

CRITERIA FOR THE UTILIZATION, DESIGN AND OPERATION OF UASB REACTORS

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ABSTRACT

This paper describes and discusses the principal ideas and parameters related to the application, design and operation of wastewater treatment systems using the upflow anaerobic sludge blanket reactor (UASB). The differences in the process brought about by the high or low concentration of organic material in the wastewater to be treated are pointed out in each consideration.

The purpose of this paper is to make the development of simple, but safe and efficient UASB reactor treatment units, by technicians not necessarily highly specialized in the subject, possible. It also attempts to point out problems which are not yet completely solved in order to help in the preparation of future research and development plans.

A number of possible questions that deal with the following subjects are discussed:

- types of waste which can be treated by the UASB reactor
- concentrated wastes (for example, stillage from sugar-cane) and diluted wastes (for example, domestic sewage)
- necessity of pre- and post-treatment
- temperature
- shape and dimensions of the reactor
- criteria and details for design
- start-up, operation and control of the unit
- forecasts of efficiency, costs, etc.

KEYWORDS

Anaerobic treatment, UASB reactors, domestic sewage, application, temperature effects, design, start-up, operation and performance.

INTRODUCTION

Until the seventies, anaerobic processes were not extensively used for treatment of wastewaters such as organic industrial effluents and domestic sewage. The main processes used were the septic tanks, anaerobic filters and the anaerobic contact process, besides the conventional digestors.

With the advent of the energy crisis, the use of the anaerobic processes as substitutes for the traditional energy-dependent aerobic processes were taken into consideration in greater depth. But it was in the late seventies that a process was developed which due to its simplicity, low cost, high treatment

rate and efficiency could compete with the aerobic processes. It is the upflow anaerobic sludge blanket reactor (UASB) developed in Holland (Lettinga et al., 1980).

The UASB reactor consists basically of a tank at the bottom of which the digester itself is located and at the top of which a settler preceded by a gas separation system is located. The wastewater to be treated is uniformly distributed at the bottom of the reactor and passes through a biological sludge layer which transforms the organic material into biogas. The gas produced is prevented from entering into the settlers through the deflectors and only enters certain areas of the reactor. The portion of the sludge which reaches the settler is separated and returns to the bottom of the reactor. The effluent is uniformly withdrawn from the surface of the settler (Figure 1).

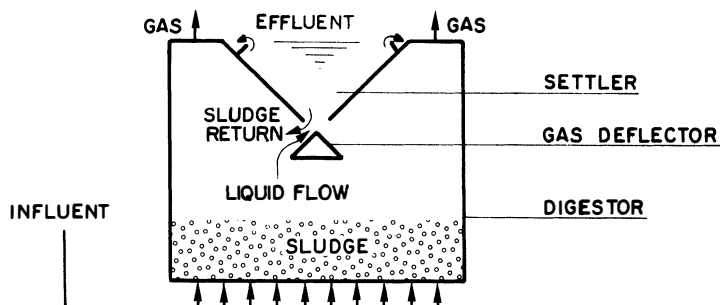


Fig. 1. Schematic diagram of a UASB reactor

It is very important for the proper functioning of a UASB reactor that biological sludge be available in adequate quantities, and that it has or may acquire better settling characteristics and methanogenic activity. A high level of substrate-sludge contact, an efficient gas/solids separation, plus an adequate bacteria selection process greatly contribute to the development of the desired sludge.

Due to the situation explained above, the purpose of this paper is to describe a simple technology for wastewater treatment in UASB reactors, particularly in the tropical countries. The information presented was obtained through experiments conducted at "CETESB" and at other local and foreign institutions, as well as experiments described in the literature.

CRITERIA FOR THE UTILIZATION OF UASB REACTORS

UASB reactors are used for the treatment of wastewater in which the main pollutant is organic material and consequently for the production of biogas from these residues. We can cite as examples domestic sewage and wastewater from the production of beers and soft drinks, sugar cane alcohol, instant coffee, citric juices, paper, etc.

Suspended Solids

The smaller the concentration of suspended solids (SS) in the wastewater, the less problematical will be the treatment. The maximum acceptable SS depends on the total concentration of organic material in the wastewater. In the case of a low-concentration waste, such as domestic sewage (typical COD 0.5 g/l) and proven to be successfully treated by a UASB reactor (Lettinga et al., 1983b; Vieira, 1984; Nucci et al., 1985; Schellin Khout et al., 1985; Souza and Vieira, 1986), the SS concentration reaches low absolute values (approximately 0.25 g/l), but high relative values (0.5 g SS/g COD). In the case of a concentrated waste such as the stillage from sugar cane (typical COD, 25 g/l)

and also proven to be successfully treated by a UASB reactor (Craveiro et al., 1982), the opposite happens, i.e., the SS concentration reaches high absolute values (for example 1 g/l), but low relative ones (0.04 g SS/g COD). Therefore, it is clear that there are two criteria which, if occurring simultaneously ($SS < 1 \text{ g/l}$ and $SS/COD < 0.5$), will not impede the treatment of the wastewater in a UASB reactor.

Wastes containing rough solids may be processed if a pre-treatment system (screening, sieving, settling, etc.) is used, which will make them compatible with the above criteria. Moreover, initial hydrolysis systems and consequent liquefaction of part of the solids may contribute decisively to the applicability of the UASB reactor.

Toxic Compounds

An important issue that can make the treatment of waste in a UASB reactor impossible is the presence of compounds potentially toxic to the bacteria. There are many papers on this subject, mainly related to the effect of heavy metals, alkaline and alkaline earth metals, sulfates, sulfides, chloroform, cyanides, phenols, chlorides, nitrates, oxygen, etc. (McCarty, 1964; Mosey, 1976; Yang et al., 1980; Souza, 1982).

Even for wastes containing some powerfully inhibitory toxic compounds, some techniques may be used in order to make the anaerobic treatment possible, such as dilution of the waste, digester effluent recirculation, mixture with other waste, pre-acidification, etc.

Sulfates, in particular, are of concern due to their presence in many wastes. The sulfate-reducing bacteria compete with the methanogens for hydrogen in the presence of sulfates. The H_2S produced by the reduction of sulfates may be highly toxic to the bacteria, besides causing possible odor and corrosion problems. It was recently established that to avoid such problems, it is necessary that the COD/SO_4 ratio in the waste has to be higher than 7 - 10 (Lettinga, 1981).

In cases of uncertainty, it is always convenient to first conduct treatability tests in the laboratory, which do not necessarily need to be performed in a UASB reactor, since their purpose is not to determine design parameters.

Temperature

Temperature is important for the economic feasibility of the process. In the mesophilic range, the optimum temperature for anaerobic digestion is approximately 37°C . The process occurs at an acceptable rate between 15 and 25°C and at a relatively high rate between 30 and 40°C . In all circumstances, it is essential to avoid sharp variations in temperature (Lettinga et al., 1984).

In regions having tropical weather, the ambient temperature is high enough to make heating, the automatic control of the temperature, and sometimes even the thermal insulation of the bio-digester unnecessary. In this case, reduction in costs is remarkable and the use of UASB reactors is much more desirable.

The production of heat resulting from anaerobic metabolism is low (the greatest part of the energy is released in the form of methane) and consequently one cannot depend on this factor to increase the temperature in the reactor, even if it is insulated. In some situations, the methane produced may be used as a fuel for heating.

For diluted wastes, the question of temperature is much more important because the quantity of methane produced is low in relation to the wastewater volume to be heated, and, consequently, where heating is necessary, an external energy source would have to be used. Fortunately for domestic sewage in general, the average temperature is almost constant throughout the greater part of the year (mainly in tropical regions), even if pronounced changes in the ambient

temperature occur. In this case, the flow velocity of the waste through the reactor is very high, and, consequently, the reactor temperature is almost the same as that of the sewage (relatively constant). Being such, heating, temperature control and thermal insulation systems are not necessary. Only in the case of sewage treatment plants in places with few inhabitants, where the minimal sewage flow reaches very low values in relation to the average during several hours of the day, would some simple system of thermal insulation, such as the construction of buried or semi-buried reactors, be justified.

For wastes with a high concentration of organic material, the flow velocity of the waste through the reactor is relatively low. Consequently, the influence of ambient temperature on the reactor temperature is greater, and efficient systems of thermal insulation and even controlled heating may be necessary, depending on the intensity of the fluctuations in the local ambient temperature.

When the wastewater is generated at high temperature (above 50°C), treatment in the thermophilic range (55 - 60°C) may be viable. This will generally bring about a higher reaction rate and greater efficiency when compared with the mesophilic range. However, available information on the thermophilic process is still limited. Besides, it is not advisable to heat waste produced under mesophilic conditions to operate in the thermophilic range, because the increase in efficiency and rate would probably not compensate for the difficulty and cost increase related to heating and temperature control.

Organic Loading and Flow Variations

UASB reactor may also be used for waste presenting significative variations in organic material concentration or flow. Some extra precautions may be taken in these cases, such as the use of initial equalization tanks. The cost increase may be compensated for by an increase in the efficiency, stability and safety during the operation of the UASB reactor.

The recirculation of digester effluent and its mixture with the waste to be treated may contribute to equalization in the case of waste with a high concentration of organic material. As the effluent quality is more uniform than the influent's, the mixture of both will increase the level of uniformity of feeding of the reactor, besides the fact it may bring about a generally beneficial dilution effect.

In cases where a large variation in flow rate may occur, the use of several UASB reactors operating in parallel could be a solution. The first units would operate with a continuous flow which would guarantee greater efficiency, safety and stability, while the last units would operate with a variable flow determined by the quantity of waste to be treated. In other words, a unit would only receive the waste when the former one was receiving it at the designed flow rate. So, the effluents from all the units would present a better and more homogenous quality than if all the units would undergo simultaneously large flow variations.

An important UASB reactor advantage is its potential use for waste generated seasonally. It has already been demonstrated (Craveiro, 1982) that, for a UASB reactor having operated satisfactorily during a determined harvest time, after some months without operation or feeding, operational conditions may be re-established during the next harvest time rapidly (in some weeks) and without difficulties. In the interim period, it is not necessary to feed the reactor or to control the system temperature. This ability to maintain the anaerobic viability in the UASB reactor does not occur similarly in aerobic processes and is more problematic in other anaerobic processes.

pH and Nutrients

If the waste lacks the nutrients N and P, its treatment in a UASB reactor is not impeded, provided that systems for addition of these nutrients are used in the following ratios: $COD/N \leq 70$ and $COD/P \leq 350$.

Several micronutrients are also necessary, and a lack of them makes treatment difficult. It is only through initial experiments with the waste (for example, digestibility tests in laboratories), that one may safely determine whether all of the micronutrients are present in sufficient quantities. A combined treatment of several types of wastes, when it is possible, may compensate for a lack of micronutrients in some of the wastes.

The optimum pH for anaerobic digestion is around 7.0. pH values below 6.5 or above 7.5 may be harmful to the bacteria, mainly to the methanogens. However, wastewaters with very low pHs may be easily treated in a UASB reactor because of the buffering capacity of the anaerobic process for most wastes. In this case, and especially for concentrated wastes or when it is intended to apply high organic loads to the reactor, it is very important to have systems of soda, lime or bicarbonate addition or, in critical cases, even automatic pH control.

For wastes with very high pH, it is advisable to conduct previous digestibility tests. The adoption of a pH control system (for example, the addition of hydrochloric acid) may be necessary.

Treatability Level

Even if all previous conditions were satisfied for a certain waste, it may not be possible to treat it anaerobically at the desirable level unless this possibility has already been proven by practical experience. Otherwise, it is very important to conduct treatability tests.

For residues of low treatability, or only partially soluble ones, the use of an acidification and/or a hydrolysis reactor prior to the methanogenic reactor may bring about a significant increase in the efficiency of the system.

It is important to note that if one observes the above mentioned restrictions, the UASB reactor, with the present level of knowledge, may be used for the treatment of wastewaters with any concentration of organic material, even the most dilute or the most concentrated ones.

CRITERIA FOR UASB REACTOR DESIGN

Basic Criteria: Organic Load, Superficial Velocity and Height

There are three basic rules for the design of UASB reactors: the volumetric organic load applied, the liquid velocity on the settler surface, and the reactor height. With the present knowledge and experience, the maximum safe design values which may be accepted for the first two parameters are 15 to 20 Kg COD applied/m³ reactor·day and 1.2 to 1.5 m/h, respectively. These limits must be applied only for the peak values (after equalization, pre-treatment, etc.) of the organic load and flow rate, respectively. To use these limits, the availability (or formation) of biological sludge with good characteristics of settlement and methanogenic activity, preferably granular sludge, is taken for granted. Besides, many other factors already discussed herein may bring about the necessity to adopt safety factors. On the other hand, these limits may be surpassed later for certain situations, as one acquires more experience with UASB reactors in full scale (Lettinga et al., 1983a).

The limiting design criteria for a certain waste depends on its organic concentration. For concentrated wastes, the limiting parameter is the applied organic load, and in these circumstances, it is important that the reactor has the highest possible height per unit of volume in order to reduce the area required. However, the advisable useful height is about 6 meters, because a height above this value may cause some problems such as difficulty in the solids and gas separation, foaming, etc. For example, for a wastewater with 15 g COD/l (concentrated) and for a reactor with a height of 6 m, if we use the maximum superficial velocity criterion, the result would be an applied

organic load of $90 \text{ kg COD/m}^3 \text{ reactor} \cdot \text{day}$, which is much higher than the permissible limit. This confirms that, under these conditions, the limiting criterion is the applied organic load.

For diluted wastes, the limiting parameter is the liquid velocity on the surface of the settler, and in this case it is important that the reactor has the minimum possible height in order to increase the surface area per unit of volume and, consequently, to reduce the hydraulic retention time as much as possible. At the present level of knowledge, it is advisable to have a height of about 4.5 m. As an example, for a wastewater with 1 g COD/l (diluted) and for a reactor with 4.5 m height, the use of the maximum permissible organic load criterion would result in a superficial velocity of 3.7 m/h , which is higher than the permissible limit. This confirms that, under these conditions, the limiting criterion is the superficial velocity.

In both cases, the settler height does not need to be higher than approximately 1.5 m, bearing in mind its specific settling function and the experience obtained from the traditional settling systems. The remaining part of the reactor height will correspond to the digester itself. It is desirable that all the organic material transformation occurs before the passage of the solids and liquids from the digester compartment to the settler, in order to avoid the formation of gas in the settler.

The Reactor Shape/Materials for Construction

Another difference between diluted and concentrated waste processing is the shape of the reactor to be designed. For concentrated wastes, since the necessary area for the settling is small, the reactor may have a uniform section, thereby making design and construction easier. Hence, it may be circular or rectangular.

In the case of diluted waste, since the largest possible settling area is needed, it can be advantageous to adopt a uniform section at the lower part of the reactor (digestion compartment) and an increasing section area in the settling region (Figure 2) so that the available area will be larger at the top of the settler than at the lower part of the reactor and result in a larger superficial area per unit of volume. Therefore, the following combinations between the sections of the digester and the settler compartments may be used:

- circular digester, circular settler;
- circular digester, rectangular settler; and,
- rectangular digester, rectangular settler.

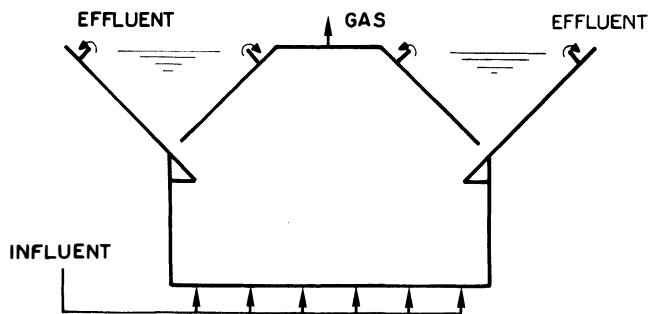


Fig. 2. UASB reactor with an increasing section area

Up to now, there is no scientific proof of the advantages of one shape over another as far as the process itself is concerned. The rectangular shape facilitates influent distribution at the bottom of the reactor, and the modularization of the system. Depending on the specific situation, the use of a certain shape can lead to reactors with smaller volumes or with more appropriate dimensions for the local installation site. However, the choice of the shape is much more connected to the cost and to the construction/installation facility for the selected construction material.

The most commonly used construction materials for UASB reactors have been steel or concrete. The choice depends on each specific case, mainly on the availability of the material and of skilled labor for the construction/installation. The use of steel generally implies easier construction/installation for shapes with circular sections, while for concrete, the rectangular section is simpler. Use of anti-corrosive internal coatings are advisable.

Other cheaper and more readily available materials which are less dependent on skilled labor should be researched.

Internal Settlers/Gas Collectors

After having chosen the reactor shape, the next step is to design the internal settling and gas collection systems. First, in order to permit an adequate return of the sludge which has reached the settler to the lower part of the reactor, the slope of the settler walls must be about 50° . Several settling units may be necessary, depending on the reactor size, due to the fact that their height is limited as has been already pointed out. There are, at least, two options for the positioning of the gas collection region at the top of the reactor: between two settling units or on the settler rim (Figure 3).

The choice of the quantity and disposition of the settlers and gas collectors also depends on the necessary surface area for the release of the gas to be produced (see subsequent estimates). As an estimate for this area, the recommended minimum superficial gas release rate should be $1 \text{ m}^3 \text{ gas/m}^2 \cdot \text{h}$ and the maximum, $3\text{--}5 \text{ m}^3 \text{ gas/m}^2 \cdot \text{h}$. In fact, this gas release rate should be high enough to avoid the formation of a scum layer but low enough for the ready release of the gas, thus avoiding the excessive build-up of sludge in the regions and pipes of the gas exit.

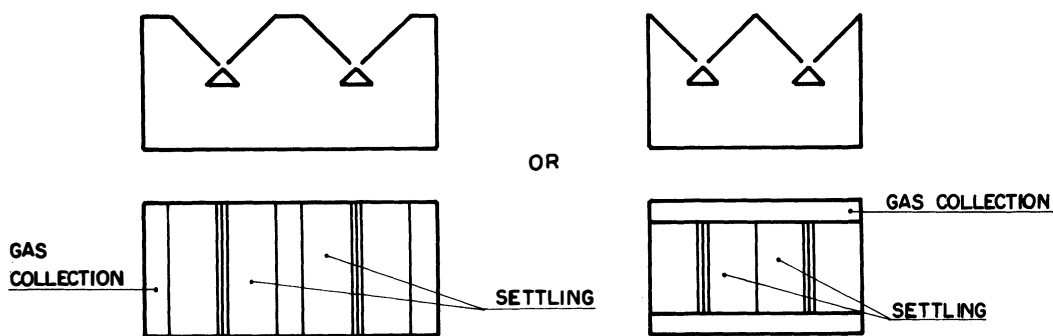


Fig. 3. Position of the settling and gas collection units

For concentrated wastes, the necessary reactor volume (criterion of the organic load), reactor height, settler slope and approximate area necessary for the gas release have already been discussed. If the section is uniform, the necessary information to determine the quantity and to arrange the settlers and gas collectors adequately is available. The superficial velocity in the settlers must be checked in order to verify that it has not surpassed the permissible limit.

Regarding diluted wastes, the minimum necessary superficial area for settling (criterion of the superficial velocity), reactor height, settler slope and the approximate area for gas release also have been discussed. So, as the reactor shape has been established, it is possible to determine the quantity and to arrange the settlers and the gas collectors adequately. The volume of the reactor can then be calculated, and if it is not satisfactory, another shape may be chosen and the operation repeated. The resulting organic load must be checked in order to avoid values above the permissible limit.

The internal settlers may be constructed of materials that are different from those used in the reactor body. The use of light materials which are easier to handle and to modularize may save a reasonable amount.

Gas Deflection/Passage to the Settler

The deflection system of the produced gas, which avoids its entry into the settlers, may be very simple. For example, a deflector may be adapted in the settler entry in order to take advantage of the tendency of a gas to flow vertically in a liquid. The deflectors should have adequate slope so as not to hinder the return of sludge from the settlers (Figure 4).

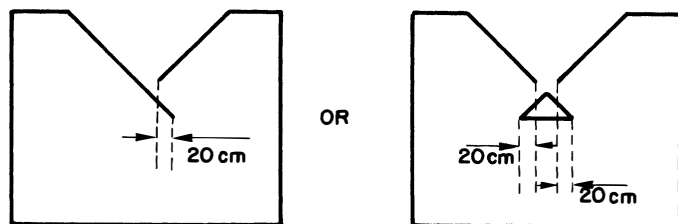


Fig. 4. Examples of gas deflectors in UASB reactors

The aperture of the passage to the settler for the liquid containing a portion of sludge may be used as a passage for the sludge going from the settler to the bottom of the reactor. Therefore, the velocity of the flow should be sufficiently low in order to permit the return of this sludge, and it is not advisable to surpass 3 to 5 m/h. If at all possible, it may be advantageous to install systems (specially in pilot plants) which would regulate the velocity of the flow during the operation. For a correct definition of the right value for this velocity, one should bear in mind that there is evidence that the flow velocity may have some influence on sludge granulation.

Feed Inlet Systems/Mixing

The mixing level in the lower part of the reactor, and consequently the contact level of the microorganisms/substrate, is very important in a UASB reactor. Generally it is not necessary to use mechanical mixing systems. The mixing is done by the produced gas and/or by the liquid flow at a relatively high velocity. Moreover, excess of mixing may cause the rupture of flocks or granules, thus damaging the system performance. An example of an efficient feed inlet system is that of a uniform distribution of the waste near the bottom of the reactor (10 to 20 cm) through adequately located pipes.

For very concentrated residues where good mixing is obtained from high gas production, it is not necessary to have a rigorous distribution, one distribution point for each 7 - 10 m² being sufficient. Regarding very diluted residues for which the gas produced will not contribute very much to mixing,

a better distribution is necessary in order to increase the contact substrate/microorganisms, and at least one distribution point should be used for each $1 - 2 \text{ m}^2$.

In relation to domestic sewage in particular, it is important to have a guaranteed uniform distribution with individual control of that part of the flow to be applied to each distribution point, for example. This is possible by injecting the sewage into main channels located in the upper part of the reactor, from which pipes would take the sewage to each distribution point; the flow rate to be applied to each pipe can be regulated through weirs (Figure 5), and the system should allow for visual control to avoid clogging. All necessary care must be taken in order to avoid the entry of air through the feed inlet system.

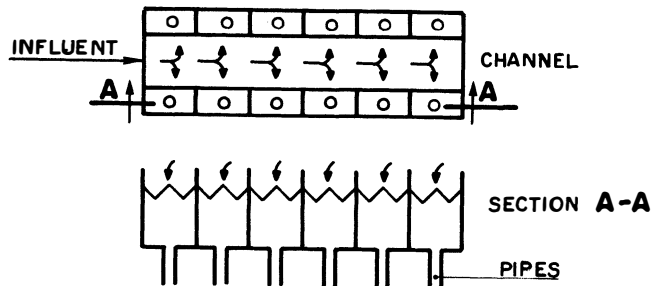


Fig. 5. Example of feed inlet system

Effluent Withdrawal/Removal of Excess Sludge

The effluent withdrawal system of the UASB reactor at the top of the settler has also to be designed in order to permit as uniform an outflow as possible. Effluent removal can be accomplished through weirs, for example, as it is normally done in conventional settlers. The weirs can be located in the center or on the rim of each settler unit (Figure 6).

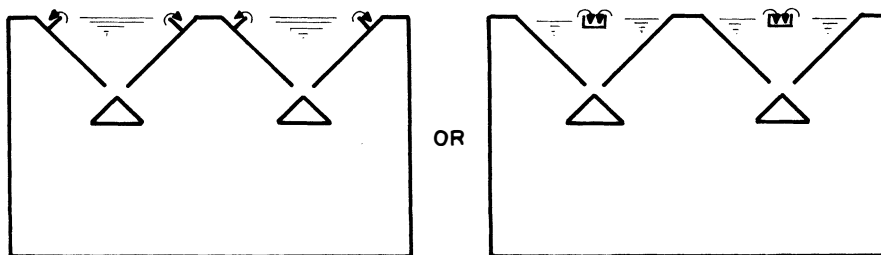


Fig. 6. Examples of effluent withdrawal systems

There are two different situations regarding the removal of the excess biological sludge formed in the system. When the main purpose is the production of biogas, there are no scientifically established reasons for the direct removal of the digester sludge, i.e., the sludge can leave the reactor naturally, together with the liquid effluent.

When the main purpose is the treatment of the wastewater, it is convenient to avoid the withdrawal of suspended solids in the effluent (except during the start-up) which would negatively affect the effluent quality. In this case, a portion of the sludge accumulated in the digester must be directly removed

from time to time. For domestic sewage which has a reasonable part of non-biodegradable suspended solids, this direct removal of the excess sludge is almost obligatory (see the subsequent estimate of the sludge accumulation).

The possibility of observation and control of the sludge distribution in the reactor is desirable. For each specific situation it is necessary to provide sample systems at several heights of the reactor, including those in the settlers.

Reactor Volume/Cover/Maintenance

Theoretically, there is no limit in relation to the maximum possible volume of the UASB reactor to be constructed. However, for units with volumes higher than about 1500 m³, the problems of construction, operation and maintenance, and of feed inlet design and unit start-up, may be excessive. Thus, the construction of several units in parallel, each one limited to the maximum of 1000 to 1500 m³, is recommended whenever the total volume so requires.

In order to make the system maintenance easier, the digester may have the settlers uncovered, being covered only in the biogas collection regions. In addition, this solution leads to a cost reduction. However, it should not be used where the possible malodorousness (generally due to sulphur compounds) may cause problems.

Inspection doors in the body of the UASB reactor should be installed in order to permit cleaning and maintenance of the unit from time to time due to the accumulation of materials such as sand, incrustation, etc. Inspection doors should also be installed in the biogas collection compartments, in case they are not removable, for removal of the scum layer.

Costs

It is difficult to make general forecasts related to the cost of wastewater treatment in UASB reactors, bearing in mind that there are particular characteristics in each situation. It is clear that significant fluctuations in the total cost of the unit installation occur, depending on factors not related to the UASB reactor itself, such as: pre-treatment and feed adjustment; heating systems; thermal insulation and control of the temperature; pumping and piping systems for feeding and effluent removal; effluent post-treatment; dewatering and disposal or utilization of the excess sludge; disposal or purification and utilization of the biogas; flow measurements; pH measurements; etc. In each particular case, besides considering the costs related to these items, the incomes generated by the utilization of by-products (excess sludge and biogas) should be taken into account.

For the UASB reactor itself, including the feed inlet and withdrawal of the effluent, the sludge and the gas systems, the costs of the first units constructed or designed with CETESB's technology in Brazil amounted to approximately US\$ 280 to 350 per m³ of reactor.

For the treatment of domestic sewage in particular, the UASB reactors themselves represent the greater part of the installation costs (except for the sewage collection and transportation and by-product processing and utilization systems). In fact, in this case, the pre-treatment (for example, screening and grit chamber), the sludge dewatering (for example, drying bed) and the effluent post-treatment (for example, chlorination and sand filtration) systems may be very simple and relatively inexpensive. In addition, heating and temperature control systems (especially for tropical regions) and pH control systems, addition of nutrients, etc., are not necessary. In these cost considerations, the cost of the land, which can represent a reasonable amount of saving in the case of the use of the UASB reactor due to the small area it requires in relation to other conventional treatment processes, is not included.

Another important aspect of sewage treatment systems in UASB reactors is the possibility of modularizing the units, which may represent an economy in the sewage collection and transportation systems because it dispenses with the construction of large and expensive collectors, interceptors, etc. Finally, it is important to point out that the costs related to the operation/maintenance of UASB reactors tend to be satisfactorily reduced compared to the conventional aerobic processes, particularly in terms of elimination of the oxygen supply.

CRITERIA FOR OPERATION AND CONTROL OF UASB REACTORS

In order to correctly evaluate the operational conditions of a UASB reactor, it is necessary to know or to estimate the efficiencies of the organic material removal and gas production possible to be obtained for the specific situation, as well as the probable sludge production.

Estimates of COD Removal

The more adapted and active the biological sludge, and the more below the maximum permissible limits the applied organic load and the superficial velocity are, the more efficient the COD removal for a certain waste will be. On the other hand, among several wastes, the one which contains less toxic compounds and less non-biodegradable organic material will have a higher COD removal efficiency.

Regarding diluted wastes, the contributions to the total COD of the reactor effluent, due to the concentrations of suspended solids in the effluent (as small as it may be) and to the methane gas dissolved in it (about 20 to 50 mL CH_4/L waste, depending on the temperature), may be significant, thereby hindering the COD removal efficiency in the reactor. For domestic sewage, for example, a maximum total COD removal efficiency in UASB reactors of about 60 to 70% can be obtained. However, as the sewage is very dilute, this efficiency is already sufficient to provide a reasonably good effluent quality.

On the other hand, for concentrated wastes, these factors are generally not important, thereby bringing about a greater total COD removal efficiency. With stillage, for example, a maximum COD removal efficiency of about 80 to 90% can be obtained. In these cases, even with high efficiencies, the reactor effluent will still contain high COD concentrations.

Estimates of Gas Production and Composition

In order to estimate the possible gas production to be obtained from a waste, at least three factors should be considered:

- in a steady state, the theoretical CH_4 production is proportional to the quantity of COD consumed in the reactor (1 g of COD consumed corresponds to the production of 0.35 NLCH_4 , N = standard temperature and pressure).
- a part of the gas produced is dissolved and lost with the effluent; and,
- part of the COD is transformed into biomass.

The free gas production in concentrated wastes is high in relation to the part which remains dissolved. In this case, one will obtain in practice a production of about 0.30 $\text{N}\text{LCH}_4/\text{gCOD}$ consumed, and a content of CH_4 in the biogas of about 55 to 65% (the remaining part being constituted mainly of CO_2).

For diluted wastes, the portion of the gas which is lost with the effluent is greater and thus the recoverable production of gas is smaller. With domestic sewage, for example, we have obtained in practice a production of about 0.15 $\text{N}\text{LCH}_4/\text{gCOD}$ consumed. In this case, the CH_4 content in the biogas is about 75% and the biogas may contain high concentrations of N_2 (up to 20% in volume), the remaining part consisting mainly of CO_2 . This N_2 contained in the biogas is not produced in the process, but is derived from the N_2 previously dissolved in the waste and which is dislocated mainly by the highly soluble CO_2 which is produced.

The H_2S concentration in the biogas is generally low and depends on the sulfate concentration in the waste and on the COD/SO_4 relationship previously discussed.

Estimate of the Sludge Production

It is also possible to estimate the sludge accumulation with a mass balance considering mainly the following factors:

- formation of biological sludge;
- suspended solids in the influent which will be retained in the reactor and will not undergo biogasification; and,
- suspended solids which will leave the system in the effluent.

It has been noted from practical observation that for domestic sewage, the liquid sludge production in terms of suspended solids quantity is about 30% of the suspended solids present in the sewage.

Start-Up/Inoculation

Once the treatment system in UASB reactors has been adequately designed and constructed, the start-up is a determining factor in the unit performance (Zeew and Lettinga, 1983). It may be considered that the start-up begins with the reactor inoculation and ends when a sufficient quantity of active, high-settlement-velocity biological sludge which is adapted to the waste and is maintainable in the reactor. Under these conditions, the system can already be exposed to high applied organic loads or high superficial velocities without hindering the efficiency.

The larger the quantity of sludge which is used for the inoculation and the better the quality of this sludge, the faster the start-up will be completed. A quantity of granular sludge which occupies 10 to 15% of the reactor total volume is enough to guarantee the success of the start-up, if the sludge is well adapted to the substrate. Even small quantities, such as 1% of granular sludge added to the digested sludge available for inoculation, may represent a reasonable contribution to the success and velocity of start-up (Hulshoff et al., 1983). Under the best conditions, the start-up may be completed in less than 1 month, but if adequate inoculum is not available, start-up may take more than 6 months.

When the necessary quantity of good-quality sludge is not available, the best procedure is to use other materials which contain the desirable bacteria as inoculum, such as digested sludges derived from digestors of sewage sludge, rural digestors, septic tanks, etc. If even these materials are not available, the alternative is to use raw sewage sludges, manure, etc. which have not been previously digested. Wastes such as domestic sewage which are self-inoculating, i.e., wastes which already have the necessary bacteria, even in small quantities, are less dependent on the inoculum, and in this case the start-up may be effected without seed sludge.

Start-Up/Initial Feed Loading Rate

Different procedures should be adopted to enhance microbial utilization after inoculation, in accordance with the concentration of the organic material in the waste to be treated. If the residue is concentrated, it is recommended to start the operation by applying a maximum volumetric organic load of 0.5 Kg $COD/m^3 \cdot day$ or a maximum organic load to the sludge of 0.05 - 0.1 Kg $COD/KgVSS \cdot day$. The pH of the sludge should always be maintained between 6.5 and 7.5 by adding chemical products if necessary. The feeding flow rate should only be increased if the gas production and composition is satisfactory (see estimates) and if the concentration of the volatile acids in the sludge is low (<500 mg Acetic Acid/l) or with a clear tendency to decrease. A tendency towards a rapid increase in the concentration of volatile acids in the sludge should be immediately avoided by reducing the feeding flow rate.

If the waste is diluted, particularly in the case of domestic sewage, the organic load initially applied is of relatively little importance. In this case, even when starting the operation with high flow rates in relation to the designed value, the volumetric organic load will be small in relation to the maximum tolerated by the process. In addition, the relatively high velocity of flow of the liquid through the sludge exerts a "wash out" effect, avoiding an accumulation of organic material around the bacteria. For domestic sewage, the operation of the system can be started regardless of the type of inoculum used with at least half of the designed flow rate, taking care to avoid an excessive loss of sludge.

Even after the completion of the start-up and after having attained the desired operational conditions, it is convenient to keep some good quality excess sludge in storage for an eventual necessity of re-inoculation due to operational problems.

OBSERVATIONS ON THE EFFLUENT, SLUDGE AND GAS DISPOSAL

Post-Treatment of the Effluent

As efficient as the UASB reactor may be, the effluent quality often does not reach the desired or permissible limits for discharge into receivers. In this case, an adequate post-treatment system is necessary in order to obtain further removal of one or more of the following factors: soluble organic material, suspended solids, pathogens, nitrogen and phosphorus compounds, etc.

The removal of pathogens in UASB reactors is generally not sufficient, particularly in the case of sewage, making the adoption of disinfection systems frequently necessary. Some processes have been considered for that purpose and the following ones are being studied; chlorination, ultraviolet radiation, ozonation, sand filtration, stabilization ponds, etc.

The N and P removal in a UASB reactor is practically nil, with transformation of only the organic N into ammonium N. There are few post-treatment methods as yet which are completely developed for full scale use for the removal of these nutrients in the quantity necessary to avoid the eutrophication of the receiving water bodies. If the nitrogen was previously transformed or if it was already present in the form of nitrates, denitrification would contribute to the elimination of N. The ammonia elimination through stripping would also contribute to the removal of N.

In relation to the suspended solids and to the soluble organic material still present in the UASB reactor effluent, some systems have been considered or researched for the improvement of the quality of this effluent, such as settlement, flotation, ozonation, sand filtration, stabilization ponds, air stripping, aerobic biological processes, etc.

A future possibility is the use of another anaerobic process for further removal of solids and organic material, which would operate in series with the main UASB reactor. The second anaerobic reactor should even be another UASB reactor, as well as anaerobic filters, fluidized bed reactors, etc. It has been proven that the quality of the UASB reactor effluent can be improved with other anaerobic processes. In an experiment performed with a UASB reactor connected to a post-treatment system consisting of a septic tank plus an anaerobic filter in which sugar cane stillage was treated, approximately 76% of COD removal was obtained in the first unit, and 35% in the post-treatment unit, amounting to a total COD removal of 84% (Souza et al., 1984).

Disposal (Utilization) of the Excess Sludge

The excess sludge from a UASB reactor, especially the granular type, is a very precious material for the inoculation and start-up of other UASB units or for the eventual re-inoculation of the unit itself. These are the most important possible uses of excess sludge, at least until larger quantities of this

material become available. Generally the excess sludge is relatively stable and has superior dewatering characteristics. Under these conditions it can be injected directly or after extra settling into dewatering systems such as drying beds, vacuum filters, etc. The excess sludge may also be used as a land fertilizer, after the elimination of pathogenic microorganisms where necessary. The fertilizing qualities of the sludge may also be supplemented with the addition of mineral salts.

Disposal (Utilization) of the Biogas

The biogas produced in anaerobic processes, depending on the situation, may be simply burned or discarded into the atmosphere. When it is used as a power source, it may greatly reduce treatment costs or even make the process profitable. For simple uses as in boilers, generators, etc., complex systems for purification, compression and storage of the biogas are not necessary. However, for use in vehicles, in addition to the necessity of a high level of purification for H_2O , CO_2 and H_2S elimination, complex systems of high pressure compression are also used. It is also important to emphasize that the biogas obtained from very diluted wastes (particularly from domestic sewage) may contain high levels of N_2 (such as 20% of N_2 by volume) which tend to make the use of biogas in vehicles difficult even after the traditional purification.

CONCLUDING REMARKS

The UASB reactor has proven to be a successful and low-cost option for sewage and industrial wastewater treatment, especially in tropical countries, provided the conditions for its utilization described in this paper are met. The process can be applied for very dilute and for very concentrated wastes.

The presently known technology related to the design of the reactor is effective for several types of wastewaters and can be simple enough to permit many technicians to make their own design. The main design parameters are discussed herein. More research and exchange of knowledge can be very useful for the development of a more secure and less conservative design.

The technology related to start-up, operation and control of the process is not so simple, but there are some rules that can be used to achieve good performance for some wastewaters. Each wastewater should be tested before a full-scale plant is designed. Good quality sludge availability can contribute very much to the success of the process. Research in this field is necessary to improve knowledge on microbiology, biochemistry, granule formation, start-up and control of the process. Post-treatment studies are also necessary.

Several pilot plants and full-scale UASB reactors have been already designed and some of them are under construction or operation in Brazil, based on the simplified technology described in this paper.

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