Anaerobic treatment of municipal wastewater in UASB-reactors

Technical Field:
☐ Energy / Environment (E)
■ Water / Sanitation (W)
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1 Introduction

In the past years, the efforts to improve water quality using modern sewage technology led to big successes in industrialised countries. Here, the commonly implemented treatment systems are mostly based on a high technology level which not only requires a large amount of process energy, but is also related to high investment and operation costs. Plant operation furthermore requires highly qualified personnel that is very often not sufficiently available in developing countries. Speaking of these countries, a process combining a low level of mechanisation with a high purification performance is therefore highly desirable.

In developing countries, pond systems are still the most widely implemented wastewater treatment process. Given advantageous geographical conditions (no need for pumps) and low land prices (below 10-12 US$/m², depending on the desired effluent quality), they require a very low degree of mechanisation and are the most economic alternative. With respect to the environment, they do however have some major drawbacks: their land demand as well as greenhouse gas and odour emissions are considerably high.

In countries with a warm climate throughout the whole year, the high wastewater temperatures – which are a requirement for anaerobic degradation – allow and favour an anaerobic treatment of the entire sewage flow, not only the sludge portion. As ventilation or other means of aeration are not necessary for these processes, the technology can be kept considerably more simple.

Although originally implemented for industrial rather than municipal purposes, one meanwhile widely implemented anaerobic treatment alternative in the domestic wastewater sector is the so-called UASB-reactor (Upflow Anaerobic Sludge Blanket). The process is essentially based on a special flow regime allowing the sewage to get into contact with a „sludge blanket“ or “sludge bed” situated in the reactor, and a following 3-phase-separation of water, sludge and gas (methane). Within the sludge bed, the organic matter in the sewage is reduced by bacteria. In the anaerobic milieu of the reactor, the methane is formed due to bacterial activity during the fermentation process, which can be utilised as energy source. In order to achieve the best performance of the reactor, several parameters such as COD (Chemical Oxygen Demand), required retention time and others have to be taken into consideration.

The UASB-process represents one important option for sewage purification in countries with warm climates as it meets the above mentioned basic necessities for a sustainable operation of wastewater treatment plants in developing countries like

- low investment costs,
- low maintenance demand,
- good performance,
- low sludge production
- net energy production.

If combined with an appropriate post-treatment, the effluent values reach the same level as the aerobic activated sludge process which is widely applied in industrialised countries (with temperate climate).

2 Advantages and disadvantages of UASB technology for municipal wastewater treatment

Speaking of municipal wastewater treatment (MWWT) in general, the UASB-technology offers a number of advantages and disadvantages in comparison with treatment alternatives such as pond systems or aerobic processes (e.g. activated sludge). The respective frame conditions for each specific situation – favourable or adverse in effect – do however have to be considered if a technology decision needs to be taken.

Advantages

- low land demand
- reduction of CH_4 emissions from uncontrolled disposal/"open" treatment (ponds) due to enclosed treatment and gas collection
- reduction of CO_2 emissions due to low demand for foreign (fossil) energy and surplus energy production
- low odour emissions in case of optimum operation
- hygienic advantages in case of appropriate post-treatment
- low degree of mechanisation
- few process steps (sludge and wastewater are treated jointly)
- low sludge production, high sludge quality
- low demand for foreign exchange due to possible local production of construction material, plant components, spare parts
- low demand for operational means, control and maintenance
- correspondingly low investment and operational costs

Disadvantages

- demand for know-how
- insufficient standardisation and adaptation for several implementation possibilities
- economically not feasible in colder climates with sewage temperature lower than 15°C
- methane and odour emissions (also of end-products) in case of inappropriate plant design or operation
- insufficient pathogen removal without appropriate post-treatment
- sensitivity towards toxic substances
- long start-up phase before steady state operation, if activated sludge is not sufficiently available
- uncertainties concerning operation/ maintenance due to still low local availability of know-how and process knowledge

3 Description of the process

In a UASB-reactor, the accumulation of influent suspended solids and bacterial activity and growth lead to the formation of a sludge blanket near the reactor bottom, where all biological processes take place. Two main features decisively influencing the treatment performance are the distribution of the wastewater in the reactor and the "3-phase-separation" of sludge, gas and water (see also chapters 8.2 and 8.3). While the sludge should remain in the reactor, the produced gas is collected before the purified water leaves the reactor. For a simple process flow scheme, see Figure 1 below:

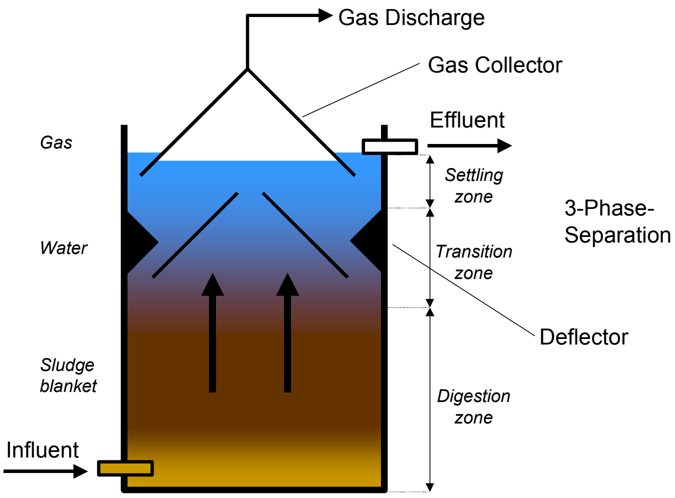

Figure 1: The UASB-Reactor (Source: TBW, modified after [6])

The influent point (sewage) is situated at the reactor bottom, the effluent discharge (treated wastewater) is situated in the upper part of the reactor, thus forcing the entering sewage to follow an upflow regime and to get into contact with the sludge blanket in the reactor. Here, the organic matter in the sewage is subject to anaerobic degradation by the bacteria contained in the sludge blanket, with methanogenic ("methane building") bacteria producing methane gas (CH_4) during the degradation processes.

In order to prevent unwanted sludge discharge, separation devices (deflectors) are installed that prevent the further upward movement of the sludge and force it to sink back into the bed. The gas is collected in gas holders installed in the upper part of the reactor; for gas rising close to the reactor walls, an additional one may be installed.

4 Parameters influencing the process

For the operation of a UASB reactor, a minimum temperature of the sewage (approx. 15°C) and an anaerobic environment are required in order to secure that the methanogenic bacteria can develop their activity. A number of additional parameters that significantly influence the process and should partly be controlled continuously are listed in the following. The given ranges may serve as orientation values.

4.1 Parameters to be controlled regularly

4.1.1 pH-value

The pH-value in the digestion substrate is decisive for the activity of the very sensitive methanogenic bacteria and therefore has to be controlled continuously. The recommended range is between pH 6.3 and pH 7.8. The utilisation of hydrogen carbonate as buffer may simplify the observation of the given range.

4.1.2 Chemical Oxygen Demand (COD)

Basically, anaerobic sewage treatment may be applied for low as well as for high COD-concentrations. Depending on the respective local conditions, the advantages of the anaerobic process do generally only become distinct at a concentration of >250 mg COD/l and achieve an optimum at a concentration of >400 mg COD/l. An upper limit for COD concentration in the influent sewage is not known.

4.1.3 Temperature

The anaerobic degradation process achieves its optimum at a temperature between 35-38°C. Below this range, the digestion rate decreases by about 11% for each °C temperature decrease [1].

However, given appropriate frame conditions, anaerobic treatment has in the past years proven to have a very high potential if ambient sewage temperatures are above 20 °C. For a successful and stable microbiological degradation and the avoidance of an acidification of the process, a water temperature of at least 15°C is necessary, although bacterial activity can still be noticed at lower temperatures (10°C and less).

4.1.4 *Wastewater flow*

The influent amount of wastewater to the plant should be considerably constant. For great flow variations, e.g. due to high precipitation, a sufficiently sized buffer tank should be installed prior to the UASB to guarantee an even feeding of the reactor.

Flow measurements should be part of continuous process control. They are necessary for the calculation of further process, design and operational parameters (e.g. organic charges per volume).

4.2 Other parameters

4.2.1 *COD charge per volume*

Measurements at UASB reactors in South-America indicate a relation between the daily COD charge per volume and the percentage of COD reduction. If a COD reduction of at least 65% is required, test series proved that volumetric charges exceeding 2-3 kg COD/m^3>d are critical.

The COD-charge per volume is calculated via wastewater flow and COD concentration in the influent.

4.2.2 *Organic acids*

During anaerobic degradation in the sludge blanket, the substrate is reduced to short-chained carbon acids: butyric acid (C_3H_7-COOH), propionic acid (C_2H_5-COOH) and finally acetic acid (CH_3-COOH) from which a great part of the methane is formed. If the concentration of one of the carbon acids exceeds the tolerable value, a disturbance in the reduction chain and therefore problems in the fermentation process can be assumed. As shown in Figure 2, the inhibitory effect of organic acids (here: acetic acid) depends on the pH-value: for low pH-values, already a slight enrichment with acetic acid causes troubles in the reduction process.

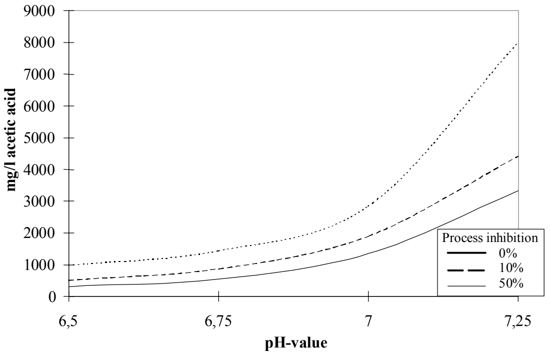

Figure 2: Interdependence of acetic acid concentration and pH-value for process inhibition

4.2.3 *Concentration of ammonia*

Ammonia (NH_3), if formed during the fermentation process, may be a cause for process inhibition. The concentrations of ammonia and ammonium (NH_4^+) are in balance, the dissociation rate however depends on temperature (see Figure 3). As opposed to the acetic acid concentration, process inhibition will be favoured by high pH-values, as these will increase the ammonia concentration. Formation of NH_3 does however only start at pH-values above 7,5. The formation of ammonia can usually be avoided by respecting the recommended pH operation range (see 3.1). Process inhibition can be notified only at NH_3 concentrations above 40 mg/l and temperatures above 30°C. With lower temperatures, an inhibitory effect will only occur at even higher NH_3 concentrations.

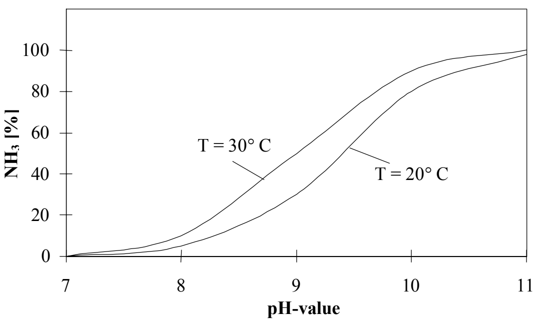

Figure 3: Dissociation rate of ammonia

4.2.4 *Retention time*

The hydraulic retention time (HRT) is the time that the wastewater remains in the reactor, calculated as ratio of the reactor volume and the wastewater flow. The HRT influences the COD reduction and is an important parameter with respect to the desired degradation rate. It should not be less than 2 hours.

4.2.5 Upflow velocity

The upflow velocity should not exceed an upper limit in order to prevent sludge wash-out, both out of the sludge blanket and out of the reactor. A minimum speed is however desired, as turbulences improve the contact between sewage and sludge. The upflow velocity should be in the range between 0,2 – 1 m/h. It may be calculated as follows:

- $\nu = Q/A$
- $\nu = H/HRT$

ν = upflow rate; Q = flow; A = surface; H = reactor-height; HRT = hydraulic retention-time

As shown above, the upflow velocity depends on flow and surface. In order to ensure optimum values, the reactor height should measure between 4 and 6 meters.

4.3 Optimum wastewater characteristics

Optimum values for the characteristics of the influent sewage are listed in Table 1.

Table 1: Optimum conditions for anaerobic MWWT (Source: [2])

Criteria	Optimum Values
COD	> 400 mg/l
Temperature	18-35°C
Substrate Flow	Continuous flow
Nutrients	Ratio CSB : N : P : S 350 : 5 : 1 : 1
Toxic Substances/ Suspended Solids	Low concentration
Micronutrients	All present

It is advantageous if the wastewater is collected in a separate sewer system so that events of high precipitation, which frequently occur in tropical climate, do not dilute the wastewater to a concentration too low for treatment (the organic loading should not be below 250 mg COD/l).

5 Operation and maintenance

The decision whether the implementation of the UASB process may be appropriate and sustainable in a specific country and location depends on a number of factors that are too specific to be listed in conclusion. Some important “frame” data with respect to process requirements, operation and performance are however given in the following.

5.1 Start-up phase

During start-up, a comparably large bacterial mass for the biological degradation processes has to develop and adapt to the characteristics of the specific wastewater so that the start-up phase of anaerobic wastewater treatment plants can be rather time consuming and difficult. Municipal wastewater has however proven to be less problematic than industrial wastewater as it already contains the composition of nutrients and micro-nutrients required for bacterial activity and growth. Generally speaking, anaerobic sewage treatment therefore does not need inoculation to start the degradation process. The danger of overloading and acidification should however still be taken into consideration in the start-up phase.

5.2 Pre-treatment

Pre-treatment prior to the anaerobic treatment step is advisable for municipal wastewater in order to reduce the coarse and inorganic fractions (sand). Common pre-treatment steps are a screen and a grit chamber.

5.3 Degradation performance

The values for the digestion rate of UASB reactors given in the following table show a relatively high efficiency concerning COD reduction, although they are not as good as the results achieved by activated sludge processes. The degradation of nutrients such as nitrogen and phosphorus is almost negligible. Therefore, if a better reduction of nutrients is required or if high standards for discharge to surface waters have to be met, the implementation of a post-treatment step following the UASB process reactors is recommended.

Table 2: Average UASB digestion rate

Parameter	Digestion rate UASB [%]
COD	60-80
TSS	60-80
Nutrients	negligible

5.4 Post-treatment

As mentioned in chapter 5.3, post-treatment to UASB reactors is recommended if the required effluent quality cannot be met by the anaerobic UASB treatment. This may especially occur speaking of large wastewater treatment plants where a eutrophication of the receiving streams needs to be prevented. A number of aerobic treatment steps may be applicable as post-treatment: e.g. pond systems, aerated processes (activated sludge), fixed bed filter, fluidised bed filter, trickling filter.

The most common post-treatment alternative are maturation ponds where nutrients are further reduced, their primary function however being pathogen removal. With a depth of about 1.5 m, maturation ponds are in principal similar to facultative ponds, but show less stratification (formation of aerobic and anaerobic layers) than the latter. [4] The oxygen required for the aerobic processes in the ponds is provided by natural aeration via the water surface and by photosynthetical algae activity.

5.5 Operational data

The following parameters and values may serve as a rough guide for control and operation of UASB plants.

Table 3: Important average operational parameters for MWWT in UASB

Parameter	Unit	Value
HRT (hydraulic retention time)	h	4-20
Upflow velocity	m/h	0,2-1
Charge per volume	kg COD/m^3>d	0,4-3,6
Sludge charge	g COD/g DOM>d	0,05-0,5
Specific energy demand	kWh/ m^3 wastewater	0,07-0,2
Gas production	Nm^3/m^3reactor>d	0,02-0,3
Excess sludge	kg DM/p.e.>a	2,5-5

DOM: Dry Organic Matter; DM: Dry Matter; p.e.: population equivalent

6 Gas utilisation

The gas produced in the UASB process as from any other anaerobic process has a very high global warming potential and should not be released to the atmosphere with respect to greenhouse gas emissions and climate protection. If gas utilisation cannot be realised due to infrastructural, economic or other reasons, it should at least be flared – the provision of possibilities for a connection to the public grid or to electricity consumers site does however have to be considered very important under ecological as well as economic aspects.

Gas utilisation is possible e.g. for steam, cold storage or household application – usually implemented in the context of smaller communal UASB plants – or in co-generation units for the production of electricity that can either cover part of the own (process and plant surroundings) demand or for feeding to the public grid or neighbouring consumers.

Table 4 shows approximate values for the gas production rate from anaerobic wastewater treatment and average demand for UASB process energy.

Table 4: Gas/electricity production and energy demand of UASB with post-treatment pond (Source: [2])

Production		Energy demand
Methane*[1]	Electricity	
0.2 m³ CH_4/ kg $COD_{removed}$	0.6 kWh_{el}/ kg $COD_{removed}$	0.08 kWh_{el}/ kg $COD_{removed}$

*[1] Biogas: 0.3 m³ /kg $COD_{removed}$; CH_4-content: 65%

7 Utilisation of products

Given appropriate post-treatment steps, sludge and purified wastewater are final products of anaerobic wastewater treatment apart from the biogas produced during the methanogenic degradation processes that can be reused for different purposes:

- sludge → fertiliser or soil conditioner
- treated wastewater → irrigation or substrate moisturising

The sludge is generally well stabilised, pathogen The applicability does however depend on the respective hygiene requirements. Special care has to be taken for utilisation in agriculture: head irrigation for food crop intended for direct human consumption should e.g. be avoided.

Table 5: Reuse possibilities of final products (Source: [2])

PRODUCTS OF ANAEROBIC PROCESSES		
Sludge Consistency	Liquid	Gaseous
POST-TREATMENT	↓	↓
Drying	Post-treatment (various)	Combustion
UTILISATION	↓	↓
Fertilisation Soil conditioning	Irrigation Substrate moisturising	Electrical/ Thermal utilisation

8 Construction

A number of alternatives concerning the construction of UASB reactors are possible, the main differences being in reactor shape and design of the 3-phase-separation and in- and outlet.

8.1 Reactor shape

In principal, three geometrical shapes can be distinguished: cylindric, rectangular and mixed (cylindric/rectangular).

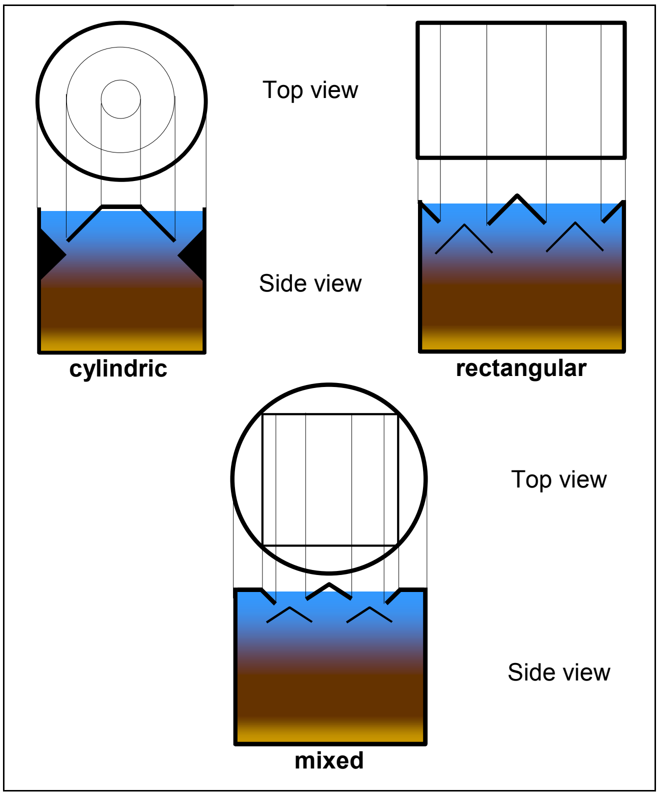

Figure 4: UASB reactor shapes
(Source: [3])

Given the same construction material, round reactors have a greater stability than rectangular ones. Depending on size, their construction may be more difficult, so that a cylindrical shape is mostly used only for small reactors.

If several reactors are required for one treatment plant, rectangular forms have the advantage that the different compartments can be planned adjoining, thus sharing one wall between two compartments and consequently saving construction material. As square reactors provide an optimum relation between wall length and treated surface, they are the most economic rectangular construction model.

A mixture between a cylindric shape for the outside wall and a rectangular shape for the collection system is possible.

8.2 Phase separator

The phase separator separates the three phases gas, liquid and solids that are present in a UASB reactor. The separation device is the most important component of UASB-reactors as it is designed to accomplish the following tasks:

- captivation and collection of the generated biogas
- improvement/facilitation of settling process of suspended solids in the reactor zone above the separator (to hold back the bacteria needed for the process)
- minimisation of solids concentration in the effluent
- creation of additional space above the separator for the compensation of high hydraulic loads (expansion of sludge bed; [3])

Ideally, the separator is composed of gas collectors at the top and a layer of gas deflectors underneath (see Figure 1, Figure 5) that increase the selectivity of the separators. If the separation device is malfunctioning, biogas formed in the sludge blanket may reach the settling zone and cause turbulence, resulting in a decrease of the settling efficiency and sludge wash-out.

The separators can be designed submerged (see Figure 5: combination of gas collectors and deflectors with approximate proportions), then requiring a hydraulic seal (see Figure 6) behind the separator exit in order to secure sufficient pressure to prevent the separator from getting entirely filled with water.

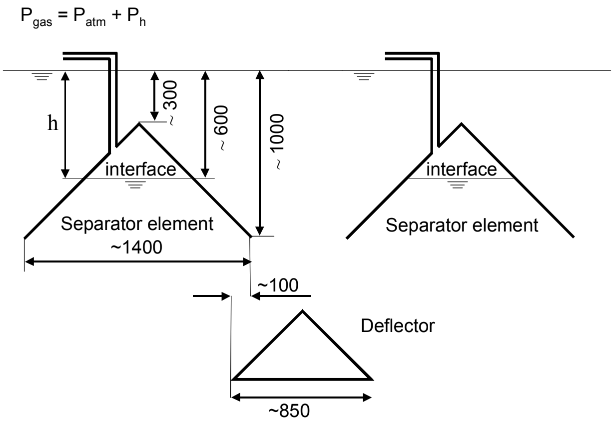

Figure 5: Submerged separators and deflector (Source: [3])

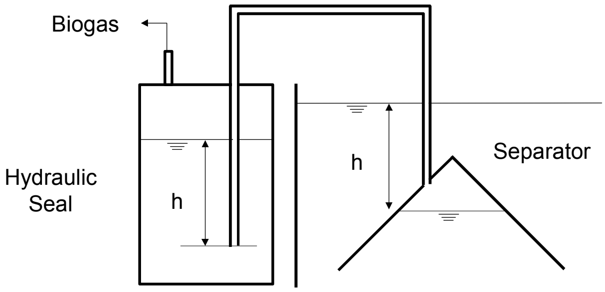

Figure 6: Hydraulic seal (Source: [3])

Submerged separators have the following advantages:

- The danger of corrosion is reduced by using steel constructions.
- The entire reactor volume is available for the settling of solids.
- The excess pressure of the gas makes it easier accessible for utilisation.
- If the gas is flared, the hydraulic seal protects the reactor from danger of explosion.

A design alternative is to situate the top of the separator above the water surface (see Figure 1, Figure 7), the gas pressure then being atmospheric. The advantage of this variation is the easier access to the reactor for inspections, maintenance or repair works.

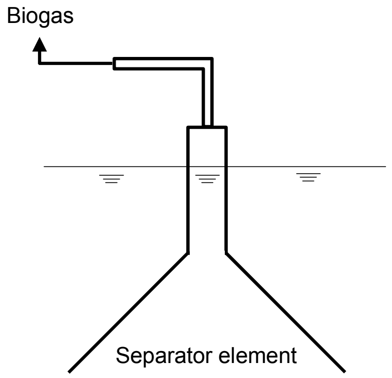

Figure 7: Separator with atmospheric gas pressure (Source: [3])

8.3 Influent and Distribution System

The construction and design of the distribution (inlet) system is of central importance to the purification performance of UASB-reactors as it decisively influences the contact between wastewater and the sludge blanket (digestive zone). It has to secure that the reactor is filled with wastewater regularly and the distribution is as even as possible. In order to ensure that each inlet point receives the same fraction of the influent flow, the distribution system should be located at an hydraulic level higher than the water level in the reactor, so that feeding by gravity is possible.

For municipal wastewater, at least 1-2 m² per inlet point are recommended, VAN HAANDEL and LETTINGA report about experiences in several treatment plants where areas between 2-4 m² per inlet point are sufficient for satisfactory treatment efficiency [3]. These plants are however operating at average wastewater temperatures of above 20 °C. In case the influent temperature is lower, a higher density of influent points is required as the mixing of sludge and influent substrate becomes less efficient with decreasing temperature.

The distribution system can be arranged circular or rectangular (see Figure 8).

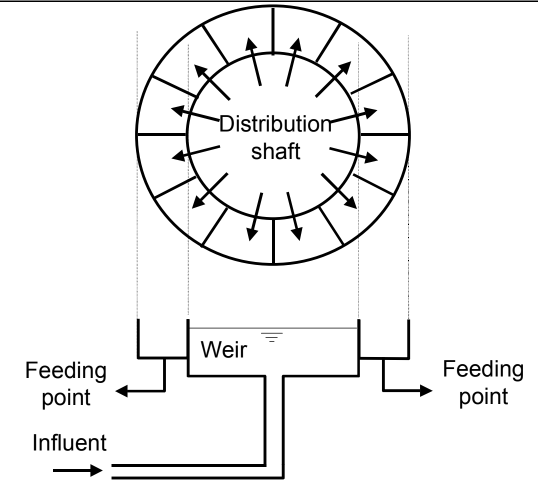

Figure 8 a: Circular inlet system

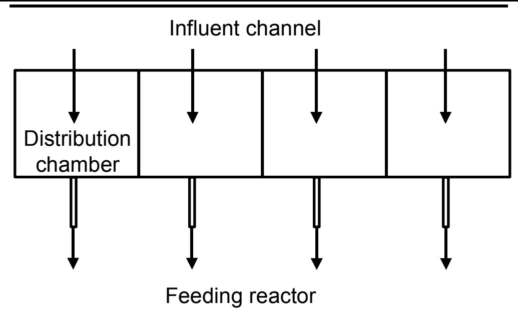

Figure 8b: Rectangular inlet system

Figure 8: Inlet system, substrate distribution

9 Economic aspects

The significantly lower level of technology required by the UASB process in comparison with aerobic processes also becomes evident regarding the economy of the process.

Construction costs for MWWT based on UASB reactors can vary significantly, depending on the overall plant concept, i.e. integration of pre-, post-treatment steps, gas use, required effluent standards, returns from product sales etc. Calculated on the basis of 50.000 p.e., investment costs for UASB-treatment without gas use are about 20 US$/inhabitant.

10 References and further information

[1] Alaerts, G.J. et al.: Feasibility of anaerobic sewage treatment in sanitation strategies in developing countries. IHE Report Series 20, Delft, The Netherlands, 1990.

[2] GTZ/TBW Supraregional Sector Project “Promotion of anaerobic technology for the treatment of municipal and industrial sewage and wastes”: Status Reports; Final Report. GTZ/TBW, Eschborn/Frankfurt, Germany, 1998.

[3] Haandel, A.C. van; Lettinga, G.: Anaerobic sewage treatment. A practical guide for regions with a hot climate. John Wiley & Sons Ltd, Chichester, England, 1994.

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[5] Metcalf & Eddy (publ.): Wastewater Engineering. Treatment, disposal, and reuse. 3rd ed., revised by G. Tchobanoglous, F.L. Burton. Tata McGraw-Hill Publ. Company Ltd, New Delhi, India, 1991.

[6] Sasse, L.: DEWATS. Decentralised Wastewater Treatment in Developing Countries. Bremen Overseas Research and Development Association (BORDA). Bremen, Germany, 1998.

10.1 Institutions and Organisations

Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente (CEPIS)
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10.2 Useful links

http://www.cepis.org.pe
http://www.cepis.org.pe/eswww/fulltext/anaerobi.html

Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente (CEPIS) Environmental technology centre of Panamerican health organisation (Organización Panamericana de la Salud). Papers about different aspects of anaerobic wastewater treatment.

http://www.ihe.nl/shortc/anaerob.htm
International Institute for Hydraulic and environmental Engineering (IHE Delft). General introduction to anaerobic wastewater treatment.

http://www.iwap.co.uk
International Water Association (IWA), IWA Publishing (IWAP): a non-profit publisher providing information services on all aspects of water and related environmental fields.

http://wastewater.net
Wastewater Net Message Forum: Links to wastewater related issues.