

Ask Tom! Column

Design of an UASB Reactor

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UASB Process

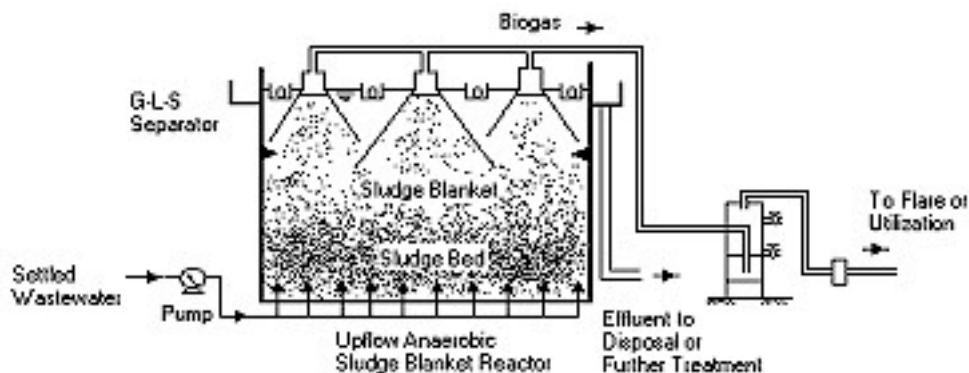
Upflow Anaerobic Sludge Blanket (UASB) reactor has been successfully used to treat variety of industrial as well as domestic wastewaters. The UASB reactor can be briefly described as a system in which substrate passes first through an expanded sludge bed containing a high concentration of biomass. The sludge in the reactor may exist in granular or flocculent form, but the granular sludge offers advantages over flocculent sludge. Most of the substrate removal takes place in sludge bed. The remaining portion of the substrate passes through a less dense biomass, called the sludge blanket.

Provision of sufficient volume of sludge blanket is necessary above the sludge bed, which will provide further treatment to the wastewater by-passed from the sludge bed due to channeling, and will help in maintaining stable effluent quality. Above sludge blanket the reactor has a three-phase separator, Gas-Liquid-Solid (GLS), which separates the solid particles from the liquid and gas, allowing liquid and gas to leave the system.

Proper design of this device is necessary to retain maximum sludge in the reactor to affirm high Solid Retention Time (SRT), about 50 to 100 days or more, and to facilitate treatment with short Hydraulic Retention Time (HRT). In general, the sludge bed occupies 30 to 60% of the total reactor volume, 20 to 30% of the total volume is provided for sludge blanket and GLS separator occupies remaining 15 to 30% of the total volume.

The design of the UASB reactor is carried out taking in to consideration the applicable loading rates, such as, hydraulic loading rate considering limitations of superficial liquid upflow velocity and Organic Loading Rate (OLR). The reactor volume is worked out to suit desired range of loading, and height and plan area are finalized considering upflow velocity. With this approach in design, it may not be always possible to accommodate the desired range of Sludge Loading Rate (SLR) due to limitation of sludge bed volume. Also, it may not be always possible to accommodate the GLS separator device, with dimensions required for providing sufficient area for gas-water interface, for settling, and for aperture at the bottom of GLS device to avoid excessive liquid inlet velocities in the settler. The schematic diagram of UASB reactor is presented in Figure 2.

Figure 2. Schematic diagram of UASB reactor



Under certain situation e.g., for low COD concentration of the wastewater (about 500 mg/L) and under very high COD concentration of the wastewater (10,000 mg/L), the dimensions required for the GLS separator may govern the overall dimensions of the reactor. Hence, it is necessary to give due consideration for the

dimensions of the GLS separator required, while designing the UASB reactor. With these objectives this article aims to discuss range of parameters recommended for design of the reactor and to illustrate the design procedure.

Design Procedure For UASB Reactor

The UASB reactor can be designed as circular or rectangular. Modular design can be preferred when the volume of reactor exceeds about 400 m³. It is necessary to select proper range of operating parameters for design, such as, OLR, SLR, superficial liquid upflow velocity (referred as liquid upflow velocity), and HRT. The literature recommendations for all these parameters and design procedure to account these recommendations are given below.

Organic Concentration and Loading

For COD concentration in the range 2 to 5 g/L, the performance of the reactor depends upon the loading rate and is independent of influent substrate concentration. For COD concentration greater than 5 g/L, it is recommended to dilute the wastewater to about 2 g COD/ L during primary start-up of the reactor. Once, the primary start-up of the reactor is over with granulation of sludge, loading rates can be increased in steps to bring the actual COD concentration of the wastewater. The loading above 1 - 2 kg COD/ m³.d is essential for proper functioning of the reactor.

For primary start-up the optimal loading rates for getting high COD removal efficiency (about 90%) within short start-up time, coupled with generation of good quality granular sludge, are OLR between 2.0 and 3.6 kg COD/ m³.d and SLR between 0.15 and 0.25 kg COD/ kg VSS.d. The OLR to be used for design of UASB reactor for different temperature is provided by Lettinga and Hulshoff. In general, for temperature between 15 and 35 degrees C, the reactor can be designed for loading between 1.5 to 18 kg COD/ m³.d. Lower OLR should be preferred for low temperature and higher OLR can be adopted for high temperature.

For sewage treatment, the design of reactor at higher loading rate is not possible due to limitations of upflow velocity, and maximum loading of about 2 to 3 kg COD/m³.d can be adopted for design. Similarly, for high strength wastewater, such as distillery, satisfying minimum velocity criteria and maximum HRT limit is difficult. Therefore, categorization of wastewater based on COD concentration was observed to be necessary for generalizing the design procedure of UASB reactor to meet the recommended operating conditions to the maximum extent. Thus, the COD concentration of the wastewater is suitably divided in four categories.

It has been proposed to adopt loading conditions as recommended in the Table 1, for design of UASB reactor depending on the average COD concentration of the raw wastewater. These loading rates recommended are suitable for temperature about 30 degrees C. For higher temperature, the loading rates can be slightly increased and for low temperature these design loading rates can be reduced.

Table 1. Recommended loading range for design of UASB reactor based on COD concentration at average flow

Category of wastewater	COD concentration, mg/L	OLR, Kg COD/ m ³ .d	SLR, Kg COD/ kg VSS.d	HRT, Hours	Liquid Upflow Velocity, m/h	Expected Efficiency, %
Low strength	Up to 750	1.0 - 3.0	0.1 - 0.3	6 - 18	0.25 - 0.7	70 - 75
Medium strength	750 - 3000	2.0 - 5.0	0.2 - 0.5	6 - 24	0.25 - 0.7	80 - 90
High strength	3000 - 10,000	5.0 - 10.0	0.2 - 0.6	6 - 24	0.15 - 0.7	75 - 85
Very high strength	> 10,000	5.0 - 15.0	0.2 - 1.0	> 24	---	75 - 80

Reactor Volume

Based on the higher suitable value of OLR, for given COD concentration, the volume of reactor required is to be worked out as:

$$\text{Volume} = (\text{Flow Rate} \times \text{COD concentration}) / \text{OLR}$$

For the suitable SLR values for that COD range (Table 1), the volume of sludge required can be worked out considering the average concentration of VSS between 25 and 35 g/L for medium and high strength wastewater, and 15 to 25 g/L for low strength wastewater. This volume of sludge should be less than 50% of the reactor volume, worked out based on OLR, to avoid overloading of the reactor with respect to SLR. If the volume is not meeting the requirements, the OLR can be reduced to increase the volume. The volume of the reactor is thus, finalized to meet both the requirements. For this volume, the HRT should not be allowed to be less than 6 h for any type of wastewater and generally, it should be less than 18 h to reduce volume and hence, cost of the reactor. For very high strength of the wastewater, COD greater than 10,000 mg/L, it may not be possible to meet this requirement, hence, under such situation the HRT may be allowed to exceed even 24 h and as high as 200 h.

Superficial Liquid Upflow Velocity

Higher upflow velocities, favors better selective process for the sludge and improve mixing in the reactor. However, at very high upflow velocity, greater than 1.0 to 1.5 m/h, the inoculum may get washed out during start-up or during normal operation granules may get disintegrated, and the resulting fragments can easily wash out of the reactor. The maximum liquid upflow velocity allowed in design should not exceed 1.2 – 1.5 m/h. Upflow velocities as 0.25 to 0.8 m/h are favorable for granule growth and accumulation, during normal operation of the reactor and maximum upflow velocity up to 1.5 m/h at peak flow conditions for short duration can be used in design.

Reactor Height and Area

The reactor should be as high as possible to reduce plan area and to reduce cost of land, GLS device, and influent distribution arrangement. The height should be sufficient to provide enough sludge bed height to avoid channeling and to keep liquid upflow velocity within maximum permissible limits. In order to minimize channeling the minimum height of the sludge bed should be about 1.5 to 2.5 m. For this reason, the minimum height of the reactor should be restricted to 4.0 m, to conveniently accommodate sludge bed, sludge blanket and GLS separator. The maximum height of the reactor can be about 8 m. The height of the reactor adopted in practice is usually between 4.5 and 6 m.

While designing, initially suitable height of the reactor (about 6m) can be chosen, and superficial liquid upflow velocity is to be worked out as height/ HRT. It is recommended to adopt upflow velocity of 0.7 m/h at average flow and 1.0 m/h to 1.2m/h at peak flow. Accordingly, if the upflow velocity exceeds the maximum limits height of the reactor can be reduced in steps up to minimum of 4 to 4.5 m. If this is not possible in the applicable range of height, HRT shall be modified and fresh reactor volume and OLR shall be worked out. For low strength wastewater, the maximum liquid upflow velocity becomes limiting and for very high strength wastewater very low velocity (less than 0.1 m/h) is required while designing the UASB reactor. Under certain situations, the revised OLR may be less than the initial OLR recommended. It is advisable to allow lowering of OLR in such situations to control upflow velocity in the reactor for proper performance of the reactor.

After these iterations for volume and height, the plan area can be worked out and suitable dimensions of the reactor can be adopted. Generally, the maximum diameter or side length of single reactor should be kept less than 20 m. Before finalizing the dimensions of the reactors, it is necessary to consider the dimensions required

for GLS separator, because to accommodate the GLS separator meeting all requirements, it may be necessary to alter height and plan area of the reactor.

Gas-Liquid-Solid (GLS) Separator

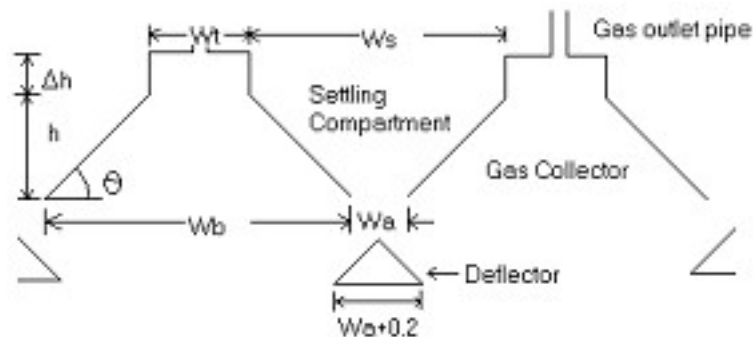
In order to achieve highest possible sludge hold up under operational conditions, it is necessary to equip the UASB reactor with a GLS separator device. The main objective of this design is to facilitate the sludge return without help of any external energy and control device. The guidelines for shapes and design of GLS separator are given by Lettinga and Hulshoff. The GLS should be designed to meet the requirements such as, provision of enough gas-water interface inside the gas dome, sufficient settling area outside the dome to control surface overflow rate; and sufficient aperture opening at bottom to avoid turbulence due to high inlet velocity of liquid in the settler, to allow proper return of solid back to the reactor. Due attention has to be paid to the geometry of the unit and its hydraulics, to ensure proper working of the GLS separator.

Design of GLS separator

The shape of the GLS device considered in design is presented in Figure 3. The gas-water interface inside the dome is considered at the depth D_h from top of the dome. In the beginning, the height of GLS separator can be considered as 25% of the total reactor height. For estimating initially the number of domes required the angle of dome with horizontal can be assumed as 45° , and base width of dome (W_b) can be calculated as $2(h+D_h)/\tan \theta$. The D_h is to be calculated as $(W_t/2) \tan \theta$, and initially the top width (W_t) can be considered as 0.2 to 0.3 m. The number of domes required for given diameter (or width for rectangular reactor) can be calculated by dividing width or diameter by W_b , and rounding this number. Where, $W_b = W_b + W_a$, and W_a can be considered as 0.2 m initially. After deciding the number of domes, the flow rate shared by each dome, is to be estimated in proportion to the base area of each dome, including aperture width, to the total area of the reactor.

Aperture width at bottom of gas dome: The area of aperture (A_p) required can be computed based on the maximum inlet velocity of liquid to be allowed. This area can be estimated as flow rate per dome for rectangular reactor (or central dome in case of circular) divided by maximum velocity to be allowed. The maximum inlet velocity of 3 m/h is safe for medium and high strength wastewater and for low strength the inlet velocity less than 2.0 m/h should be preferred. The width of aperture (W_a) is to be calculated as aperture area divided by length (or in case of circular reactor by diameter) of the reactor. It is recommended to use minimum aperture width of 0.2 m and if the width required is greater than 0.5 m, then increase the number of dome by one and repeat earlier steps till it is less than 0.5 m.

Figure 3. Details of the Gas-Liquid-Solid (GLS) Separator



Width at gas-water interface: The gas production expected in the reactor can be estimated based on the OLR selected for the design and expected COD removal efficiency in the range 70 to 90 percent. The gas production can be estimated as $0.35 \text{ m}^3/\text{kg COD removed}$ at ambient temperature. From this gas production the biogas collection per dome is to be worked out in proportion with percentage of area covered by the dome. The biogas loading at gas-water interface can be calculated as gas collection per dome divided by product of

top width of gas collector (W_t) and length of the reactor (diameter, in case of circular reactor). The loading of biogas at gas-water interface should be kept less than $80 \text{ m}^3 \text{ gas/ m}^2 \cdot \text{d}$ (about 3 m/h). Initially the top width can be assumed as 0.3 m and for this width if the biogas loading is less than 3.0 m/h then adopt 0.3 m as top width.

If the biogas loading is greater than 3.0 m/h , calculate the top width required. Generally, top width of 0.3 to 0.7 m can be adopted in design with maximum of 1.0 m . When even with maximum top width, if biogas loading is greater than 3.0 m/h reduce the height of GLS separation device to 20% and repeat the earlier steps of GLS separator design, with fresh number of domes. Even with reduction in height of GLS separator if these checks are not satisfying, provide additional layer of gas collector dome. When two or more layer of gas collectors are used the height of each layer can be 15 to 20% of the overall reactor height, with minimum height of each layer as 1.2 m and maximum up to 1.5 to 2.0 m . The fresh biogas collection per dome is to be worked out and further steps are repeated until all design conditions are satisfied.

Check for Surface overflow rate

The width of the water surface (W_s) available for settling of solids for each gas dome, at top of the reactor, can be calculated as difference of W_b and W_t . The corresponding surface overflow rate is calculated as hydraulic flow rate per dome divided by product of length (or diameter) and W_s .

It is recommended that the surface overflow rate for effective settling of solids back to the reactor should be less than $20 \text{ m}^3/\text{m}^2 \cdot \text{d}$ at average flow and should be less than $36 \text{ m}^3/\text{m}^2 \cdot \text{d}$ under peak flow conditions. If the calculated surface overflow rate is meeting these criteria the design of the GLS separator is final. When it is exceeding the limits recommended, it is advisable to reduce the height of the reactor, thus, for same volume of the reactor more plan area will be available. When the height of the reactor is reduced all earlier steps for design of GLS separator should be repeated to satisfy all design criterion. The minimum height of the reactor should be restricted to 4.0 m (preferably 4.5 m). Once, all the design criteria are satisfied the angle of inclination of the gas collector dome with horizontal (q) can be calculated as $q = \tan^{-1} [2h / (W_b - W_t)]$.

Baffle of sufficient overlap (0.1 to 0.2 m) should be provided below the gas collector in order to avoid entry of biogas in the settling compartment. The diameter of the gas exhaust pipes should be sufficient to guarantee easy removal of the biogas from the gas collection cap, particularly in case of foaming. Generally, lower reactor height is required for UASB reactor treating sewage. Under certain situation, particularly for very low strength of wastewater, even with reduction of height to the minimum may not meet all design requirements. In such cases the OLR adopted for design can be reduced to provide greater volume of the reactor and hence more plan area to meet the entire design criterion.

Effluent Collection System

The effluent has to leave the UASB reactor via number of launders distributed over entire area discharging, to main launder provided at periphery of the reactor. The effluent launders can be designed in such a way that the weir loading ($\text{m}^3/\text{m} \cdot \text{d}$) should not exceed the design criteria of Secondary Settling Tank (i.e. $185 \text{ m}^3/\text{m} \cdot \text{d}$). The width of the launders may be minimum 0.20 m to facilitate maintenance. The depth of the launder can be worked out as open channel flow.

Additional depth of 0.10 to 0.15 m shall be provided to facilitate free flow. On both sides of the launders 'V' notches shall be used. When effluent launders are provided with scum baffles, the 'V' notches will be protected from clogging as the baffles retain the floating materials. A scum layer may form at the top of reactor and sludge accumulation can occur in the launder hence, periodical cleaning of launders and removal of scum should be carried out.

Design of Feed Inlet System

It is important to establish optimum contact between the sludge available inside the reactor and wastewater admitted, and to avoid channeling of the wastewater through sludge bed. Hence, proper design of inlet distribution system is necessary. Depending on topography, pumping arrangement, and likelihood blocking of inlet pipes, one could provide either (i) gravity feed from top (preferred for wastewater with high suspended fraction), or (ii) pumped feed from bottom through manifold and laterals (preferred in case of soluble industrial wastewaters).

The rough guidelines for the number of feed inlet points required in UASB reactor is presented by Lettinga and Hulshoff for different concentration of the sludge inside the reactor and applicable loading rates. In general, the area to be served by each feed inlet point should be between 1 and 3 m². Lower area per inlet point (1 m²) is to be adopted for reactor designed for OLR of about 1 kg COD/m³.d, and higher area (2 to 3 m²) per inlet point can be provided to the reactor designed for OLR greater than 2 kg COD/m³.d. Apart from the number of feed inlet points, the minimum and maximum outflow velocity through the nozzles should also be given due consideration while designing.

This outflow velocity through nozzles can be kept between 0.5 and 4.0 m/s. The equation of 'condition for maximum power transfer through nozzle' can be used for working out nozzle or inlet pipes diameter. The clogging of the nozzles may represent serious problem resulting in uneven distribution of the wastewater over reactor bottom, particularly when treating partially soluble wastewater. Hence, arrangements should be made for cleaning or flushing the inlet system.

Other Requirements

It is necessary to keep provision for removal of excess sludge from the reactor. Although, the excess sludge is wasted from about middle height of the reactor, it is also necessary to make arrangement at bottom of the reactor. In addition, 5 to 6 numbers of valves should be provided over reactor height to facilitate sampling of the sludge. For treating high strength wastewater it is recommended to apply effluent recycle, in order to dilute COD concentration and to improve contact between sludge and wastewater.

For treating wastewater with COD concentration greater than 4 - 5 g/L, it is recommended to apply dilution during start-up, for proper granulation of sludge inside UASB reactor. Auxiliary equipment has to be installed for addition of essential nutrients, and alkalinity for control of pH of the influent. The other equipments to be provided are for measurement of pH, temperature, influent flow rate, and gas production rate.

Thus, this design of the reactor will meet all design recommendation proposed in the literature. The proper design of reactor along with GLS separator will help in better retention of the sludge inside the reactor. This will help in reducing start-up time, required for the reactor to achieve steady state, and better performance of the reactor during steady state.

In this design procedure first priority is given for maintaining maximum possible COD conversion efficiency of the reactor, by selecting proper loading conditions for that COD concentrations, and then to try for minimizing cost of the reactor. For given COD concentration of the wastewater maximum possible loading rates are used in the beginning and reduced in steps till the design satisfies all the requirements. Thus, this design will provide minimum volume of the reactor satisfying all design recommendations.

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Welcome to Ask Tom!, a monthly column by our resident water treatment guru, Tom Keenan of National Environmental Services Agency (NESA). Tom addresses the issues that bug you the most. And Tom knows!! With 35 years experience in providing environmental support services to public and private sector clients on a wide range of environmental issues.

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