# Lec 27: Wet Scrubber for Particle Removal

Hello everybody, welcome to this massive open online course on solid fluid operations. So as we are discussing about the particle separation by different mechanisms, where we were actually discussed that what is actually the different mechanism of that particle separation like gravity effect, even cyclone effect or centrifugal action. Also we have discussed more about that particle separation by electrostatic precipitator. Even in the previous lecture we were discussing about that particle separation by or it is called that back filtration process where that industry outlet or carbonaceous particle how can be separated by that filter cloth. Now in this lecture also we will try to learn more about that particle separation, but it will be based on that scrubbing technology where there will be wet method that means some liquid it will be sprayed over the flowing of particle adenine gas where that particles will be separated by attaching that particles on the surface of the water as a droplet which will be coming downward and it can be separated. So in this case it will be called as that wet scrubber for particle removal or separation.

So in this lecture we will try to know what is actually scrubber, why that is very important there. We will see that the scrubbing process maybe that scrubbing basically used for that gaseous compound to be separated in a liquid medium that is scrubbing or the gaseous component can be adsorbed on the solid particles there. So in this case here that gaseous compound not only that the particulate materials can be adsorbed or can be separated by the liquid drop, making liquid drop where that you will get that more interfacial area between that interfacial area of that liquid droplet and based on which that particles would be attaching on that liquid droplet and it will be carrying downward and separating. So this is the basic concept of that scrubber or scrubbing process.

you will see that we are operating this particle separation by this liquid or solvent. So it will be called as wet scrubbers or sometimes it is called wet collectors. So in this case the scrubbing or separation of that particles is a very effective means of removing small particles from a gas. In this case you will see that water is being employed for washing those particulate materials or to remove that particulate materials from the gas system directly and also this removal of particles will be resulted from collisions between that particles and the collecting medium. So here collecting medium is the liquid or solvent and also that particles which would be colliding with that particle as well as collecting medium there in the operation in the system.

So removal of particles that will be resulted from collision between particles and that colliding medium. Now this collision whenever you are talking about that collision will be that particles and that liquid medium. How that liquid medium will be colliding with that particles that is why to get that collision between that particles with that liquid you have to make that liquid as a droplet. So that liquid will be supplied from certain mechanical provision so that there you can produce that droplet of that liquid. So there will be a several mechanism of that.

So before coming to that you will see what are the different systems or equipment that are being used for this particle collection or separation by that liquid or solvent. So in this case there are mainly two types of those equipment can be segregated for that scrubbing of particles. Type one is in which an array of liquid drops that is spray you can say from the collecting medium that will be produced. In this case generally you will see that special name of that equipment is called spray tower that means liquid will be allowed to fall as a liquid droplet or as a spray you can say. And also cyclone spray tower there also liquid will be allowed to pass through that equipment from the top as a spray whereas that whenever it will be sprayed that liquid droplet will be circulating as a centrifugal action inside the bed.

So that is why it will be called a cyclone spray tower. Also there will be another type of scrubber for this type one it is called spray bubble scrubber or a spray bubble collector. So in this case some mechanical provision as a bubble you can say that some plate or rod it will be placed inside the bed so that whenever gas and also liquid droplet will be passed through that you will see there will be some obstruction and because of that obstruction that gaseous stream changes flow direction after getting obstruction from that mechanical devices or provisions like baffle here. So in that case during that change of direction there will be that contact between that droplet and gaseous streams will be enhanced and then that intensity or you can say that efficiency of that collection will be enhanced. So these are three different types of spray tower or spray scrubber we can say based on the type one where that area of liquid drops that will form the collecting medium and type two in which you will see that weighted surfaces of the various types that constitute the collecting medium.

So where that you have to collect that particulate materials that you have to weight those surfaces. So that is why here it is called that the surface to be weighted on which that particles to be collected. So in this case it will be called as plate scrubber and then venture scrubber and packed towers. Here plate scrubber is basically where in a tray there will be a pool of liquid and in that tray you will see that from the bottom part that tray will be porous so that from that bottom part through the pores that gaseous stream will be flow upward as a dispersed phase of bubbles and that bubbles will be coming in contact with that liquid and then getting that more contact between that liquid that means slurry that liquid plus soil with that bubble surface. And then you will see that there will be a transfer of particles from that gaseous stream to that liquid and then that liquid will be taken out from the bottom part.

So these are called plate scrubbers as a plate. So that is why maybe more than one plate will be in the system. So successively you will see that or consequent trays will be acting the same way mechanism to produce that bubbles and from that bubbles how that particles to be segregated to the liquid medium. So there will be more than one number of trays or plate will be there. And then another is called venture scrubber.

In this case you will see that liquid will be passed through that vensory and there will be in the venture you will see there will be one suction chamber and another will be diverging section. In the suction chamber you will see that liquid whenever it will be allowed to pass through a venture or through a nozzle you will see that the liquid will automatically suck that gaseous stream, particle laden gaseous stream and then it will be sucked that you will separate those particles from that gaseous stream whenever it will be come in contact with that gaseous medium with that collective medium. So in this way it is called venture scrubber. In this case you will see that not only that formation of droplet from that venture of that liquid passing through that venture then there will be parallel formation of that your know gaseous bubble along with that particulate material. So there it will be very intensive to collect that solid material or particulate materials in the droplet which is formed in that venture.

So this is basically the advantage is that gas is automatically sucked by that liquid jet and that liquid jet whenever it will be coming through that venture in the pool there will be formation of again that liquid droplet and those droplet will be collecting that gaseous materials unwanted materials or constituents and it will be separated out. So in this way you can separate that particulate matter. The packed towers is another mechanism you will see that here you will see some materials to be used as a packing materials where that gaseous contents or constituents or you can say that some contaminants it will be adsorbed on the surface of that packed materials whenever it will be passing through that packed bed. So it is called packed tower. So these are different types of collecting devices for particulate materials as a wet scrubbers or collectors.

So here in this slide it showed that spray scrubber here particles are collected by liquid drops here liquid drops is produced inside that scrubber there either by you know that nozzle or some spray provisions that is mechanical provisions by which you can spread that liquid as a droplet and liquid drops produced by atomization by the spray nozzles. So in this case collection efficiency would be depending on the droplet size, gas velocity, liquid gas flow ratio and also the trajectory of the droplet. And you will see that the optimum droplet diameter for fine particle collection lies in the range of 100 to 500 micrometer in the case of spray scrubber. And in this case gravitational settling scrubbers can achieve cut dimensions of diameter of about 2 micrometer where you will see that sometimes the gravitational settling scrubber also is useful where that fine particles can be separated by this droplet. So in this case you will see that they are optimum size of that particles will be 2 micrometer and the liquid or gas ratio is in the range of generally 0.

001 to 0.01 meter cube per meter cube of gas which is to be treated like this. So another important scrubber it is called cyclone scrubber. Here also you will see that as shown in the picture or slide here. In this case you will see the drops can be introduced into the gas stream of a cyclone to collect the particles. In this case the spray can be directed outward from a central manifold or inward from the collector wall.

Here in this picture shown that is there. So from the spray ring the liquid drops would be produced and which will be coming out to the bottom as a spray drops you can say that and which will be introduced into that gaseous stream. Here the particle laden gaseous stream enters into this system. In this case the spray can be directed outward from a central from a that central manifold that means from the central part it will be directed outward that means to the wall of this devices and because of which there will be circular motion of this droplet inside this devices. So here this whenever that spray will produce the droplet, the droplet will be circulating inside the bed but that will be alongside of the wall.

So during that cyclonic movement of this droplet, the droplet will come in contact with the gaseous particles which will be coming from this part here at the inlet and then because of that collision and attachment of that particles will be on the surface of the droplet and then that droplet will be collecting from the bottom and those droplet will be coming along with the particles. So in that way that particles will be separated. We have talked about that baffle scrubber also. In this case the changes in the gas flow velocity will be there here dirty gas will be entering and these are the yellow these are marked it is called baffles and here the bottom part of this equipment is a sludge removal that is particles which will be separated here from the liquid. And from the top you will see that water spray will be produced and water spray and it will be coming as a droplet and whenever dirty gas will be flowing you will see that it will be changing its flow direction whenever it gets obstruction from this bubble and then it will be moving like this.

So here in this case we are having that mechanism that changes in the gas flow velocity and direction that is induced by the solid surface of the baffles. So because of which you will get that more contact between droplet and the particle laden gases as well as sometimes on the surface of the baffles there will be particle attachment. So after that from the liquid you can separate those particulate materials which will be collected from the sludge outlet here as shown in the picture. And then Vensury scrubber you will see that one picture it is given as Vensury here this is called Vensury this one which has two parts one is that called converging and this one is the diverging section and here gas inlet with pollutants. So and from that chamber one nozzle should be attached this will be high pressure nozzle and through this high pressure nozzle scrubbing liquid to be supplied as an inlet and there you will see that through that nozzle the liquid will be coming as a jet and whenever jet will be coming that gas that is coming out in the inlet to be sucked by that liquid jet and getting contact with that liquid and gas pollutants and there you will see that from this converging to this diverging section there will be a change of pressure from this high pressure to the lower pressure.

You will see that there will be a formation of droplet and then droplet will be collecting those sucked polluted gas materials and then it will be coming downward and after that it will be separated from this provision. Whereas the gas whatever it is coming out with that liquid that will be separated here. Whereas here it will be itself the separator and from this separator clean gas will be coming out as an outlet whereas that dirty liquid will be coming out as a liquid outlet here. So in this case we are having here convergent divergent section this is represented as a Vensury and those Vensury will be creating that droplet of that water whereas during that formation of droplet by that high pressure nozzle that liquid jet will be sucking that gas inlet gas with that pollutants and then there will be coming there will be a contact between that pollutants and then liquid and that liquid it will be taking out that pollutants and it will be coming out as a liquid outlet whereas that gas will be separated in the separator and it will be coming out as a gas outlet. So this is the mechanism of that Vensury scrubber.

So in this case main thing is that the moving gas system is used to atomize liquids into the droplets and in this case high gas velocities around 60 to 120 meter per second lead to high relative velocities between gas and particles and promote that collection. And another one it is called plate scrubber. In this case a vertical tower that will contain one or more horizontal plates. Here maybe sometimes it is called as trays. In this case gas enters the bottom of the tower here and it will pass through the you know perforations in each plate here there will be plate these are the plate.

So in each plate there will be perforation through which that gas will be flowing. In that case through that perforations whenever a gas will be flowing counter currently of that liquid flow rate which is coming out from the top here at the liquid inlet and you will see that in this plate whenever liquid will become in contact with that gaseous pollutants which is coming from the bottom of this plate to the perforations you will see that will be that will be contact between liquid and particles and then liquid will be flowing downward with that solid particles and then it will be separated from the outlet. And in this case plate scrubbers are usually named for the type of plates they contain sometimes it will be called sheep plate tower. Here instead of this porous perforations perforated plates they are sometimes using as a sheep. So it will be called as then sheep plate tower.

And collection efficiency increases as the diameter of the perforations decreases. If your perforations diameter that means hole diameter through this plate if it is decreases then collection efficiency will increase because they are more finer bubbles will be produced and which will get that more interfacial area between gas and liquid and then it will give you the better efficiency of the collection. In this case a cut diameter that collected with 50% efficiency of about 1 micrometer diameter can be achieved with 3.2 millimeter diameter holes in sheep plate. So this you have to remember.

So this is the basic concept of that plate scrubber. Then we are coming to that packed bed scrubber. In this case it operates similarly to packed bed gas absorber here. In this case the gas is forced to impinge on a liquid surface to reach a gas exit there. In this case some of the liquid atomizes into drops that are entrained by the gas.

Here you will see that liquid will be allowed to pass through this nozzle or you can say the distributor where that liquid will be coming as a distributed liquid in the packed bed. Sometimes that liquid whenever it will be distributed there itself with the formation of droplet those droplet also will be coming through that packing voids. So whenever liquid will be coming through that void of that packed and parallelly whenever gas will be going upward the counter currently then gas and liquid will come in contact and then that separation of that particles will be happened just by attaching that solid particles with the liquid. Now you have to select that liquid in such a way that some will be hydrophilic some will be hydrophobic materials. So those who are hydrophilic in nature those will be easily separated by this scrubbing liquid whereas hydrophobic materials may not be that effective to collect by this solvent.

So in this case the gas exit is designed so as to minimize the loss of entrained droplets here. So whenever liquid will be passed through that packing materials you will see that there will be a formation of droplets. In this case it will be easier to design that packed bed condition to have more in capacitate that packed bed scrubber. In this case it will be better to design that packed bed just by lozhing that droplet in that packed void fractions. So here it is advisable to produce as much as possible to produce that liquid droplet in that void.

But sometimes it is very difficult to get that droplet but it needs that high pressure. So that is why it will be more energy consumption to produce that more finer droplet inside the packing bed. Whereas you will see that sometimes whenever gas will be at high flow rate those liquid droplet also will be coming out through that gaseous medium. So in that case as much as possible that gas exit should be designed in such a way that droplet should not come with the gas medium which is coming out from the top. So in this case collection efficiency maybe affected by liquid flow rate even packing material what type of materials even what is the size of that material what is the packing size what type of materials that and what will be the effective size of the packing material that is important.

So collection efficiency would be affected by those parameters. And then we are having another important devices to separate this particulate materials in wet basis it is called fluidized bed scrubber. So in this case you will see that this is one of the picture of that fluidized bed scrubber typical bed scrubber here. It is called circulating fluidized bed scrubber. You will see that from the bottom part of this fluidized bed that is inlet flue gas and ashes to be allowed to pass from this bottom and it will go through a distributor it may be distributed distributor as a dispersed phase of bubbles or void you can say.

Whereas the liquid will be allowed to pass from that top where are the counter current operation it will happen inside the bed of this fluidized bed you will see that they are then particles will be come in contact in more intensive way in this fluidized bed and then that particles will be collecting from that gaseous medium to that water in this fluidized bed. And whereas you will see the some particles those who are not attaching on the liquid bed a liquid inside the bed those can also be separated from this outlet of the gas by some other mechanism it may be that fabric filter or cyclone separator there it may be there. So here you will see that the fluidized bed scrubber is also one of the important you know equipment based on which you can get that separation of the particle more intensively or more efficiently. In this case you will see that gas and liquid will be come in contact in the fluidized bed more enhanced way you can say because they are gaseous particles will be fluidized in the liquid medium and there may be that more mixing will be happened inside the bed and also there will be a that more contact between gas and liquid they are inside the bed and that is why the separation efficiency will be more. And in this case gas passes upward through the packing while liquid will be sprayed up from the bottom and or flows down over the top of the fluidized layer of the packing.

So in this way you can say whereas that if some particles which are not separated in the liquid then those also can be separated out from the other part that is from the upper part and then it will be attached to that fabric filter or cyclone scrubber, cyclone separator and on which that can be separated. So then it will be again that whatever gas or liquid or moisture it will be coming out that can be utilized here. So in this way you can have this fluidized bed scrubber for the particle separation. This fluidized bed scrubber is used not only for particle separation it is used for separation of gaseous component also from the gaseous mixture of like carbon dioxide, sulphur dioxide, hydrogen sulphide those gaseous materials to be separated just by solvent of liquid maybe sodium hydroxide or other amine solvent where that there will be absorption capacity of that liquid of that gaseous materials will be more high. So in this case that gas liquid contract to enhance it that fluidized bed scrubber is being used.

Then what are the factors for this collection efficiency of any of fluidized bed scrubber or that other type of scrubber. So in that case the total energy loss in the equipment to be considered and also per unit volume of gas treated what will be the drop size what will be the packing structure all those parameters to be considered here. Almost all the energy is introduced in the gas and thus the energy loss can be measured by the pressure drop of gas to the unit. So here pressure drop whatever it will be produced based on which you can calculate what will be the energy consumption. So that pressure drop is created basically based on that gas and liquid flow rate inside the bed.

And you will see that some advantage and disadvantage of this wet scrubber compared to the other type of mechanism. In this case some advantage is that the major advantage of wet collectors is the wide variety of types allowing the selection of unit suitable to the particular removal problem. Whereas some disadvantage also will be there in this case high pressure therefore that more energy will be required to operate this equipment and also you have to operate this equipment in such a way that cleaning of that equipment should be one of the important things and also maintenance also will be very high. Disposal of large volume of scrubbing liquid also must be undertaken for this. So that is the disadvantage of this type of wet scrubber.

Then spray tower as a scrubber that we have already discussed that the simplest type of wet collector is a spray tower into which water droplet is introduced by means of spray nozzle. In this case water droplets fall freely at the terminal settling velocities counter currently through the rising gas stream. And in this case particle contacting liquid collectors in a pool at the bottom and must be pumped out of the pool of liquid for treatment to remove that solids and the cleaned liquid will be recycled to the tower for again collecting of unwanted if there any material out there or not. Now how to actually calculate that collection efficiency of that scrap scrubber as free scrubber that also of course you have to know. Here it basically depends on that what will be the flow rate of that gas also what will be the geometry also what will be the terminal velocity of the particles and what will be the efficiency of that each droplet for collecting that material.

All those factors will be giving that collection efficiency. So the overall free spray scrubber efficiency can be calculated by equation number 7 here given.

Here the Equation

$$\eta_t = 1 - \frac{N(L)}{N_0} = 1 - \exp\left[-\frac{3}{2}\eta_{drop}\left(\frac{u_t}{u}\right)\frac{W}{u_g A_c}\frac{L}{d_s}\right]$$

It is basically that total efficiency or overall efficiency you can say that it will be depending on that number of particles that will be removed per second from the gas stream. Here it is basically 1 minus n by n0 what is n? n is basically number of particles removed per second from the gas stream and n0 is basically initial number of particles enter per second here. And l is basically along the length of spray tower or spray scrubber that is also to be measured because this number may be increasing or decreasing based on that geometry of that scrubber.

So the number of particles or concentration of the particles that is actually varying with respect to height of the column. So that is why the number is depending on the length or height of the column. And also one of the important point whenever the spray tower is producing that spray there will be a formation of droplet. So in that case the terminal velocity of the droplet also will be affecting on that collection efficiency.

Also you will see that what will be the net velocity. You will see that whenever droplet will be falling downward parallely you will see that gas flow system also will be flowing upward and also the particles also will be moving downward with its terminal velocity. So there are terminal velocity of the droplet, terminal velocity of the particle even gas flow rate that is in the upward direction or opposite direction of the liquid and particles will be there. So what will be the effective velocity at which that drop will be falling downward that is also important. So that is represented by here u only u. So here u is basically the drop at which velocity it will be fall down relative to a fixed coordinate system in the presence of a rising gas velocity.

And also you will see that this will not be the same as particle terminal velocity. So the droplet terminal velocity and that effective velocity of the droplet which is falling out relative to that gas velocity which it will not be exactly the same as that terminal velocity that also you have to remember. And also another important point that what is the size of the droplet that is also important that is represented by ds. And also what is the length of the chamber and what will be the collection efficiency of individual droplet for collecting that particle.

So that also to be considered. So here if we consider that single droplet and what is the particles is collecting from its initial particle concentration, then you will be able to calculate what will be the particle collection efficiency of individual droplet. Now for overall collection efficiency to calculate it you have to consider that whole number of droplet there that how many droplets will be forming that depends on that flow rate of the gas, flow rate of the liquid, even geometry of the system and also through which mechanical provisions you are producing that droplet. Whether it is from that nozzle or it is from that perforated plate or other mechanism that you are producing the droplet. So depends on that droplet diameter based on that distributor of the liquid.

So based on who is that efficiency will be depending. So if you are having more finer droplet, it will have more number of droplet will have more interfacial area to collect those particulate material, then you will get that more efficiency. So in that case you have to calculate what will be the overall or total spray scrubber efficiency. So that will be is equal to 1 minus exponent of minus 3 by 2 eta drop into ut by u into w by ug sc into l by ds as shown in the slide as an equation 7 here.

Here the Equation

$$\eta_t = 1 - \frac{N(L)}{N_0} = 1 - \exp\left[-\frac{3}{2}\eta_{drop}\left(\frac{u_t}{u}\right)\frac{W}{u_g A_c}\frac{L}{d_s}\right]$$

Where you will see that eta drop is basically the efficiency of that single droplet for its particle collection. Ut is the terminal velocity of the particle and u is the that means relative velocity of the water droplet at which it will be falling downward relative to the gas velocity and ug is the gas velocity, s is the cross sectional area of the chamber, w is basically if it is suppose the cross section is suppose cylindrical or then what will be the width and also here you will see that l is the length of that chamber and ds is the you will see that droplet diameter.

and in this case quantity w by uc sc is the ratio of volumetric flow rate of water to the volumetric flow rate of air. Here w is that volumetric flow rate of water. Here w it is not that width, here it will be volumetric flow rate of water. So here the quantity w by ur HA across ug sc is the ratio of volumetric flow rate of water to the volumetric flow rate of air. And in this case ut that means terminal velocity of the particle that will be equal to this is the terminal velocity of the water droplet ut the water droplet.

So it will be 958 into 1 minus exponent of minus ds by 0.171 whole to the power 1.147. So ds is basically droplet diameter. Droplet diameter.
Here the Equation

$$u_t = 958\left\{1-\exp\left[-\left(\frac{d_s}{0.171}\right)^{1.147}\right]\right\}$$

So droplet diameter that will give you the terminal velocity. Whereas terminal velocity of the particle that actually it will be very negligible compared to that droplet diameter because the particle is very fine. So the terminal velocity of the particle can be omitted there. So it will not be effective on that relative velocity of that water droplet falling relative to the gas. And eta drop is basically what is that efficiency of the particle collection for a single droplet. This is basically area swept free of particles divided by drop rate cross sectional area as shown in the equation number 8.
Here the Equation

$$\eta_{drop} = \frac{\text{area swept free of particles}}{\text{droplet cross-sectional area}}$$

So based on this equation number 7 and 8 you would be able to calculate what will be the collection efficiency of the spray scrubber. And the overall efficiency of a spray tower that will increase as the collection efficiency of a single drop increases. As the ratio of the volumetric flow rate of water to that of air increases as the length of the chamber increases also it increases with the increases as the diameter of the drops decreases. So I think you understood that what is the mechanism of wet scrubber what are the different type of equipments for that what scrubbing of that particulate material separation and also how to calculate the efficiency of the wet scrubber and also what are the different factors that will effect on the collection efficiency of that particle by this wet scrubber either plate or spray or packed or fluidized wet scrubber. So all those cases that one thing is the geometry effect even the flow rate effect and also the physical properties of the system either particle properties even the solvent properties even the packed material surface properties all those things will be affecting on the collection efficiency.

So I think it is well understood to you please go through once again these slides for your understanding and if you have any doubt you can ask through this email here. So the next couple of lecture will discuss more about particulate matter separation but this will be it will be regarded as a filtration and there are different types of filtration will be there. So we will be discussing in the successive lecture. So thank you for giving attention. So next lecture will be equal to filtration of cross-flow micro filtration and membrane. Thank you have a nice day.