Water Quality Management Practices

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Designs of Anaerobic Reactors: UASB reactor I

Hello everyone, welcome to this NPTEL online certification course on Water Quality Management Practices. My name is Gourav, Professor Gourav Dhar Bhowmick. I am from the Department of Agriculture and Food Engineering of Indian Institute of Technology. In this lecture we will be discussing about the USB reactor, the design of anaerobic reactors majorly the airflow anaerobic sludge blanket reactor. So, this design and the one numerical design will be solving in like in the coming lecture. Design part will do it today I mean like the functionality and all we will discuss about it today and in the coming lecture we will be solving one problem design problem.

So, that it will be will be able to do it in a real life situation and we will be doing it like you know in how it is to be done and it is not that difficult once you will do it you will be able to understand it much clearly. So, coming to today's lecture so, the concept that we will be covering today the design of anaerobic reactors. The important nomenclature like the hydraulic retention time, hydraulic loading rate, organic loading rate, solid loading rate and the airflow velocity we all know a bit about it I will be going through it more in details in today's lecture. Design of USB reactor, the design of the system, design of the gas liquid, a solid separator, the effluent collection systems, design of feed inlet systems etcetera.

To start with we all know we already have experienced I have been even using this term in the design problem. So, let us let us do a you know quick check upon the on the existing nomenclatures that we have already learned. The first one is the hydraulic retention time in the hydraulic retention time it normally refers to the average time of residence of the liquid present inside the reactor. So, it calculated by using the volume by flow rate. So, in this figure if you see it is suppose if you have a cube of cubical of 200 meter cube and 200 cubic meter and you have 100 meter cubic meter per hour of flow rate is given. So, what will be the hydraulic retention time that is

$\theta = V/Q$

where it is 2000 divided by 100. So, that is 20 hour this 20 hour is then the hydraulic retention time or HRT. Hydraulic loading rate hydraulic loading rate is what it is a load it is means the volume of wastewater that we apply per unit area of filter packing medium of the anaerobic filters or any USB reactor what is the total and what is the surface area that they have. So, this hydraulic loading rate which is like nothing, but the can be have an unit of meter cube per meter square per day which is nothing, but

$HLR = Q/A$

Q is the average inflow flow rate that is meter cube per day divided by the surface area of the packing medium or surface area of the reactor this anaerobic reactor ok.

Now comes the organic loading rate organic loading rate means it is the it is simply the volumetric organic loading rate or simply organic loading rate or OLR also we call it. It refers to the load of organic matter applied daily per unit volume of the reactor load of organic matter. So, what is the unit of organic matter BOD here right BOD or COD. So, what how you will calculate it? So, you will calculate it total organic matter that is coming into the picture that is say like the inflow flow rate the inflow rate multiplied by the COD of the inflow COD of the influent wastewater. So, if you multiply the COD of the influent wastewater with the inflow rate.

$L_v = (Q \times S_0)/V$

So, you will get the total amount of like you know the organic load that is coming into the picture divided by the volume of the reactor. So, that is the V by this equation you will be able to understand the organic loading rate that per unit volume how much organic you are supplying to the system ok. So, because it is very important because based on this only the reactor performance will depend ok. Then there comes a solid loading rate. What is a solid loading rate or the sludge loading rate? It refers to the amount of organic matter applied daily to the reactor per unit of mass of biomass present in a reactor.

$L_s = (Q \times S_0)/M$

It is more like how much food you are providing for your microorganisms with in terms of amount of microorganism present as easy as that. So, that is why it sometimes represents also sometimes known as the food to microorganism ratio ok. So, this food to microorganism ratio how you are going to calculate this food to microorganism ratio? First of all you can you need to calculate the amount of food that you are supplying. What is this amount of food that is organic matter? It is like the an influent like flow rate average influent flow rate meter cube per day multiplied by the influent substrate concentration kg of COD per meter cube or gram per like you know or obviously, if you have a gram per liter if you have you know the milligram per liter to gram per liter. Now, you use this as 0 into 10 to the power minus 3 in that case to convert it into kg of COD per meter cube.

So, that is the total food and what is the total mass present there? I mean like the unit mass of organism present in the systems. This mass of organisms present in the system is the kg of VSS per meter cube. How you will calculate this kg of VSS per meter cube? That is nothing, but the mixed liquor volatile suspended solid ok. If you calculate this mixed liquor volatile suspended solid multiplied by the volume of the reactor this m into the volume of the reactor from there you will get the total amount of mass present in the system ok. So, from like using that equation also you can easily calculate the L.

So, here the $(Q \times S_0)/M$ and if it is possible some in some cases you if it is a food to microorganism ratio if you talk about there you need to be specific about the mass of microorganisms present in the reactor multiplied by the volume ok. So, from there you will be able to calculate the exact amount of the solid loading rate of your system. Off flow velocity also known as surface overflow rate in some cases what do what do I mean the off flow velocity suppose your wastewater is coming from the bottom and it goes up. So, off flow velocity it is like you know if you have a say a cylindrical reactor you cut it in like say in you use one cut sectional one cross sectional cut you if you do. So, what will happen because of through this cross sectional area amount of how you get the off flow velocity you need to know the flow rate say in meter cube per hour and if you know the this area this surface area ok.

So, that is say like something say like some a meter square meter. So, this Q meter cube cubic meter per day divided by the a square meter you will get it in the velocity what is the exact velocity of water which is crossing that boundary crossing this each boundaries of this cut section that is

$$v = Q/A$$

So, from this equation you will be able to understand the off flow velocity or in some cases it will be considered the same equation will be useful for get in the value of surface overflow rate ok. The V is that off flow velocity and the a Q is the flow rate mean meter cube per hour a is the area of the cross sectional of the reactor or in case the surface area in some cases. Alternatively this off flow velocity can also be expressed by height by h r t how because if you see Q by V a right V equal to Q by a, a means V by h volume by height so, the volume will stay in the bottom h will go to the numerator ok.

So, in the numerator it now it will become

$$v = (Q \times H)/V = H/\theta$$

Now Q by V means or V by Q means we already calculated what is the how we will calculate this hydraulic retention time volume by the flow rate. So, same way V by Q in the bottom you will replace it with the theta that is the h r t. So, V equal to capital H by theta the height of the reactor divided by h r t. So, if you know the height of the reactor if you know the h r t you will be easily tell the what will be the velocity off flow velocity same way as Q by a ok.

Sludge production sludge production in it is always represents by this equation 7,

$$P_s = Y \times COD_{rem}$$

where P s is the select production of biosolid in the system in kg of V s s per day and y is the sludge yield or the production coefficient in kg of V s s per kg of COD remaining and COD remaining is the COD load that removed or from the system in kg of COD. So, values of y it is actually normally normally stays between 1 0.06 to 0.15 kg of V s s per kg of COD removed ok. So, this equation you remember it will be useful for calculating the sludge production.

What will be the biogash production? How you will be able to quantify the biogash production? It is by equation

$$COD_{CH4} = Q \times (S_0 - S) - Y_{obs} \times Q \times (S_0 - S)$$

Whereas, the COD with this Q is the average influent flow S 0 and S is the influent and effluent COD concentration in kg of COD per meter cube and y OBS is the coefficient of solid produced in the system production in the system in terms of COD that normally stays 0.08 to 2 0.20 kg of COD sludge per kg of COD removed ok. When we design a USB reactor now we discuss about all the nomenclature very important nomenclature already.

Now, let us focus on the design of an of a of an USB reactor. So, when we design of a of flow anaerobic sludge blanket reactor higher loading rate it is initially not possible, but in in some cases theoretically compared to the activator sludge process or other aerobic treatment processes higher loading rate is compared to those there is there is there are the loading rate can be very high in case of USB systems and all. When we design the USB reactor the COD concentration of this reactor wastewater is normally suitably divided into 4 categories to propose the adapt loading condition as you can see in this table. Low strength the COD if it is less than 750 milligram per liter where we can find this in the sewage in the sewage the municipal sewage it never goes more than 750 milligram per liter of COD. So, in that case it is a low strength wastewater.

So, in this case organic loading rate of 1 to 3 kg of COD per meter cube per day is enough and solid loading rate of 0.1 to 0.4 kg of COD per kg of VSS per day is good and with an HRT of 6 to 18 hours is sufficient and liquid airflow velocity has to be maintained between 0.25 to 0.7 meter per hour ok. So, in case of medium strength wastewater like when the wastewater COD in the influence COD in let us influence COD will range between 750 to 3000 milligram per liter. In that case the organic loading rate should be 225 kg of COD per meter cube per day, the solid loading rate should be 0.2 to 0.5 kg of COD per kg of VSS per day and HRT will be 6 to 24 hour and with a liquid airflow velocity of 0.25 to 0.7 meter per hour. In case of high strength it will be somewhere between 3000 to 10000 if it is more than 10000 if it is a it is a very high strength ok. Like the tannery wastewater like the processing wastewater there is it is possible to have a very high petroleum wastewater. So, it may have a very high strength of wastewater these are very high strength wastewater it may have COD more than 12000, 15000, 20,000, 30,000 something like that ok. So, in this cases the organic loading rate should be as high as 5 to 15 kg of COD per meter cube per day, SLR can be 0.2 to 1 kg of COD per kg of VSS per day, HRT can be as high as 240 hour that means, for 10 days as at all as well.

And also the liquids of offload velocity of 0.05 to 0.3 that has to be maintained because it should be very much reduced to increase the chances of the consumption of this pollutant by the microorganism present in the USB system ok. In general the based on the recommendation of HRT and the offload velocity from this table you will choose the height and the area you will work out the height and the area required for the reactor. Also based on the suitable value of OLR this organic loading rate from this equation from this table the volume on the reactor applied can be easily estimated by equation 3 at the given COD concentration.

If you remember in this equation 3 we from here if you know the organic loading rate we can easily calculate the volume of the reactor ok. Then the suitable SLR if for the suitable

SLR we can calculate we can choose it from this table and from there we can easily calculate the we can easily work out the average concentration of VSS which should be between 25 to 35 gram per liter in case of medium and high strength waste water and for from 20 15 to 25 gram per liter in case of low strength waste water ok. The HRT should not be allowed to be less than 6 hour in any cases typically it should be somewhere around 8 to 10 hour that is like a normal practice for low or medium strength waste water ok. Volume of sludge it should be less than 20 50 to 60 percent of the reactor volume estimated based on the OLR to avoid the overloading of the reactor with the respect to SLR otherwise reduce the organic loading rate in case if you cannot do that. At very high a flow velocity greater than 1 to 1.5 meter per hour the inoculum may get washed out during the startup. So, that is why you should not be in any case the a flow velocity liquid a flow velocity should not exit more than 1.2 to 1.5 meter per hour. The a flow velocity in the range of 0.2 to 0.8 meter per hour are favorable for granular biomass growth and maximum a flow velocity of 1.5 meter per hour should be checked for peak flow condition ok. But a taller reactor can be designed to reduce the plane area and also cost of GLS device and influence distribution arrangement, but you cannot go beyond a certain limit ok. So, you cannot in general to minimize the channeling of minimum depth of the sludge bed of around 1.5 meter is present we normally consider and in that case the minimum height of the reactor should be restricted to 4 meter.

Preferably the maximum height should be 8 meter and in between 8 meter like 4.5 to 8 meter and 6 meter is typically used for design of the USB reactors ok. After finalizing the volume and now the height now the plane area can be easily worked out and based on that suitable design of the dimension of the reactor can be adopted. Maximum diameter of this or the side length of single reactor should be kept less than 20 meter ok. Now, the design of the gas liquid solid separator on the top that is like a dome like structure.

You see this picture in this picture this h and the del h those are the very important height of the dome and the the wt which is like the available area for the biogas collection in the in the the width of the dome each dome each GLS separator is wb with the theta is the angle of inclination and wa is the settling compartment. You see in the settling compartment this is the aperture like you know length that is available or the width that is available for the settling phenomena to happen it will to for the effluent to reach the that side of the that side of the chamber. Then in the bottom you have a deflector in the deflector what is happening that is that the deflector the width should be wa that aperture width plus 0.02 meter. And this way and this is the in the right side in the in the left side if you see this is the side wall of the USB reactor.

So, if you see in this case the aperture width is 2 into wa right because wa in the bottom and half of wa in the left side and the half of w in the right side that aperture width. So, total width total in case of 2 number of dome the total number of like the aperture will be total width of the aperture will be wa 2 into wa ok. So, this is you picturize this thing this wa is very important wb is very important the the GLS at the each domes the width of each dome wt is very important this the width of the biogas collection line h is very important h is the height of the GLS separator and the del h that will also be useful. So, when we design a GLS separator of this short so, that the what is what is the purpose of GLS separator. So, that the when the gas liquid solid this mixture will come in contact with this systems because of a certain slope and all what will happen the liquid and solid will start settling the liquid will obviously, like the solid will start settling down and the liquid and the gas and liquid because of this deflectors and all because of the presence of this dome this gaseous will escape from the system.

So, it will escape from the systems and will have to maintain a certain surface overflow rate. So, that the water will not be able to escape, but I mean like water will escape from the effluent line, but it will not be carrying more amount of biogas. So, it will release the maximum amount of biogas possible from its from we have to design it in such a way ok. So, this is how the gas liquid a solid separator is designed. If you see we when we design a gas liquid separator we have to provide enough gas water interface area inside this gas dome.

So, that this interface will act as you know so, release the help the help releasing the gases from the gas collection line. It should provide sufficient settling area outside the biogas collection dome to control the surface overflow rate. It should provide sufficient aperture opening at the bottom to avoid the turbulence due to high inlet velocity because this what will happen when the surface area is small the water will go it will rush right the velocity will increase. So, and because of that there may be chances of generation of turbulence we do not want that. So, because of that we need to provide sufficient this opening of this aperture.

The gas water interface inside the gas collection dome is considered to be the depth of del H you see this is the area where this gas water interface inside the biogas collection dome is considered in the figure. In del H normally is provided in the range of 0.3 to 0.5 meter at the beginning the height of the GLS separator can be considered as 25 percentage of the total reactor height. So, total reactor height if it is 4 meter the gas the H value will be 1 meter that means, almost 1 meter of dome height should be provided GLS separator should be provided height of the GLS separator.

The angle of inclination it is better to be kept between 45 to 75 70 degree so, that enough amount of slope is provided for the sludge to settle on the bottom solid to settle on the bottom and that area that will be used for you know the separation of a biogas from the liquid. How we can estimate the number of domes required? Initial angle of the dome say like assume 45 degree ok. Now the base width of the dome the W b can be easily estimated by this equation 2 into H plus del H divided by tan theta isn't it. So, number of domes that is required for any given diameter per length is can be estimated by dividing the reactor length or diameter by W b ok. Since W b is the W small b and W small a this small b is the width of the aperture opening and can be 0.2 to 0.3 ok. And this W b the total is W capital B is W small b that is the width of the each GLS separator and W is the width of the aperture opening ok. So, now the area of aperture what is the area of aperture it is normally computed on the minimum on the basis of the maximum inlet velocity of a liquid to be allowed and it is essential for proportional flow rate per settling zone in case of rectangular reactor or central settling zone in case of circular reactor divided by the maximum velocity to be allowed. The maximum inlet velocity should be kept around less than 3 meter per hour which is considered as safe for medium and high strength waste water as well ok. The width of the aperture width of this aperture W a it is computed as aperture area divided by width of the width or the diameter of the reactor minimum aperture width of 0.2 meter is recommended the number of domes are increased if width are required more than 0.5 meter. So, if it is more if it is required more than 0.5 meter you have to increase the number of dome in the system. The gas production is expected in this in USB reactor can be estimated based on the OLR selected for the design and expected COD removal efficiency which is in the range of 70 to 90 percent in general. And from there you will be able to understand the smith and production which is can be easily estimated by 0.35 meter cube per kg of COD removed ok. In case of ambient temperature and methane content of 65 to 70 percentage in biogas. From the methane production at in the biogas collection per dome we can easily estimate by in proportional to the percentage of area covered by the dome. And this biogas loading at this gas water interface is estimated by gas collection per dome divided by area. And the loading of biogas as the gas water interface should be kept between less than the 80 meter cube cubic meter of biogas per square meter per day which is about 3 meter per hour ok.

Top width this Wt is normally kept point in between 0.3 to 0.6 and adapted in a design with a maximum of 1 meter that is the top width of the this GLS separator Wt which is also like the area which is available for the gas to escape from the system ok. If the biogas loading is greater than 3 meter per hour we should reduce the height of the GLS separator device to at least 20 percentage and repeat the earlier steps to design the and design and finalize the fresh number of domes required. In some cases we also provide additional layer of gas collector domes if the checks are you know like not satisfying even with the reduction in height of the GLS separator. When two or more layers of gas collectors are used with the height of each layer can be 15 to 20 percent of the overall reactor height with minimum height of each layer is 1.2 meter and maximum of maximum up to 2 meter ok. So, if this typical two layer dome structure nowadays started becoming quite popular and this providing this multi layer domes it can keep the biogas loading under control at gas water interface for the treatment of wastewater with a COD greater than 10000 milligram per liter that means, it is a high strength wastewater ok. Excessive gas loading at this gas water interface which lead to the severe foam formations and this turbulence will push the sludge particles in the gas collection pipe along with the foam leading to the gas pipe blockage on the top of it is Wt part you know. The width of the water surface Ws can be estimated by difference of total length of reactor minus the total top width of the dome and then divided with the number of biogas collection dome from there you can easily calculate the width of the water surface ok. The surface overflow rate it is normally estimated by hydraulic flow rate per dome divided by the area of the settling compartment. We discuss about it remember of flow velocity this surface overflow rate this way also we can calculate it by just we just need to provide the flow find out the hydraulic flow rate divided by the this area of settling compartment.

For effective settling of solid surface overflow rate should be less than 20 meter cube per meter square per day at average flow and 36 meter cube per meter square per day in case of peak flow conditions ok. The minimum height should be restricted to 4.5 meter it is possible with 4 meter also is there in some cases.

Deflector baffles of sufficient overlap of say like 0.1 to 0.2 meter should be provided below the aperture between the gas collectors to avoid the entry of the biogas as we design. As you can see in the earlier figure the diameter of the gas exhaust pipe which should be sufficient to guarantee the easy removal of the biogas from the gas collection dome in ease of foaming I mean like so, that it will not lead to the froth formation on the top of it ok. Now, the effluent collection system if you see this picture in the left side say like in the on the inside where there is like you know first we have the baffle like structure then we have this you know this 90 degree this v notches this v notches and then there is a one small channel and this after the channel there is this baffle after the baffle also you see this inside of the reactor in the left side. In the right side you have this launders effluent launders after the effluent launders water is collected from the other side of it. In the this side in the left side we have this waste effluent I mean like the USB on the top of it then it will cross the this baffles after this baffles you have a certain drainage line and from there then it will cross this v notches after v notch it will there is a cemented laundering structures launders we call it this launders after the launders it will reach to the effluent line ok.

So, in general we provide this effluent launders which are designed in such a way that their wire loading should be should not exceed the maximum value which is 185 meter cube per meter of launder per day ok. The width of this effluent collection launders may be maximum minimum of 0.2 meter to facilitate the cleaning and the maintenance and the depth of this laundered is estimated using the open channel flow designs.

Additional depth of 0.1 to 0.4 meter should be provided to facilitate the free fall of treated wastewater into the launder system you see this structure is given. Additional depth of the on both side of the launder v notches should be provided at point at 15 to 15 20 centimeter center to center distance. That means, on one top of this v notch to another top of v it is the distance is 15 to 20 centimeter ok. When effluent launders are provided with scum baffle this v notches will be protected from clogging as the baffle will retain the floating materials. If you see in this case as I told the baffle will retain the floating materials then there is a certain drop and then this water will pass through this launder.

So, this additional structure this v notch it be this v notches will not be affected which will not be clogged by the floating materials. A scum layer may form on the top of the reactor and sludge accumulation can occur in the launder. So, hence the periodical cleaning of launder and as well as the removal of scum from the top from the surface of the wastewater I mean surface of this USV reactor should be carried out. Design of the feed inlet systems which is very important proper design of the inlet distribution system is very much important for establishing optimal contact between the sludge available inside the USV reactor and the organic matter present in the wastewater. Optimal contact it will help the channeling the wastewater through the sludge bed and normally it is done by there by gravity fed from the top or pump fed from the bottom only through manifold of the laterals.

It is always preferred in case of soluble industrial wastewater this pump fed ones, but in case of gravity fed is much more preferred in case of wastewater with the high suspended solid ok. So, what is happening you see this picture this is this picture this structure is called the splitter box ok. This is called the flow splitter box it is splitting the flow from the bottom actually say it is in the from the bottom you see this main feeder pipe and the top of it you see like you know it is there is a cover is there and it is it is connected to the this collection system. There is a pump which will lift the water from the reservoir this wastewater reservoir and it will pump the water to through or it is quite a good amount of height it will be placed on top of the USB reactor ok. So, if the USB reactor has a say like 8 say 5 meter height or 6 meter height this distribution system this gravity fed inlet distribution systems or the splitter box should be even present a placed on top of it on top of this 6 meter ok.

And then the what will happen the wastewater will enter I mean the wastewater will be pumped through this main feeder pipe and it will flow like you know like a tiny bit of a fountain on right next to it and then it will fill up the first the central box will fill up and then it will be equally distributed because of the design it will be equally distributed into this 12 number of different boxes you see there are 12 boxes are there. In this 12 boxes the and from this box also this center in there is a hole flow distribution holes are there which is connected with a pipe that pipe will go and connect in the directly into the center and just in the bottom of the USB reactor. This is how the feed is inlet a feed is actually distributed in the USB reactor. In general the area served per inlet point should be between 1 to 3 square meter the lower area per inlet points about 1 square meter is provided for reactor design for lower organic loading rate and higher area 2 to 3 square meter per inlet point for organic loading rate of 2 kg of COD per meter cube per day. You understand this inlet point right like the number of inlet point will definitely vary with this number of distribution pipe here in this case 12 distribution pipes are there.

So, it will be connected with the 12 number of inlet point ok. So, your reactor will be having 12 inlet point in this case minimum and maximum offload velocity through this feed inlet nozzles should be considered the offload velocity of this nozzles always should be kept well in between 0.5 to 4 meter per second and the nozzle with the diameter of less than 20 millimeter shall be avoided due to the possibility of clogging. So, it should be much more than that. The this in this case the pictures are actually for demonstration purpose this kind of this kind of nozzles cannot be used actually theoretically speaking it is impossible almost impossible to use it for USB reactors you can have those nozzles which are having much higher you know the nozzle diameter and all ok. The nozzle in the equation of condition for maximum power transfer through the series of nozzles should be used for working out the diameter of the manifold or the main feeder pipe in case of pump feeding.

Number of laterals which attach to this main feeder lines are located on the specific specified spacing on this later clogging of this nozzles may result in uneven distribution. So, we have to make sure that there is no clogging phenomena. The arrangement should be provided for facilitating cleaning and flushing of this influent distribution systems and this nozzles are normally provided at the downward direction with the angle of 40 to 30 to 45 degree to the bottom surface of the your USB reactor ok. So, in case to avoid the blockage in case the lateral is touching the floor of the reactor. So, in conclusion we get to know about the design we get to know clear our concept about how USB reactor looks like and what are the different design considerations.

It may still you may still feel like little bit confused little bit skeptical because of the design issues that involves it will be much more clearer to you in the coming lecture once we will actually design a USB reactor then it will be much more clearer to you will be able to actually do it by yourself ok. So, do not get confused do not get like you know frightened this USB reactor it has a lot of component, but it is quite easy to design and we are not asking you to remember it this kind of whenever you have issues whenever you were asked you will become an engineer and like say you will become an water engineer and you will be asked by your client to design a USB reactor you can just go through this manual this papers that I have referred to in this material in this lecture plus you can also follow the this lecture video just go through this lecture video this one and the next one you will be able to understand what are the design criteria that we need to understand. So, it is not a very rocket science it is very easy, but it need involves certain involvement ok. So, you have to understand the you have to write it down this whole concept it should be better for you.

You follow this both the papers both these papers and the books. Thank you so much. So, we will see you in the coming lecture with the design of this USB reactor and we will do it by ourselves. So, it will be easier for us to you know apprehend that how that USB look like and actually how to actually what are the different components that it involves ok. So, very good. So, have to see you in the coming lecture. Thank you so much.