**Course Name: Industrial Wastewater Treatment**

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**Week – 06**

# Lecture 29: Treatment and disposal of sludge

Welcome you all. Today I am going to deliver my lecture 4 of module 6, which is on Treatment and Disposal of Sludge. Under this we will be covering about the basic concepts of anaerobic sludge digestion process. Then we will be discussing about the type of digesters, anaerobic digesters we design. And then finally we will be looking into the various design parameters which are used for design of digester followed by numerical examples which will illustrate the application of these design concepts in design of anaerobic digester.

So, first of all let us talk about the anaerobic digestion process. So, as we know the process of stabilization of sludge solids into digested form into stabilized form is called as the digestion and when it is carried out in anaerobic condition then this process of sludge digestion referred to as anaerobic digestion system. So this is the flowchart which basically represent the entire process of anaerobic digestion of sludge. So as we can see this is like the hydrolysis process where the particulate matters which are converted into the solubilized form in the form of solubilized compounds which are then acted upon by the acidogenic bacteria and this acidogenic bacteria if we see they are anaerobic and facultative bacteria and basically they give rise to the formation of acids and in this process basically the monomers which are present they will be converted into various forms of acids organic acids volatile fatty acids and other higher molecular weight of acids and then these acids are acted upon another group of bacteria called acetogenic bacteria and these bacteria basically they convert all forms of acids in the form of acetic acids and hydrogen and carbon dioxide. Then these are the end products after this acetogenesis process which are then again acted upon by a group of bacteria in the methanogenesis process which converts this acetic acids into final end product which is methane, carbon dioxide and water. So again in the methanogenesis process there are two groups of bacteria one is Acetoclastic methanogens basically these type of methanogens they are active and they split the acetic acid into methane and carbon dioxide. There are another group of bacteria which are called as hydrogen utilizing bacteria and this group of methanogens they basically act upon the hydrogen and carbon dioxide and they convert this hydrogen and carbon dioxide in the form of methane so the final end product in this process becomes $CH_4$ plus $CO_2$ and then plus $H_2O$. So this is finally the sludge or the organic fraction of the sludge that will be finally converted into these end products.

So then let us talk about what are the various types of digesters where we can carry out this digestion process so these are the basically three types of digester one is what we call that is the standard rate or conventional digester and the other one we say that is high rate or completely mixed type of single stage digester and then there are another type of reactor which is two stage digester which is the combination of these two the conventional and high rate completely mixed type of digester.

So let us see more details about these different types of digesters one by one. So let us talk this is the conventional type of digester or we also say that is the standard rate digester so here if we see the sludge they are inserted through these sludge inlets. So, this is a tank where the sludge is taken into and then there are the group of bacteria they act upon the organic fraction and they start carrying the digestion process and as the digestion proceeds, there happens the stratification of different layers in the digester. So if we see there is a one layer form which is Scum layer another layer which is supernatant layer and then this zone what we call this is digestion zone or active digestion zone and then finally at the bottom if we see that is the digested sludge. So there are different layers so this is come layer if we see that is basically the layer form because of the dead organic matters are floating impurities which are present in the sludge so because of their less specific gravity they will be floating on to the surface above the supernatant layer and this supernatant layer is basically the water which is released during digestion process. So this can be taken out from this outlet which is called as the supernatant outlet and then below this if we see this is the active digestion zone, where the bacteria they are in active digestion phase they will try to digest the organic fraction. So here basically the main this is the major component of the digester where the active digestion takes place and convert this sludge into digested form and when the sludge is converted into digested sludge what happens there is the increase in the specific gravity of the sludge density of the sludge because of this they will try to settle down and they will form another layer of digested sludge here in the digester. So because of here if we see there is no heat heating is done there is no mixing is done only the sludge is taken into a digester and is kept into for several days for its digestion. So because there is no heating take place there is no mixing is required so this makes the process very economical so this is one of the most economical type of digester but because there is no heating there is no mixing, so the efficiency of digestion is comparatively lower than the other type of digester and if we see there is a stratification of content into the digester into different layer like scum layer, supernatant layer active digestion layer and then digested sludge. So what happens because of this stratification the active volume which is required for digestion is significantly reduced to less than 50%. So this is the major drawback associated with this standard rate digester because here we are not able to use complete volume of the digester, so it requires comparatively higher size of the digester compared to the another type of digester.

So let us see another type of digester which we call high rate completely mixed type of single stage digester so here if we see here there are the sludge inlets where the sludge is taken into the digester and here if we can see for mixing there is a stirrer provided here it ensures the complete mixing of the sludge coming into the digester and then you can see there is a sludge heaters also here is provided at the bottom so this will try to increase the temperature of the sludge. So here both the heating and mixing both is carried out so the efficiency of this type of system because rate of digestion basically depends upon the temperature so if heating is done temperature is increased so rate of digestion will increase and that basically will require lesser size of reactor lesser detention time which in turn will result into more efficient process and lower size of reactor and also because complete mixing is taking place, so there is no stratification takes place there is no stratification of layer there is a uniform mixing of the sludge so making the process more efficient. So, this is the concept behind the high rate completely mixed type of digester. So if we compare with the standard rate digester because heating is done mixing is done so it becomes more efficient but because here a lot of energy is involved in heating and mixing. So it becomes costlier compared to the standard rate digester but in terms of efficiency it will result into more efficiency compared to the single stage digester.

So then let us see two stage digesters, where we use two stages of digestion, one is one type we use like high rate single stage digester completely mixed type of digester whereas in the another stage we use a standard rate digester. So here if we see the heating and mixing that is to be done in a single stage reactor high rate system but in case of a standard rate digester this heating and mixing is not to be carried out so it is basically a hybrid system of the two types of reactor which result into more most efficient way of digesting the sludge and will become more economical and more efficient.

So this is diagram of two stage digester here if we see this is the first stage digester this is the second stage digester so here if we see this is a completely mixed type of single stage digester where mixing is also done mixer is there and then heating is also done. So this process is like two stage digester connected in series with the another single stage standard rate digester where no mixing is done no heating is done so this second time basically here it is used as for extended digestion of the waste with from the first stage digestion process so this is basically the combination of the two types of digester so it combines the benefits of single stage and standard rate digester both. So this becomes most economical and most efficient digester to be used for digestion of sludge.

So then in design of digester the estimation of methane yield that is to be carried out in order to estimate the quantity of biogas that will be generated through digestion process. So for this if we see what is the theoretical yield so how we can calculate the theoretical methane yield which is generated out of digestion process so here if we see if we take organic matter suppose if we take the $C_6H_{12}O_6 \longrightarrow 3CH_4 + 3CO_2$. So, one mole of this glucose will form three moles of $CH_4$ and three moles of $CO_2$. So here if we see how much $CH_4$ is produced by one mole of this glucose and then if we compare with its equivalent COD, like one mole of this how much it will have COD. So, if we see the stoichiometric relation of its oxidation by air so what we will get that one mole of this compound, this glucose will require six moles of oxygen so from this equation we can find out its COD equivalent and then finally we can calculate this methane yield per unit of COD equivalent or BOD equivalent. So how to do this let us see if we need to calculate how much methane is produced if we see that is the molecular weight of methane that is C is 12 and H is 4 so 12 + 4 = 16 and if we multiply by 3 because there is 3 moles, so it will have 48 gram. So now similarly if we see the molecular weight of this glucose that is around 180 grams, so what we can see 180 gram will produce 48 grams of methane. So per gram of glucose, how much methane will be produced we can get by dividing the amount of methane being generated per unit weight of this glucose. So here this comes around 0.267 gram of methane per gram of glucose being digested and now if we find out the COD equivalent of this glucose. So here if we see one mole of glucose will require six mole of oxygen which is equivalent to 192 grams, so and this one mole of this glucose is equivalent to 180 grams. So the COD equivalent will be per gram of glucose that will be equal to 192/180, so what we get that is 1.067 gram of BOD per gram of glucose

BOD or COD. Here we can say because BOD or COD is inter related and can be used to represent the organic matter. So here if we see that is the amount of methane that will be produced per unit weight of COD reduced. So whatever this methane generation per unit weight of glucose if divide with the methane COD equivalent of glucose, so we will get the amount of methane that will be produced per gram of BOD. So this comes to around 0.25 gram because 2.267 gram of methane will be produced per gram of glucose and its equivalent BOD or COD load that is equal to 1.067. So if we divide 1.067 from 0.267 that is basically the methane produced so we'll get how much amount of methane that is 0.25 gram of methane produced per unit weight of BOD. Now if we see at a standard temperature and pressure like one mole of methane means 16 gram of methane will have a volume of 22.4 liter, so if we convert per gram of methane, so this will come 22.4 x 0.25/16, because 0.25 gram of methane will be generated per gram of BOD. So if we see this value comes to 0.35 $m^3$/kg BOD. Which is basically the theoretical yield so if we don't have any other data except its BOD and its percentage digestion then we can directly calculate how much methane will be generated. And now if we have to calculate how much total amount of biogas will be generated. So we have to find out the fraction of methane in the total biomass and accordingly we can find out the total amount of biogas that will be generated through digestion process.

So then there are formulas also for estimation of methane generation. So this is the most widely used formula where $V = 0.35 \times (EQS_0 - 1.42P_x)$, where V is basically the volume of methane that will be generated per unit time and this 0.35 is basically the theoretical methane yield, where E is the efficiency of digestion, Q is the flow rate and $S_0$ is the infinite BOD concentration and this $P_x$ if we see that is the amount of biomass that is being generated per unit time. So this we can calculate by using this formula where $P_X = \frac{YEQS_0}{1+K_d\theta_c}$, where this $Y$ if we see that is basically the biomass yield coefficient which is basically varies in case of anaerobic digestion process this is hardly 5-7%. So value is something 0.05-0.07 kg per kg of VSS, whereas in case of aerobic digester this yield coefficient is something 0.5-0.7 kg of biomass produced per unit of BOD removed. So, these two formulae we can directly use and can calculate the total amount of methane that will be generated in a sludge digestion facility for a given flow and for a given BOD concentration.

So now let us discuss about the design aspects of anaerobic digester. Let us discuss one by one. So let us discuss about the dimensions and number of the units how much units we require. So here if we see if the plant flow capacity is less than 4 MLD, so up to 4 MLD we can take one unit but in case the plant capacity increases more than 4 MLD, so we can design in multiple of units like say two or more depending upon the capacity of the plant. Then the diameter of the tank which is used for anaerobic digestion that we can take from 6-30 m and in that if we see that is the side water depth which is basically the depth of the water, so this we can take from 4-9 m and then there is a free board free board is provided for accumulation of biogas which is generated in the digestion process and this basically depends upon the type of the roof we are providing about the digesters. So if we have fixed dome type of roof then the free board is very less that is 0.4 meter, but if there is a floating dome then this free board can be taken as 0.6 meter and in case there is a fixed slab or fixed roof so in that case the maximum free board that should be taken equal to 0.8 meter.

Then there are various process criteria like mean cell residence time if we know this mean cell residence time is the total amount of the time for which the sludge remains in the digester. So this is basically temperature dependent. So this value of $\theta_c$ that is basically 28 days for a normal temperature like up to 18°C-20°C and whereas if the temperature is increased to more than 30-40°C. Then its retention time or solid retention time that accordingly gets reduced. So that is around 10 days, so this shows that if we do the heating if we have high temperature to be maintained in the digester high rate digester then thus MCRT value that should be taken equal to very less that is 10 days, whereas in case of standard rate digester this should be taken equal to 30 days 28 days like higher retention time for sludge is required. And similarly this is the hydraulic retention time as we know this hydraulic retention time is the time for which the liquid or the wastewater remains there in the tank. So for a standard rate digester the criteria for HRT that is 30 to 90 days, means 1 to 3 month is required in case of standard digester and rate digester whereas it is very less in case of high rate digester it is within 10 to 20 days. So the digestion process in high rate digester can be completed early as compared to the standard rate digester. Then the another criteria that is very important criteria which is called as the volatile solid loading rate or solid loading rate, so for this we assume like 120 g SS/person/per day and in that if we see that much of 0.48-1.5 kg VSS/$m^3$.d it can be adopted for standard rate digester whereas this VSS loading rate for high rate digester that is comparatively high that is 1.5-6.5 kg VSS/$m^3$ digester.d. So if it is a high rate digester then VSS loading rate can be increased that in turns will require lesser size of reactor. So this is how we can select the solid loading rate criteria for designing the different types of digester then there is one more criteria which we call per capita volumetrical loading rate this is basically the thumb rule we adopt in case of no other data is available. So here what we presume if it is primary sludge if it is primary plus trickling filter mixed sludge and similarly if it is the primary and activated sludge process. So different volumetrical loading rate can be adopted for different types of sludge. So like the first if we see that is for primary sludge which is very-very less that is 0.05-0.08 $m^3$/person. So we have to calculate how many population and after multiplying with the population we can get directly the total volume of digester required similarly if it is a mixed type of sludge then these criteria depending upon the type of the sludge whether it is trickling filter sludge or activated sludge we can adopt these criteria as a standard criteria for designing the digesters.

So now let us discuss about the various approaches we adopt in order to determine the total volume of digester which is required for treatment of the sludge. So here if we can see there are four different approaches the first approach if we see that is based on the MCRT value that is mean cell residence time value. So as we have seen if we have increased the temperature like in case of high rate digester then this MCRT value to be adopted that is around 10 to 15 days whereas if it is a standard rate digester then the values are very high something 28, 30 days we have to adopt and accordingly if we see $Volume\ of\ sludge\ generated/d \times MCRT$, we can directly find the volume of digester required using this approach. And then in the second approach which is basically based on the volatile solid loading rate. So we have to calculate $Kg\ of\ VSS\ produced\ per\ day/VS\ loading\ rate$ will get directly the volume of digester. So using this approach also we can find out the volume of the digester required for anaerobic digestion of sludge. Then in the another approach if we see that is based on the per capita volumetrical loading rate as I said this is like the thumb rule if nothing is there you can calculate

$per\ capita\ volumetric\ loading \times population$ you will get directly volume of digester required for anaerobic digesters. And then the last approach which is basically based on the sludge volume reduction, so this is the formula $V_D = [V_{sl(r)} - 2/3\left(V_{sl(r)} - V_{sl(d)}\right)] \times t$, which is the detention time that may be in days that may be in months as per the unit we can put this value here and we can calculate the total volume of digester required. So we have learnt here the different approaches and then how these approaches we can use in determination of the volume of the digester.

So for this we will see one numerical so if we read this numerical, so here if we see what it does says assuming the following criteria and conditions for digesting the sludge generated from 10 MLD of domestic wastewater plant. So flow we have got that is 10 MLD of wastewater treatment plant and having 60% of suspended solid removal efficiency, so whatever the suspended solid 60% of the suspended solids they are removed in the primary clarifier from where the sludge will be generated and the initial suspended solid concentration which is given that is 250 mg/L in the wastewater and then we have to determine the capacity of the anaerobic digester by using different approaches and then compare the capacity and give your comments. So the data whatever is given you can see that is the moisture content that is 96% of the raw sludge and the initial volatile solid content that is 70% and during the digestion this volatile solids that is digested around 65% of the VSS that will be digested and if we see the solid concentration in the sludge, so that is 8% in the digested sludge, whereas the specific gravity that is 1.03 for the primary sludge and for the digested sludge this specific gravity is little higher that is 1.04 and if we take density of water equal to 1000 kg/m$^3$ and the given residence time that is MCRT value that is 10 days. So using this we have to use all four approaches and then to find out what will be the total volume of the digester.

So here let us see the first approach which is based on the mean cell residence time that is $\theta_c$ value. So here if we see if we have to use the $\theta_c$, so what we have to get is the total quantity of the suspended solids that will be generated from the primary clarifier. So this we can get by using this because if we see initial concentration is 250 mg/L and 60% of this is basically the suspended solids that will be removed here in the primary clarifier and if we multiply with the flow rate which is 10 MLD, so 10 MLD if we convert in liter per day, so we are we have to multiply by $10^6$ so this will give us the amount of total solids that will be removed in the primary clarifier and by calculation if we see that is equal to 1500 kg/day or we can say this is 1500 kg/day. Now this is the total weight of the solids which are produced per day and now we have to calculate the its equivalent volume. So if we have to convert this weight into volume so we have to use this equation which is the $V_{sl} = \frac{W_s}{\rho_w \times S_{sl} \times P_s}$ so here if we see weight of the sludge we have got that is 1500, so if we put this value here and here this is the density of the water which is 1000 kg/m$^3$ and this is the specific gravity of the raw sludge which is 1.03 and this is the percentage of solids which is 4% in the raw sludge. So by putting this all value we can get this much of volume of the sludge will be produced per day.

Now if we have to calculate the volume of the digester then multiply with the MCRT value which is the mean cell residence time and here if we see in the problem it is given mean cell residence time equal to 10 days, so here we have taken this 10 days and by putting this value we can get the total volume of the digester required which is equal to 364 $m^3$. So this is the one approach where we have got the volume of the digester required that is 364 $m^3$. Now let us we take another approach which is based on the volatile solid loading rate, so here if we see percentage of solid in the raw sludge which is 4% so there will be 96% of the moisture and for this the volatile solid loading rate we can adopt as per the design criteria equal to 3 $kg/m^3.d$ and the mean cell residence time already we have taken that is 10 days. So let us compute the total weight of the primary sludge which will be generated so this is again the similar way this is the initial suspended solid concentration 60% is removed and this is if we multiply with the flow rate we get equal to 1500 kg of total solids which are produced per day.

And in this if we see that 60% of the total solids they are volatile in nature so by multiplying by 0.6 we can get the total amount of volatile solid content in the sludge which is equal to 1050 kg/day. And now if we want to find the volume of the sludge using volumetric sludge loading rate so we have to use this formula that is basically the total volatile solids applied divided by volatile solid loading rate. So the total volatile solids which are being produced which is 1050 kg/day and if we divide with the volatile solid loading rate which is 3 $kg/m^3.d$. So, we get the required volume of the sludge that is equal to 350 $m^3$. So, this is another approach by which we have got a different volume which is comparatively lower than the previous one because previous one gives around 364 $m^3$. So let us see another approach that is approach III so which is based on the thumb rule or per capita volumetric loading rate so as I said we have to assume some per capita volumetric loading rate equal to 45 $m^3$/1000 capita and a solid contribution per percent per day that is around 75 grams. So, using this we can find out how much population will be there who will be generating this much of the total solids. So, first of all again we have to find out the total amount of the solids which are generated so we have to use the same formula that is 60% of the total suspended solids multiplied by the flow rate we get this the same amount of total solids being generated.

And in this if we divide the per capita solid contribution then we will get the population equivalent which is something around 20,000 persons which are contributing around 1500 kg of total solids per day. So now we got the population then we can determine the volume of the digester by multiplying the per capita volumetric loading rate and that we have assumed 45 $m^3$/1000 persons. So here we have 20,000 persons, so by multiplying this we get this 900 $m^3$ of sludge digester volume. So, this is the maximum value we have got using this approach but this approach is not very accurate so we have to see another approach also.

So let us see the last approach which is called as the design based on the sludge volume reduction. So here if we see this is the equation to be used that is $V_D = [V_{sl(r)} - 2/3\left(V_{sl(r)} - V_{sl(d)}\right)] \times t$. So using this formula if we have to use this formula then what we need to know that is the volume of the digested sludge because volume of the raw sludge we have already got or we can calculate again so here if we see this is the similar way we have calculated 1500 kg/day that is the total weight of the total solids they are produced and then we have converted using this volumetrical relationship the volume is something 36.4 $m^3/d$, this much volume is generated.

And now determine the volume of the digested sludge also so for determination of volume of digested sludge we have to first find out the fixed solids, so here if we see as per the numerical

70% of the solids they are volatile while rest they will be of fixed solids. So here fixed solid that will be 100-70 = 30% of the total solids. So 30% of the total solids which are generated equal to 1500, so if we multiply with 0.3 so we get the value equal to 450 kg/day that will be the amount of fixed solids that will be generated per day. And then similarly if we see the volatile solids how much it will be generated because the digested solids that will be equal to the fixed solids plus volatile solids so summation of these two solids that will give us the total amount of solids remain in that digested sludge. So here to calculate the volatile solids in the fresh sludge if we see that is 70% of the total solids so 70% of this will give 1050 kg/day of volatile solids and further if we see in the problem of total volatile solids there is a 65% of the volatile solids they are digested so now rest 35% will be remain there in the digested sludge. So if we calculate how much volatile solids they are destroyed so we can find out 65% of the total volatile solids so this is 0.65 times of 1050, so we get a value of 682.5. So this much amount of volatile solids will be destroyed so if we subtract this value from the total volatile solid which is 1050 so we get how much volatile solids that will remain in the digested sludge so that will be 1050 minus 682.5 which is the volatile solids which will be there and this is the fixed solids which will be there in the digested sludge so summation of the two will give the total solids which are present in the digested sludge so summation of the two that will give us 817.5 kg per day.

So this is the total amount of digested solids now let us convert this in the form of volume so again this we have to use the volumetrical relationship weight volumetrical relationship and accordingly we can put the value that is weight of the digested sludge which is 817.5, so 1000 here is the density of the water, so this we have put and then specific gravity of the digested sludge which is comparatively higher than the rock sludge which is 1.04 and then that is the percentage solid which is increased to 8% from 4% so this is 8%. So by substituting this value we get that is the volume of the digested solid which is producing is equal to 9.825 $m^3/d$. So now from this if we use the relationship to find out the volume of digester and put this value we get the volume of digester so here if we replace the value for volume of the rock sludge which is $[36.4 - 0.66(36.4 - 9.825)] \times 15$, so by multiplying this we get a value that is 282.9 $m^3$ which is the lowest value out of the four approaches. So if we analyze this is the approach I this is the volume requirement for approach II and this is the volume requirement for approach III and this is the volume requirement for approach IV, so here if we see this this is the most absurd value should be neglected because this is based on the thumb rule and here if we see this value is very less compared to these two approaches so any value between these two we can adopt as a design capacity for the digester. So, this is how we can use this formula design criteria to determine the size of the digesters.

So, these are the references you can use.

Thank you.