in the environment. So, for the separation of particles or the particulates there are a number of techniques and methods, we will be discussing those like say gravity settlers, then electrostatic precipitator and filters that is fabric filters and cyclones.

So, these are the mostly used equipment or the processes which are used for the removal of particulates from the gas stream, so, we will be discussing those. And for the removal of gas molecules like say SO_X, NO_X, etc. we will be discussing two major methods, one is based on absorption that is wet process and another is dry process which is based on adsorption.

And there are some methods where both particulates and gas components can be removed like say scrubbing. So, wet scrubbers are also available, we will discuss all those processes and devices and we will learn how to remove the particulates and other gas components from the exit gas and what are the mechanism of these equipment and the principle of working of these equipment's. And in this part 1, we will be mainly focusing on the gravity settlers.

So, here this slide shows us a horizontal flow settling chamber, as we know, if we fall a ball or any particle from a height, so, initially the velocity is 0, then gradually its velocity will increase and it will attain a maximum velocity that will be stable thereafter, that is called terminal settling velocity. So, this terminal settling velocity bigger the particle size more the terminal settling velocity. So, to travel a certain distance the more the terminal settling velocity lesser the time required. So, the same principle will be applicable for the separation of the particles in the gravity settlers.

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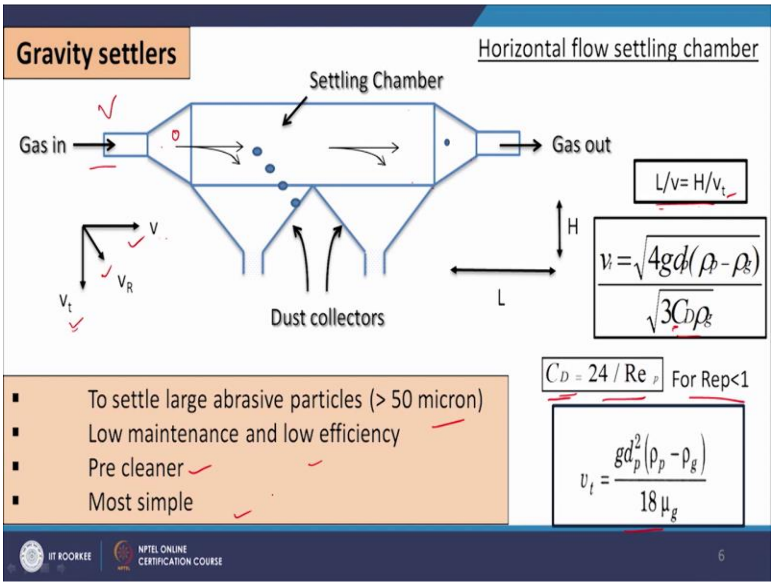

So, this figure if we see, so, here is the gas in, so inlet gas is coming here. So, it will be having some velocity, so, that velocity is equal to say v. So, this velocity gas is coming so, if particles are present in it so, that particles will also be having the velocity v and here the gravity is also working on the particle, so the particle is under the action of multiple forces.

So, one trajectory we will get through which this particle will move. So, now it is having a horizontal velocity v and vertical velocity V_t that is terminal settling velocity. So, this is our resultant velocity. Now, if you see one particle is here, so, I want to get it separated. So, the basic principles or separation of any particles while it is in motion, just if we can put something in its path and then its flow will be arrested and the velocity in that particular direction will be 0 and the particle will fall.

So, if this particle we want to settle here certainly, the time required to travel from this point to this point, the inlet to outlet within this time the particle must travel the vertical distance which is, as per the dimensions of this settling chamber. So, this is the basic requirement or the design principle for this settling chamber. So, if we consider the length is L and height is H.

So, in this case, $\frac{L}{v} = \frac{H}{v_t}$

V is the horizontal velocity, L/V is the time required to travel from inlet to outlet by the particle, Vt is the terminal settling velocity that is the time required to travel the particles from the top to the bottom of this chamber, so this time requirement should be equal.

So, this is that critical condition for the separation. So, L/V = H/Vt.

Now, this Vt is equal to what? Vt is terminal settling velocity and terminal settling velocity will depend upon the particle size, the viscosity of the fluid, the density of the particle etc and what is the g value? That is a gravitational acceleration, so, those values will be influencing the value of Vt.

$$v_t = \frac{\sqrt{4gd_p\,(\rho_p-\rho_g)}}{\sqrt{3C_D\,\rho_g}}$$

So, these expressions we will discuss where from this is coming by the force balances on it and the C_D is nothing but the drag coefficient.

So, this drag coefficient will be depending on the velocity of the gas stream. So the velocity is higher that is your it will be in turbulent but velocity is less we will be getting this in laminar flow. So, up to certain Reynolds number we will be getting laminar flow and, in that case, when the Reynolds number is less, the V will be getting the laminar flow and, in that case, $C_D = \frac{24}{Re_p}$. Rep is nothing but the particle Reynolds number so this C_D value we can replace it by 24 by Rep.

$$v_t = \frac{gd_p^2\,(\rho_p-\rho_g)}{18\mu_g}$$

So, this expressions is the expression for the terminal settling velocity of a particle which is falling in a laminar zone the flow of the particle is not that high so, that the Reynolds number be less. And this equipment the gravity settlers are very simple and it is not costly and to settle large abrasive particles like say greater than 50 micron these devices is workable and it has low maintenance and low efficiency as well and it is also considered as pre cleaner. So, for the separation of very fine particles, it may not be that good device, but for the separation of relatively larger particle this can be a good option and this is a very simple method.

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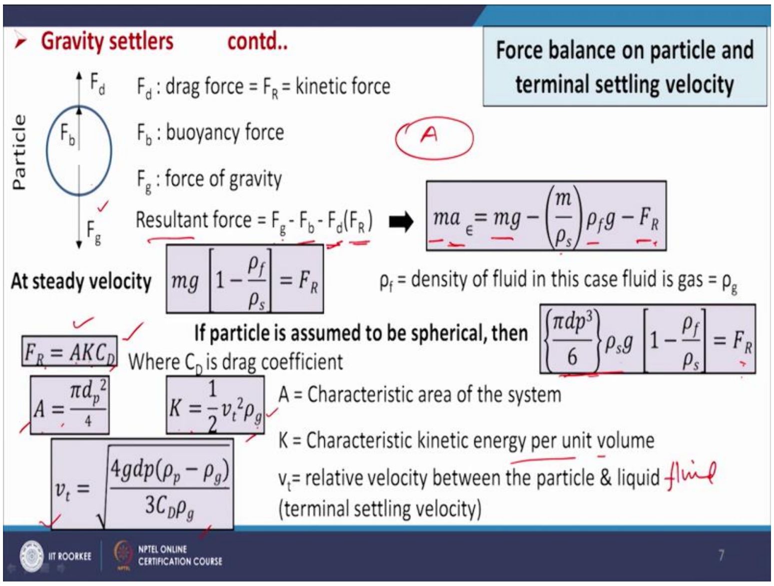

Now, we will see how the Vt expression we are getting. So, let us see this is the particle which is falling. So, there is one force that is F_g that is gravitational force which is working in downwards direction. So, upward directions on force is working that is F_b that is Buoyancy force, as we know when a solid particle falls, then in a fluid, same volume of fluid is replaced and it gives a force to the particle in opposite directions.

So, that is buoyancy force and another force we will be seeing here that is drag force. So, this drag force is also working on this particle when it is falling in the air so that force will also work in the same direction of the buoyancy force opposite to the gravitational force. So, if we think about the force acting on this particle, and we consider the force balance, then we can say that the resultant force on this particle is equal to the (force due to gravity) – (force due to buoyancy) – (force due to drag). So, these are F_g - F_b - F_d.

So, this drag force is basically mentioned as kinetic energy force. So, in many books, it is written as F_R that is related to the kinetic energy of unit volume of the of the fluid. So, this is the expression for the resultant force on this particle. Now, when it will be moving with terminal settling velocity, so, there will be no resultant force, so that it will be moving into constant velocity that is terminal settling velocity.

So, in this case, we will be getting resultant force equal to 0. So, now, let us express this resultant force. So, m is the mass of the particle and a_E is the resultant acceleration. So, m into a_E that is the resultant force.

$$ma_{\epsilon} = mg - \left(\frac{m}{\rho_s}\right)\rho_f g - F_R$$

So, F_R is a drag force. So, drag force as I mentioned it is related to the unit kinetic energy per unit volume.

$$FR = AKC_D$$

So, A is the cross-sectional area and K is the characteristic kinetic energy per unit volume and C_D is nothing but the drag coefficient.

$$K = \frac{1}{2} v_t^2 \rho_g$$

So, if I take one volume unit volume of the fluid, so v into rho g, so, that is equal to mass of the fluid and then $1/2mv^2$ that is kinetic energy of the fluid. So, this is the expression of K and the expression of A, A is a particle is falling from this so, we will be taking the cross-sectional area here, so this cross-sectional area is A.

$$A = \pi r^2 = \frac{\pi dp2}{4}$$

so this is our A the K expression we have described, if we put the value of A and K in this F_R and also put the values of this F_R here in this expression and put m a_E equal to 0 then we will be getting the value of Vt. say in this case what is Fr.

$$F_R = mg - \left(\frac{m}{\rho s}\right) \rho_f g$$

$$mg \left[1 - \frac{\rho_f}{\rho_s}\right] = F_R$$

So, if we are interested to convert this m in terms of volume, because, you know we cannot measure the weight, we do not need to measure the mass, but dp is known to us so, we can get the volume. So, accordingly mass can be can converted to this volume.

$$\left\{\frac{\pi dp3}{6}\right\} \rho sg \left[1 - \frac{\rho f}{\rho s}\right] = F_R$$

If we consider it the particle as a spherical particle.

So, when you will be considering the particle as a spherical particle, so, this expression will be like this so here Fr value will be putting like AKC_D and A value is given here, K value is given here we will put this expression here, so by we arranging will be getting the value of Vt

$$vt = \sqrt{\frac{4 g d_p (\rho_p - \rho_g)}{3 C_D \rho_g}}$$

So, Vt is the terminal velocity within the particle and liquid and the fluid in this case that is air. Now, we are able to understand, how the particle will be separated in the gravity settler and how the Vt value can be calculated. Now, how the collection efficiency can be calculated, because you know, the more the particle size, more will be the terminal settling velocity less will be the time requirement. So, the time required to travel from inlet to outlet within this time all particle size will not be equally settled, so bigger the particle more easily settle, lighter the particle it will be lesser settled, so we can get one cumulative analysis.

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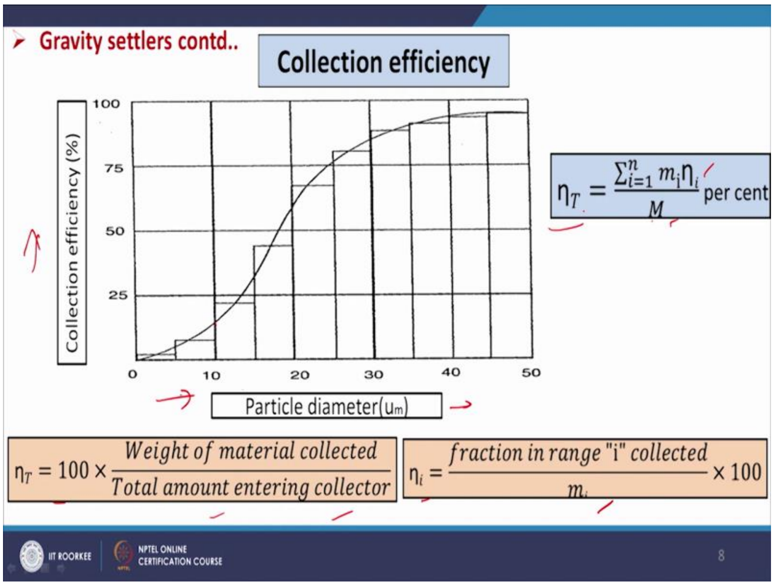

And if we say x axis if we plot the particle diameter and y axis if we write the collection efficiency, we will see that when the particle diameter is less, the collection efficiency will be less, gradually it will increase cumulatively when we can get the maximum collection efficiency when we will be considering the particle size in the higher range, so that way physically it is happening.

So, now mathematically if we want to express then we can write that

$$\eta_T = 100 \times \frac{\text{Weight of material collected}}{\text{Total amount entering collector}}$$

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M}$$

$$\eta_i = \frac{\text{fraction in range "i" collected}}{\text{mi}} \times 100$$

So, that way we can calculate the collection efficiency by using this formula. Now, we will see one numerical problem.

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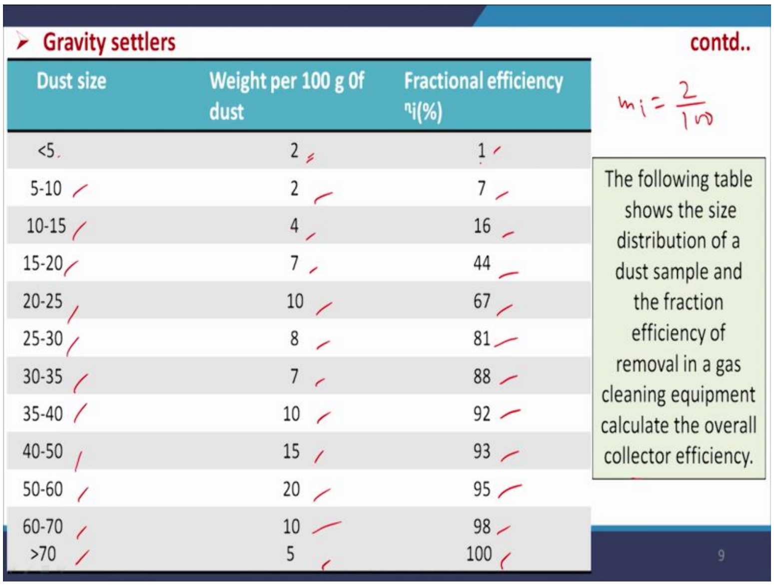

Dust size	Weight per 100 g 0f dust	Fractional efficiency η_i(%)
<5	2	1
5-10	2	7
10-15	4	16
15-20	7	44
20-25	10	67
25-30	8	81
30-35	7	88
35-40	10	92
40-50	15	93
50-60	20	95
60-70	10	98
>70	5	100

So, the following table shows the size distribution of a dust sample and the fraction efficiency of removal in a gas cleaning equipment, calculate the overall collector efficiency. So, this table is giving so, dust size less than 5 and then weight per 100 gram of dust equal to 2 gram and then fractional efficiency is given that is 1.

Similarly, for 5 to 10 it is 2 and it is 7 and 10 to 15 it is 4 and 16. So, 15 to 20 is 7 and 44. So, 20 to 25, 10 and 67 and 25 to 30, 8 and 81 and 30 to 35, 7 and 88 and 35 to 40, 10 and 92 and 40 to 50, 15 and 93 and 50 to 60 that is 20 and 95 and 60 to 70, 10 and 98 and greater than 70, 5 and 100. So, we are getting this is the data given to us we need to calculate the collection efficiency.

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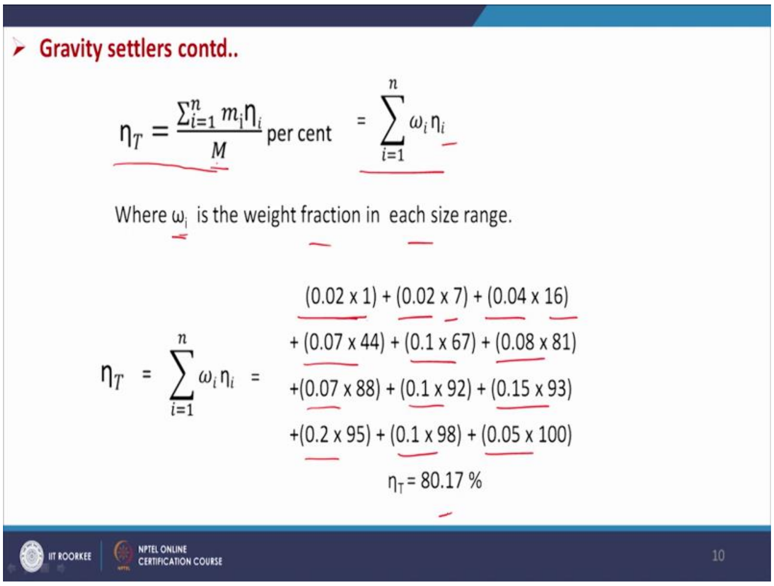

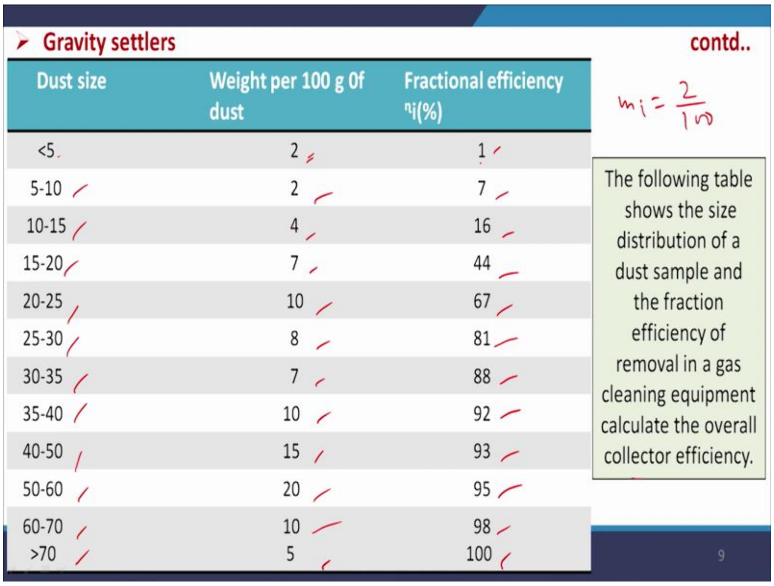

So, how we will do it we have the formula

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M} \; percent = \sum_{i=1}^{n} w_i \eta_i$$

wi is the weight fractions in each size range, so, mass fraction and weight fraction both are same.

So, we have to find out the wi value, wi is nothing but mi/M.

$$\eta_T = \sum_{i=1}^{n} w_i \eta_i = (0.02 \text{ x } 1) + (0.02 \text{ x } 7) + (0.04 \text{ x } 16)$$

$$+(0.07\text{x}44) + (0.1\text{x}67) + (0.08\text{x}81)$$

$$+(0.07\text{x}88) + (0.1\text{x}92) + (0.15\text{x}93)$$

$$+(0.2x95)+(0.1x98)+(0.05x100)$$

$\eta_T = 80.17\ \%$

Now, in practice, you know, if we can reduce the height for the separation, then more separation is possible.

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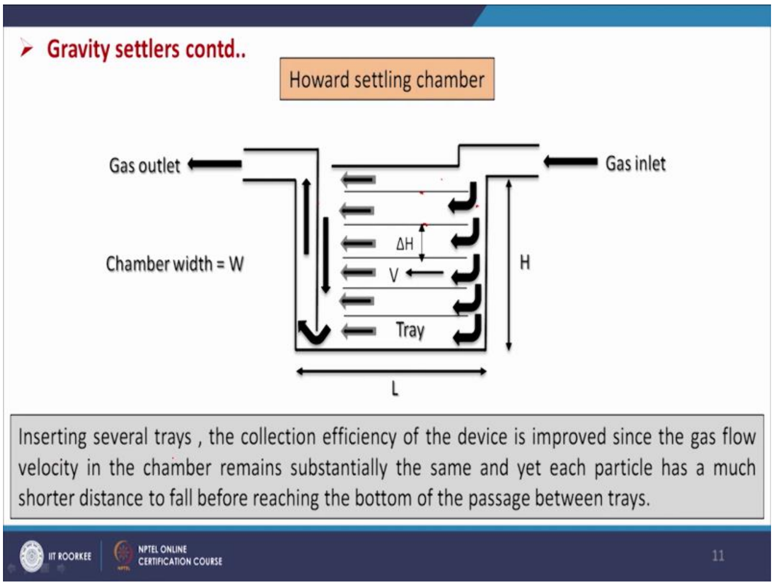

So, if we have like this figure, if this is our height in this height, if we place some horizontal trays, so in between inter tray distance will be reduced. So, air will pass through it. So, particle need to travel vertically from this point to this point, when in the same time when it is moving from inlet to outlet, but we do not put any internal share or any plates inside. So, then the particle has to remove from this to this the complete H height during the time when it will travel the length.

So, by inserting these plates, we are reducing them vertical length for travel by the particles. So, more separation is possible. So, inserting several trays, the collection efficiency of the device is improved since the gas flow velocity in the chamber remains substantially the same and yet each particle has a much shorter distance to fall before reaching the bottom of the passage between trays.

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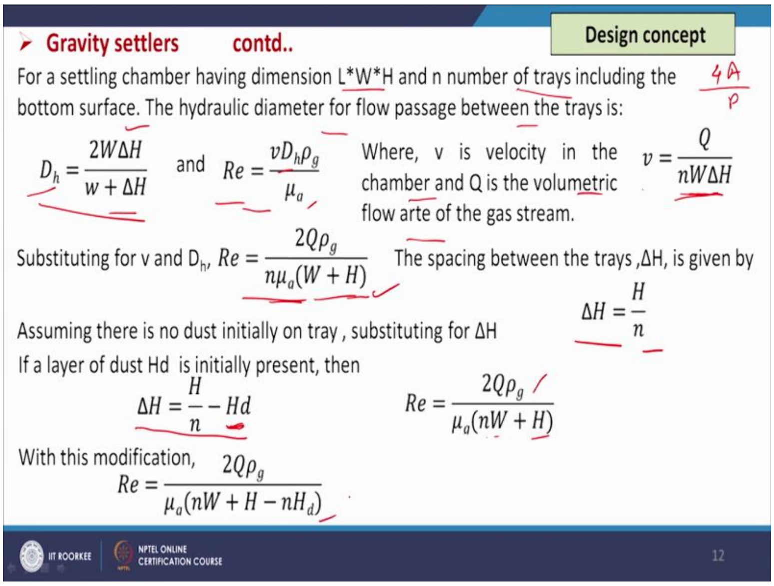

So, in this case what will be the mathematical expression that we are going to discuss. So, for a settling chamber having dimension L, W, H. So, L is the length. So, W is the width and this H is our height. So, in that case and n number of trays, including the bottom surface, the hydraulic diameter for flow passage between the trays is then if I want to calculate the hydraulic diameter that is

Hydraulic diameter = 4 * Area (A)/ Perimeter.

So in these cases this is our W and ΔH this side. Air is flowing from this direction, so this will be our surface area, so, W*ΔH.

$W * \Delta H = A$

Hydraulic diameter = $(4 * W * \Delta H)/2(W+\Delta H)$

$$Dh = \frac{2W\Delta H}{w+\Delta H}$$

We will be getting the Reynolds number we know that

$$Re = \frac{\rho v d}{\mu} = \frac{vD_h \rho_g}{\mu_a}$$

So, D will be this characteristic diameter that is D_h and V is the velocity in the chamber. So now, if we want to get the value of V in terms of the known dimension that is W and ΔH then we can calculate

$$v = \frac{Q}{nW\Delta H}$$

where Q is the volumetric flow rate of the gas stream, n is the number of that channel. So, if we put this value v here so,

$$Re = \frac{2Q\rho g}{n\mu g(W+H)}$$

Now, when we do not have any interval, but if we have some, we have some plates and intervals then ΔH is equal to H/n.

$$\Delta H = \frac{H}{n} - Hd$$

If there is no layer initially at the bottom of the any layer any plate then H_d will be 0

ΔH = H/n

$$Re = \frac{2Q\rho g}{\mu g(nW+H)}$$

$$Re = \frac{2Q\rho g}{\mu g(nW+H-nHd)}$$

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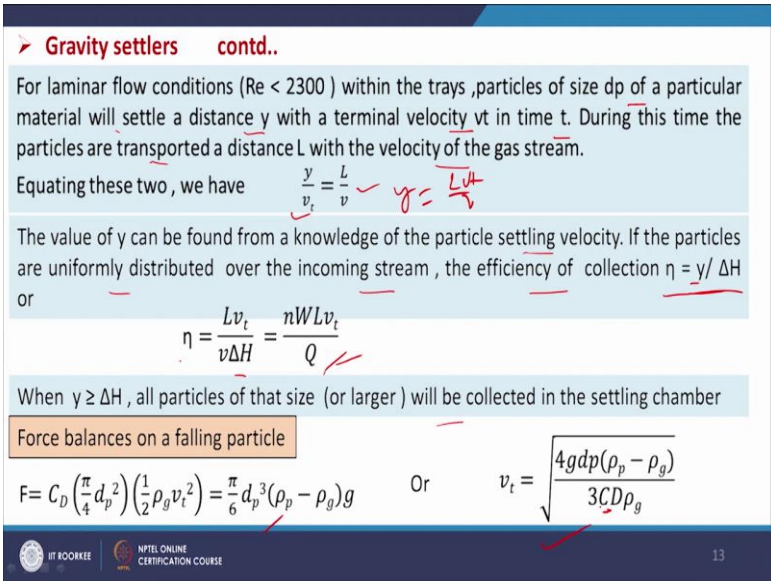

Now, we are assuming that the flow is laminar, but in reality it may not be laminar and it is very difficult to be laminar. So, which we are assuming that will not these expressions will not hold good and there needs some modification. So, for laminar flow conditions within the trays particles of size Dp of a particular material will settle a distance y with a terminal velocity Vt in time t, during this time the particles are transported a distance L with the velocity of the gas stream.

$$\frac{y}{vt} = \frac{L}{v}$$

Similar expressions we have also had in the previous slide. So, y is replaced by capital H in that case, so, now, the value of y can be found from a knowledge of the particle settling velocity if the particles are uniformly distributed over the incoming stream the efficiency of the collection that $\eta = y/\Delta H$. That is very interesting equations or assumptions. So, say number of particles are there and it is falling vertically.

So, from the bottom initially maximum height is H and then it is falling. So, when the particles are at the bottom that will be certainly removed, but those particles at the top may not be able to come to the bottom so, may not be removed. So, efficiency is depending upon the term ΔH term and the y value the distance through which the particle will travel during this time. So, that y/ΔH this value is your efficiency.

So, now efficiency is equal to

$$\eta = \frac{Lvt}{v\Delta H} = \frac{nWLvt}{Q}$$

So, when y is greater than ΔH, then all particles of the size are larger will be collected in the settling chamber and the force balance already we have discussed that

$$v_t = \sqrt{\frac{4gdp\,(\rho_p - \rho_g)}{3C_D\rho_g}}$$

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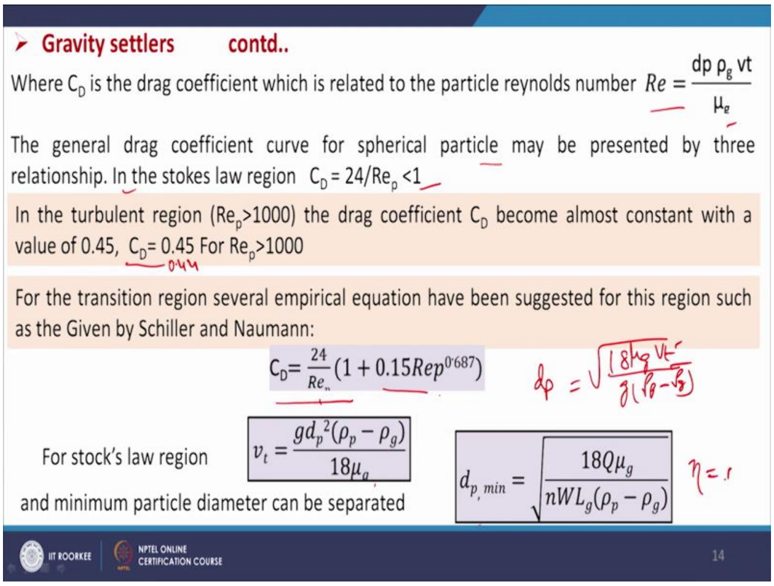

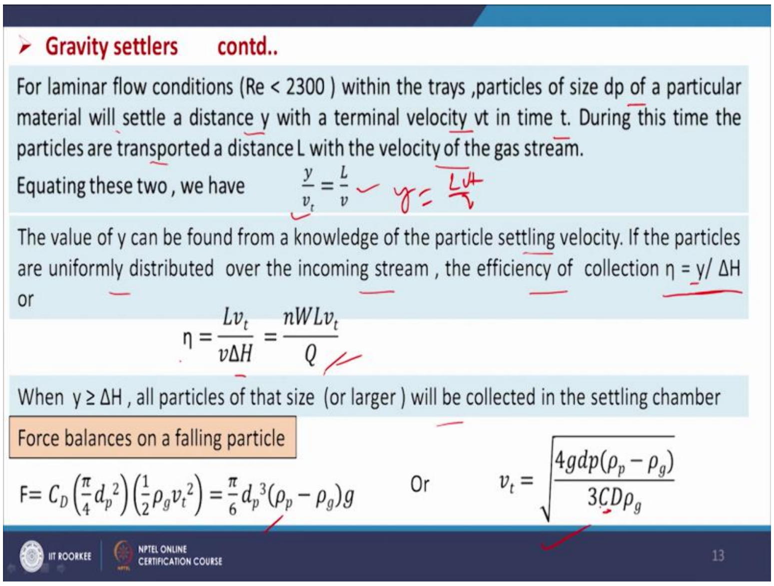

And where C_D is the drag coefficient which is related to the particle Reynolds number and particle Reynolds number

$$Re = \frac{\rho v d}{\mu} = \frac{d_p \, \rho_g \, v_t}{\mu_g}$$

Now, the general drag coefficient curve for spherical particle may be presented with three relationships if we see the drag coefficient, so drag coefficient value will change with the Reynolds number.

If it is laminar flow, then Reynolds number is less so, in that case C_D it is equal to 24/Rep when Rep is less than 1. And when the turbulent region that is Rep greater than 1000, then again C_D is equal to 0.45 or somewhere it is 0.44. For the transition region, several empirical equations have been suggested. And one is here

$$C_D = \frac{24}{Rep}\left(1 + 0.15Rep^{0.687}\right)$$

So, if we consider the Stokes law, so

$$vt = \frac{g d_p^2 (\rho_p - \rho_g)}{18 \, \mu_g}$$

Then what is the minimum particle diameter that can be separated from this expression we can get

$$d_{pmin} = \sqrt{\frac{18 Q \, \mu_g}{nWLg(\rho_p - \rho_g)}}$$

In this case, η is equal to 1. So, that is why we are getting this expression.

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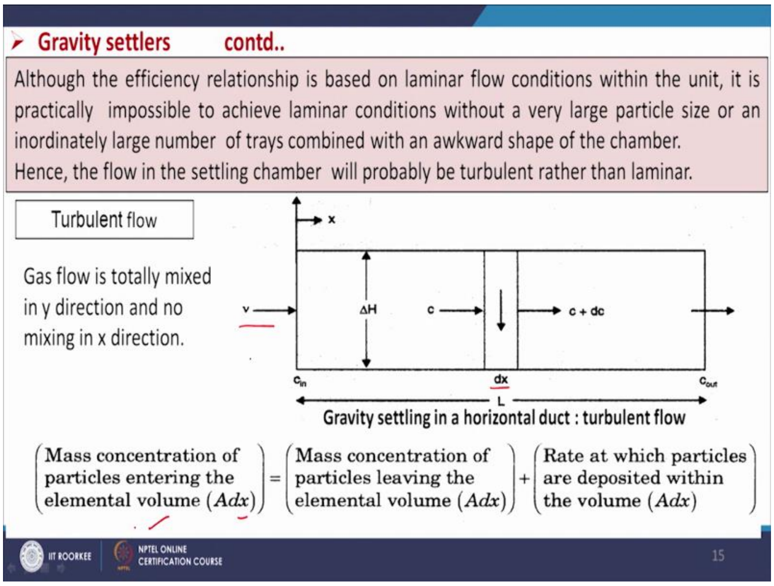

Now, although the efficiency relationship is based on laminar flow conditions within the unit, it is practically impossible to achieve laminar conditions, so, there will be some turbulence. So, there will be some variation as we have mentioned, now let us see, we have the velocity of the gas stream as v and it is going through this chamber and we are considering a small volume and this is the distance dx.

So, in this case if we get the mass balance,

$$\begin{pmatrix} Mass\ concentration\ of \\ particles\ entering\ the \\ elements\ volume\ (A*dx) \end{pmatrix} = \begin{pmatrix} Mass\ concentration\ of \\ particles\ leaving\ the \\ elements\ volume\ (A*dx) \end{pmatrix} + \begin{pmatrix} Rate\ at\ which\ particles \\ are\ deposited\ within\ the \\ elements\ volume\ (A*dx) \end{pmatrix}$$

So, this is the mass balance of the particles.

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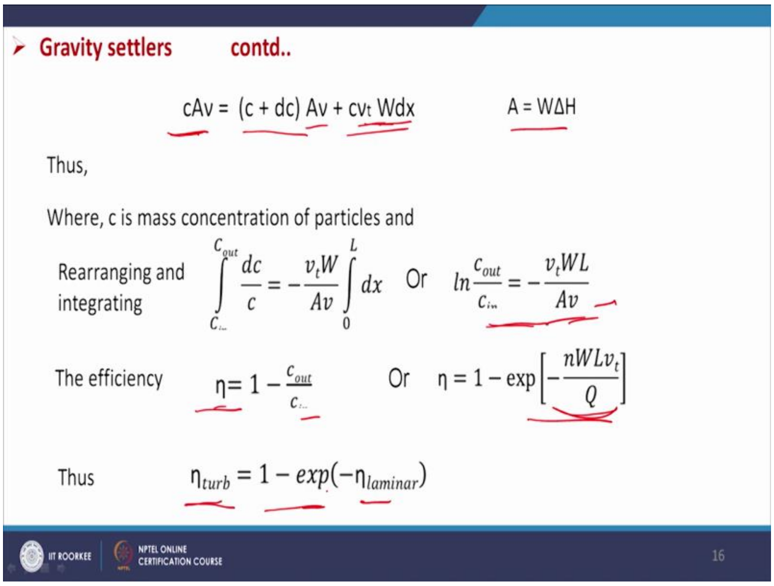

cAv = (c + dc) Av + cvt Wdx, A= WΔH

Where, c is mass concentration of particles and

$$\int_{Cin}^{Cout} \frac{dc}{c} = -\frac{vtW}{Av}\int_0^L dx \quad \text{or} \quad \ln\frac{cout}{cin} = -\frac{vtWL}{Av}$$

Now, if I want to get the efficiency.

$$\eta = 1 - \frac{C_{out}}{C_{in}} \quad \text{or} \quad \eta = 1 - \exp\left[-\frac{nWLv_t}{Q}\right]$$

$$\eta_{turb} = 1 - \exp(-\eta_{laminar})$$

So, laminar conditions if we can find out the efficiency of collection that can be converted into turbulent conditions by using this expression. So, these are the different mathematical expressions which can be used to calculate the efficiency for the separation of the particles, up to this in this class. Thank you very much for your patience.