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Review

Anaerobic reactor design concepts for the treatment of domestic wastewater

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Abstract

Since the earlier anaerobic treatment systems, the design concepts were improved from classic reactors like septic tanks and anaerobic ponds, to modern high rate reactor configurations like anaerobic filters, UASB, EGSB, fixed film fluidized bed and expanded bed reactors, and others. In this paper, anaerobic reactors are evaluated considering the historical evolution and types of wastewaters. The emphasis is on the potential for application in domestic sewage treatment, particularly in regions with a hot climate. Proper design and operation can result in a high capacity and efficiency of organic matter removal using single anaerobic reactors. Performance comparison of anaerobic treatment systems is presented based mostly on a single but practical parameter, the hydraulic retention time. Combined anaerobic reactor systems as well as combined anaerobic and non-anaerobic systems are also presented.

1. Historical evolution of anaerobic treatment

When the first anaerobic treatment systems were developed by the end of the 19th century, the design was not really adequate for good performance, possibly due to the misconception that the settleable solids were the most important sewage component to be removed (McCarty 1982). Although they are the most visible constituent, they account for only about 1/3 of the organic load in raw sewage, whereas another 1/3 is present in the form of colloids and the remaining 1/3 as dissolved matter. Much of the colloidal and soluble fractions were not removed because the design of the treatment systems was such that there was no possibility of contact between the non-settleable fractions and the bacteria that were active in the biological reactor. As a result the organic material removal efficiency was low, of the order of 30 to 40%. After the development of the first aerobic systems in the decade 1910–1920, another misconception was that the lower efficiency of the anaerobic systems was attributable to a lower metabolic capacity of anaerobic bacteria and therefore a long retention time would be necessary. This has confused sanitary engineers for a long time and to a large extent persists until today. In reality, the excellent performance of the aerobic process like activate sludge was mainly due to the intense contact of the active bacteria and the influent organic material, guaranteed by intense mixing by aeration. By contrast in classic anaerobic systems, mixing was unintentional.

The high potential of anaerobic systems was shown by Young and McCarty (1969), who successfully operated an upflow anaerobic filter, treating concentrated mainly soluble rum distillery wastewater. Two very important improvements were made: (i) the influent introduced at the bottom, following an ascending pathway, thus guaranteeing intense contact between the bacterial mass and the incoming organic material and (ii) the active sludge mass increased by introducing a sludge retention device: a bed of macroscopic bodies (stones) in the reactor, onto which the bacterial mass could adhere and grow. The improvements resulted in a digestion capacity of organic material, in terms of chemical oxygen demand (COD), of more than 10 kg m^{-3} day^{-1}, which had not been possible even with the most advanced aerobic systems. Thus, the poor performance of the early systems was not because of the ''weak'' anaerobic biomass, but because of the poor design. The anaerobic filter today is still widely applied in sewage treatment and considered as a precursor of the new modern high rate systems developed in subsequent decades. The basis for the anaerobic treatment of high capacity with high efficiency was established by the provision of the two essential requisites: intense contact and large bacterial mass retention.

An important breakthrough was the development of the upflow anaerobic sludge blanket (UASB) reactor by Lettinga and co-workers (Lettinga et al. 1980). Originally developed for the treatment of concentrated (agro) industrial wastes, soon its potential for sewage treatment became apparent, especially in regions with a hot climate. Hundreds of UASB reactors are now in operation in many countries, especially in regions with hot climates.

Although by now it has been amply shown that anaerobic systems, when properly designed, have a high capacity and efficiency, a single anaerobic reactor alone often cannot produce an effluent compatible with legal norms and regulations. One alternative is to combine units in order to have a pre-treatment step mostly to remove solids, and subsequent anaerobic digestion of the soluble organic material in a high rate reactor with an active anaerobic sludge. However in many cases, it is still necessary to introduce a post-treatment system in order to adapt the anaerobic effluents to the required discharge standards, in terms of residual organic matter, pathogenic microorganisms and possibly nutrients. Post-treatment of anaerobic effluents with aerobic or physical-chemical options are discussed in a next chapter.

2. Classic anaerobic treatment systems

Classic anaerobic sewage treatment systems are related with the earlier digesters developed by Mouras in France (1872), Cameron and Travis in England (1896 and 1903, respectively), and Imhoff in Germany (1906). They conceived tanks that are known as decanter-digesters, in which settleable solids were retained and digested at the bottom by the anaerobic sludge. Typical of these classic systems (septic tank and Imhoff tank) is the horizontal sewage flow through the system in the upper part, while the anaerobic sludge rests at the bottom of the tank. Consequently, no specific effort is made to ensure and enhance the contact between influent organic material and the biological sludge at the bottom. These two classic systems found wide application until the decade of 1930, when they started to loose place in favour of aerobic sewage treatment systems, like the trickling filter and the activated sludge process. The maximum efficiency in the classic anaerobic systems does not exceed 30 to 50% of the biodegradable matter, depending on the nature of the sewage and the settling efficiency. Nevertheless, both systems are still applied today in many countries, especially for on-site treatment of sewage of individual dwellings or for small communities. Another flow-through reactor with horizontal flow is the anaerobic pond, which is amply used for communal sewage treatment, normally associated with other units of waste stabilization pond (WSP) systems.

2.1. *Septic tank (ST)*

Septic tanks are treatment units where primary treatment (solids settling) is coupled to anaerobic digestion of the settled sludge. A septic tank may be constructed either as a single unit or divided into two parts: an upper chamber for settling and a lower for digestion. The latter configuration (Figure 1) is called the Imhoff tank after its inventor. The advantage of separating the two functions is that the generated biogas bubbles cannot hinder the settling of the solids. For that reason the liquid retention time in single chamber units (12 to 24 h) is longer than in the Imhoff tank (2 h in the settling section). The shorter retention time is a considerable advantage, since the volume is reduced in the same

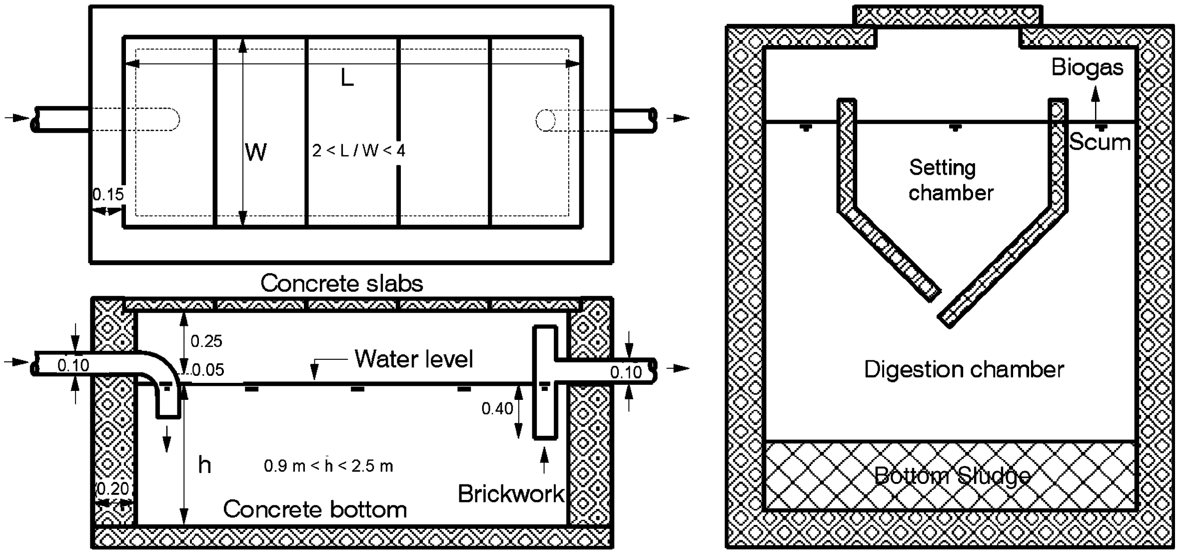

Figure 1. Schematic drawings of septic tanks with (a) single chamber, left; and (b) two chambers (Imhoff tank), right. Measurements are in meters.

proportion. The treatment efficiency of organic material and suspended solids in raw sewage generally is of the order of 30 to 50%.

Because of their simplicity and low cost, septic tanks are probably the most widely applied treatment system in the world for treatment of sewage from individual households. They can be pre-fabricated in fibre-glass or plastic, or constructed on-site in masonry or concrete. Normally they are installed under the ground and the effluent is infiltrated into the soil, or discharged on the surface (gutters) or receiving waters, eventually after some form of post-treatment, commonly the anaerobic filter. Septic tanks for single households usually have only one chamber. In Brazil the design of these units is regulated by a national norm (NBR 7229), which states that the single chamber septic tanks should have a volume such, that the retention time is 24 h for flows up to 6000 L day^{-1}, decreasing gradually to a minimum of 12 h for flows of more than 14,000 L day^{-1}. The minimum volume of these tanks is 1250 L. In case of sewage treatment, the biological sludge establishes itself in the septic tank without the need of inoculation, due to the presence of the required bacteria in the influent. With time the non-biodegradable sludge mass increases and eventually will take up much of the useful volume of the tank, decreasing the liquid retention time and the settleable solids removal efficiency. The accumulated digested sludge must be removed periodically from the septic tanks. The desludgeing period varies considerably from one to several years. Along with the low efficiency, the need for periodical desludgeing is the main draw-back of the septic tanks.

2.2. *Anaerobic pond or lagoon*

In practice, the anaerobic pond is not used as a treatment system alone. In conventional WSP systems, it receives the raw sewage and treatment is complemented with facultative and maturation ponds, where more organic material as well as pathogens (worm eggs and coliforms) are removed. This configuration is amply applied in small and medium communities, especially in developing countries. Ponds are normally constructed as shallow earthen dams with reinforced material on the slopes to avoid erosion. Plastic lining or a clay layer is placed on bottom to avoid infiltration.

The organic material removal mechanism in anaerobic ponds is the same as in the septic tank: the liquid flows through the pond and the settleable influent material accumulates at the bottom, where the biodegradable fraction is digested by the anaerobic sludge mass. Due to the large flow, the required area of an anaerobic pond is considerable and it is unpractical to cover it, so that the produced biogas escapes to the atmosphere. The escaping biogas may frequently cause serious odour problems that can be perceived at a long distance from the pond. The odour problem is caused mainly by hydrogen sulphide (H_2S), a volatile compound that is formed in the anaerobic environment due to decomposition of proteins and reduction of sulphate eventually present in the wastewater. A second problem related to the escaping biogas is the emission of methane into the atmosphere. It is well known that methane is an important contributor to global warming (green house effect).

The retention time of sewage in anaerobic ponds (typically 2 to 5 days) is often longer than in a primary treatment system (septic tank) and correspondingly the removal efficiency of organic matter tends to be higher. Mara (1976) reported a biochemical oxygen demand (BOD) removal efficiency of 50 to 70% for raw sewage in anaerobic ponds operated at retention times of 1 to 5 days. The results of several researchers concerning the BOD removal in regions with a hot climate are plotted in Figure 2 (log–log scale) and showed that the efficiency tends to improve with increased liquid retention time. For the set of experimental data (all with temperatures >19 °C), it was possible to derive the following empirical relationship, Equation 1:

$$E = 1 - 2.4(\mathrm{HRT})^{-0.50} \qquad (1)$$

where
E = removal efficiency of organic material (BOD) (fraction)
HRT = hydraulic or liquid retention time (h)

Efficient BOD removal (more than 80%) can be achieved only with a long retention time of approximately 6 days. This is only possible due to the removal of part of the non-settleable organic influent matter, probably as a result of a relatively good contact between the influent and the sludge. Mixing of the liquid phase (depth 2 to 5 m) may occur due to agitation caused by rising biogas bubbles, wind and sunshine (mechanical and thermal mixing, respectively). It must be noted that below a load of about 1000 kg BOD ha^{-1} day^{-1} or 0.1 kg BOD m^{-2} - day^{-1}, a pond tends to be facultative (i.e. with an aerobic top layer), rather than anaerobic. For a usually employed value of the pond depth (2.5 m) and influent BOD of 250 mg l^{-1}, a load of 0.1 kg BOD m^{-2} day^{-1} is attained for a retention time of 6.25 days. Hence a retention time of less than about 6 days is required to assure anaerobic conditions in the pond.

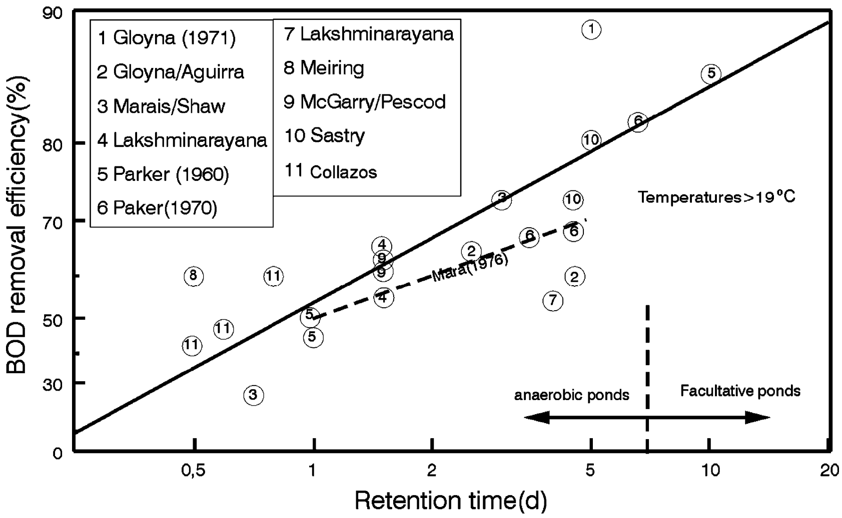

Figure 2. Experimental data of the BOD removal efficiency E (%), as a function of the liquid retention time HRT (day) in anaerobic ponds.

3. Modern anaerobic single reactor configurations

A breakthrough in design of anaerobic treatment systems came about with the development of "modern" or high rate systems in the 1960s and 1970s, characterized by reactor configurations resulting in proper hydraulic mixing and sludge retention mechanisms. Different types of anaerobic treatment systems have been applied to a great variety of industrial wastes, but so far the anaerobic treatment concept is still less employed for sewage, so that experimental information is scarce. In fact, experimental results of anaerobic sewage treatment in modern systems is restricted to the use of the anaerobic filter, the conventional UASB and some of its modified versions, and to a lesser extent the fluidized and expanded bed reactors.

It is important to note that, in spite of the sludge retention mechanism, the sludge hold-up in the anaerobic reactors is limited. Thus if no action is taken, the reactor unavoidably will become "full" of sludge in the sense that no newly produced sludge can be accommodated. From that point on the anaerobic reactor will expel sludge at the same rate it is being produced in the reactor. Naturally the presence of sludge particles in the effluent will increase its total suspended solids (TSS) and COD concentrations. Therefore, sludge must be discharged periodically from the reactor, or a separation device (for example a settler) must be introduced to separate washed-out sludge particles from the effluent. If sludge is not discharged, the quality of the effluent will be suboptimal as the sludge particles in the effluent will lead to relatively high TSS and COD concentrations. The excess sludge normally is stable and no specific treatment is required; it can be processed directly to remove water.

3.1. *Anaerobic filter (AF)*

Full-scale AF-systems (Figure 3) are operated to treat various types of industrial wastewaters, but for sewage the system is hardly used at large scale. An important concern can be the high price of many carrier materials that may result in costs of the same order as that of the construction costs of the reactor itself (Speece 1983). In Brazil, AF reactors have frequently been used as a unit following the septic tanks for the treatment of the soluble fraction of domestic sewage. Although septic tank-AF systems are used predominantly for individual households, they have also been used for urban or rural small communities (200 to 5000 inhabitants) and housing projects in urban areas where there is lack of service by a central sewerage network and treatment plant. In most cases, the carrier material consists of 5-cm construction stones. Recent studies showed the feasibility of using alternatives materials like bamboo rings, river stones, bricks, and pieces of plastic electro ducts. They are relatively easily available in the market, of lower price, lighter and good specific superficial area for bacterial adherence (Andrade Neto 2004). While industrial carrier materials like Pall rings or other modular media tend to improve the performance of AF (Young 1990), their price is still very high.

3.2. *Upflow anaerobic sludge blanket (UASB): conventional and variations*

3.2.1. *Conventional UASB*

The UASB reactor is by far the most widely used high rate anaerobic system for anaerobic sewage treatment. Several full-scale plants have been put in operation and many more are presently under construction, especially under tropical or subtropical conditions. Some studies have also been carried out in regions with a moderate climate. Figure 4 is a schematic representation of the conventional UASB reactor. The most characteristic device of the UASB is the phase separator, placed in the upper section and dividing the reactor in a lower part, the digestion zone, and an upper part, the settling zone. The sewage is introduced as uniformly as possible over the reactor bottom, passes through the sludge bed and enters into the settling zone via the apertures between the phase separator elements and is uniformly discharged at the surface. The biogas produced in the digestion section is captured by the separator so that unhindered settling can take place in the upper zone. To avoid blocking of the biogas outlet and allow separation of biogas bubble from sludge particles, a gas chamber is introduced under the separator element. The

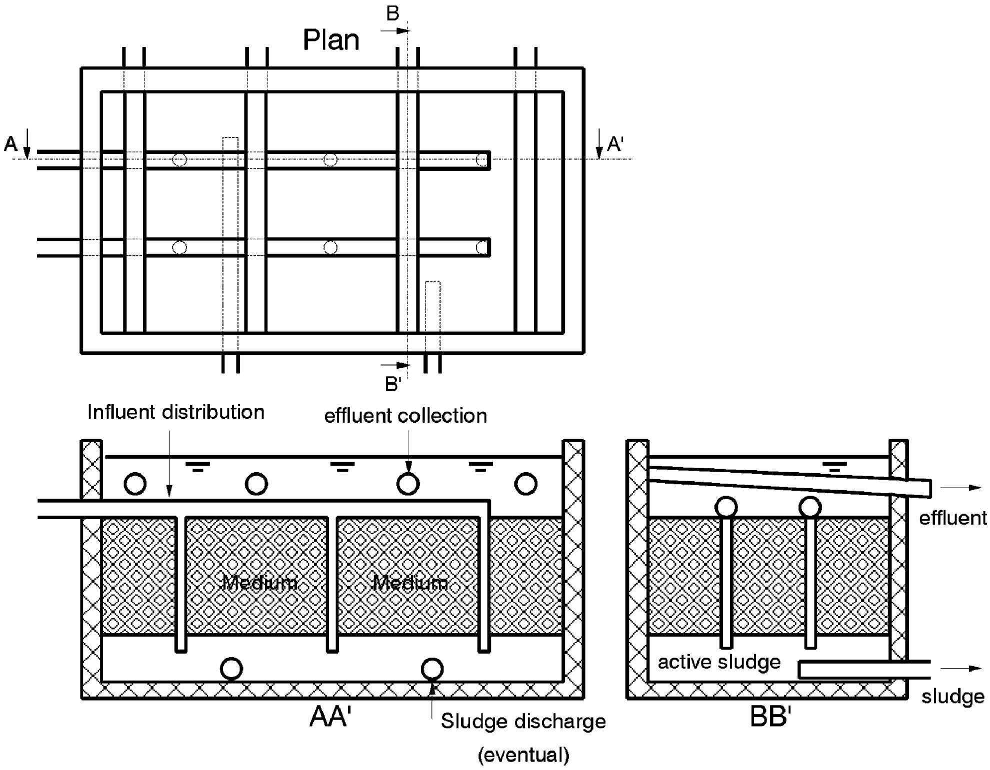

Figure 3. Schematic representation of an upflow anaerobic filter with sludge discharge at the bottom.

settled sludge particles on the separator elements eventually slide back into the digestion zone. Thus, the settler enables the system to maintain a large sludge mass in the reactor, while an effluent essentially free from the suspended solids is discharged.

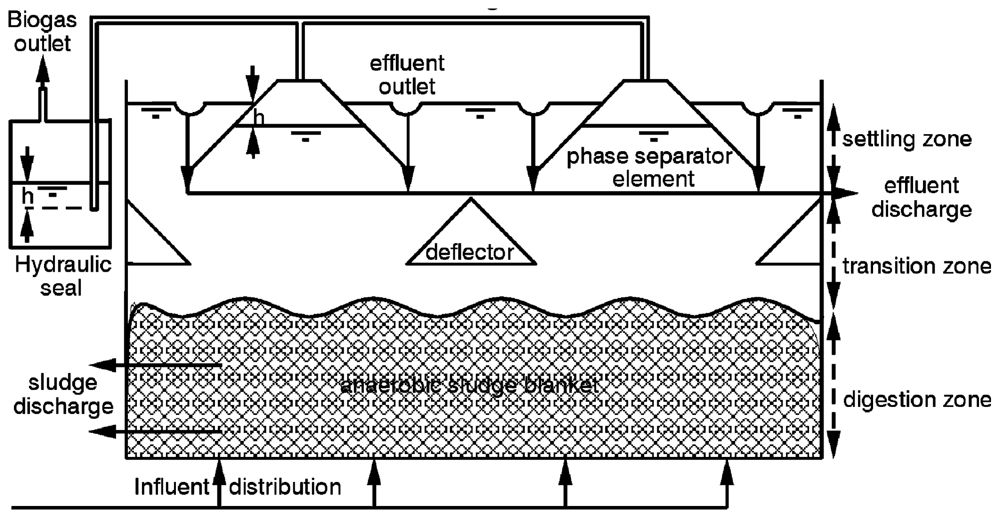

Figure 4. Schematic representation of a conventional UASB reactor with external hydraulic seal to maintain the required water level in the biogas chambers.

After the conventional UASB concept had been developed in the seventies by Lettinga and his group in the Netherlands, some modified versions of anaerobic reactor have been proposed, to improve certain characteristics or to broaden its application. Some versions worth considering such as modified UASB are: the UASB without internal settler (RALF), the improved anaerobic ponds, the expanded granular sludge bed (EGSB) reactor, the UASB for individual households and the compartmented UASB.

3.2.2. *UASB without internal settler (RALF)*

In the (mainly) subtropical state of Paraná-Brazil, several dozens of plants have been designed and built for the treatment of domestic sewage by the local sanitation company Sanepar (Gomes 1985). These reactors, locally called RALF, were equipped with a different phase separator. Some have small lateral settlers like the unit represented in Figure 5, instead of having a settling zone. In smaller units the settler was omitted altogether so that the treatment unit transformed itself effectively in an upflow anaerobic pond. The phase separators were applied to simplify construction and to reduce costs. Figure 5 shows a schematic representation of a RALF unit built in the city of Londrina and operational since 1997.

3.2.3. *Improved anaerobic ponds*

To improve the COD and TSS removal in classic anaerobic treatment systems, such as anaerobic ponds and septic or Imhoff tanks, a variety of single or combined processes has been proposed by introducing an upflow direction through the sludge bed for the influent sewage, as used in the UASB concept. Since the mixing intensity is an important requisite, especially at lower temperatures, the upflow mode, instead of the horizontal flow, can improve significantly the contact needed between the anaerobic sludge and the organic matter. Some traditional existing earthen anaerobic ponds were modified by introducing the influent in several points at the bottom, in order to induce an upflow mode. In general, the attempts to improve performance by redirecting the sewage flow have been successful, allowing at the same time a reduction of HRT to 0.5–1.0 day (Silva 1989). The RALF units shown previously can also be considered as upflow anaerobic ponds.

3.2.4. *Expanded granular sludge bed (EGSB)*

An important and interesting feature of the UASB process is that a granular type (1 to 5 mm diameter) of sludge can develop in these systems. These granules have a high density combined with a high settling velocity, an excellent mechanical strength, and a high specific methanogenic

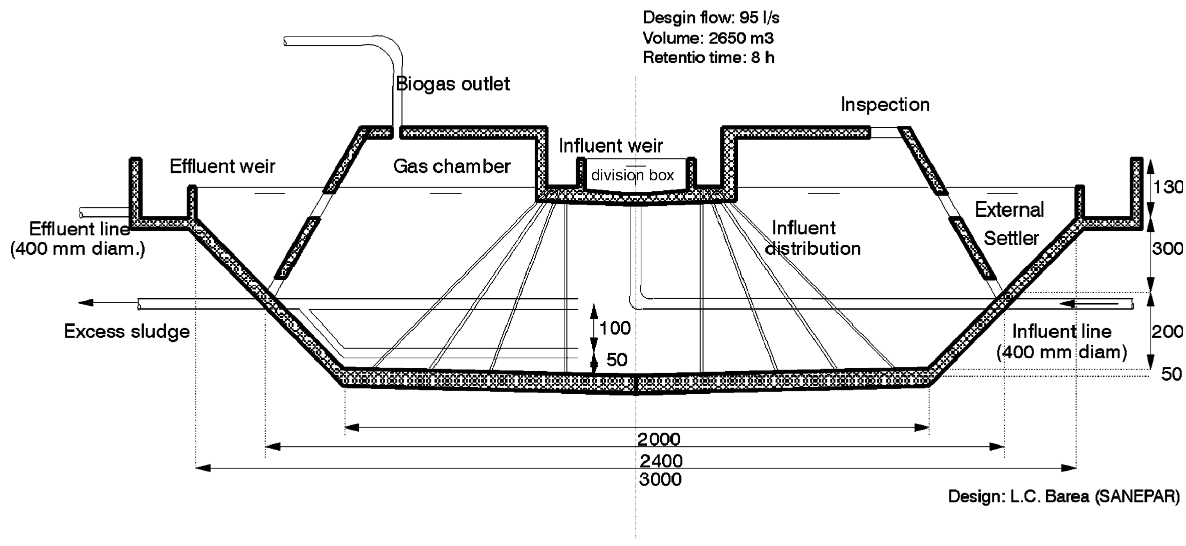

Figure 5. UASB without internal settler but with a modified phase separator (RALF). Measurements are in centimeters.

activity. Consequently, the use of granular sludge offers, at least in principle, important benefits. However if the granular sludge settles very well and the wastewater has a low concentration (and hence gas production), problems such as preferential flows, hydraulic short circuiting and dead zones can occur in the conventional UASB reactor with granular sludge. The EGSB was developed to overcome those problems by applying a higher upflow liquid velocity that can be achieved by using an adequate height/diameter ratio or effluent recirculation (de Man et al. 1988; van der Last and Lettinga 1991). Improved sludge bed expansion and bulk mixing can be achieved and thus, promote better biomass-substrate contact (Kato 1994; van Lier et al. 1997).

The EGSB concept looks particularly useful at lower temperatures and relatively very low strength of wastewaters, when the production rate of biogas and, consequently, the mixing intensity induced by it, are relatively low. Under these conditions, the higher kinetic energy content of the influent and the extended height of the expanded granular bed contribute to a better performance compared to a conventional UASB reactor. Unless a good settler is installed, an EGSB reactor is inadequate for the removal of particulate organic matter in the case of employing high upflow liquid velocity. The influent suspended solids are "blown" through the granular bed and leave the reactor with the effluent. On the other hand colloidal matter is partially eliminated as a result of sorption on the sludge flocs. In a first experiment carried out in EGSB reactors, the granular sludge bed expanded as a result of the higher upward velocity that was applied, in the range of 6–12 m h^{-1}, against less than 1–2 m h^{-1} usually applied in a UASB reactor (van der Last & Lettinga 1991). It is usual that a seed granular sludge from UASB reactor is needed to start-up the EGSB reactor. However, so far the anaerobic sludge developed in existing full-scale UASB treating municipal wastewater is predominantly flocculent. Nevertheless, since excellent BOD and TSS removal efficiencies were achieved, sludge granulation certainly is not necessarily a prerequisite for successful anaerobic sewage treatment in a UASB reactor. In the case of very dilute domestic sewage (COD < 250 mg l^{-1}) treated in an EGSB reactor with flocculent sludge from a UASB reactor, the results showed good performance in the COD and solids removal when a 4-h HRT and upflow velocity values up to 3.75 m h^{-1} were applied (Kato et al. 2003).

3.2.5. *Compartmented UASB*

The compartmented UASB version differs from the conventional UASB only in the operational mode. The reactor is divided in 3 parallel chambers with vertical walls rising up to the sludge bed height in the bottom part, in order to divide the incoming flow in 1/3 depending on the period of the day. When the minimum, medium or maximum flow arrive at the plant, 1, 2 or 3 chambers will be used to receive it, by operating an adequate influent distribution system. In this way and in the case where there is great flow variation, which can be very common in many places, the upflow velocity in the operating chamber will be kept relatively constant and with decreased dead zones, favouring the mixing and contact and less loss of solids with the effluent.

3.2.6. *UASB for individual households*

The classic septic tank can also be substituted by the UASB reactor resulting in an advantageous UASB-ST reactor (Coelho et al. 2004; Luostarinen & Rintala 2005). Additionally to the change in flow direction from horizontal to ascensional, a liquid-solid separator has to be introduced. Higher removal efficiency can be obtained due to the fact that in the modified version the sludge mass has now access not only to the settleable material, but also to the colloidal and dissolved organic matter. In addition to a larger sludge mass that is retained, Coelho et al. (2002) have reported the better performance of a single family 380-l UASB-ST reactor (Figure 6) compared to a classic septic tank (1500 l). After formation of the sludge bed, the colloid removal efficiency was higher and the suspended solids removal was better than in the classic septic tank. The better performance occurred even when settleable solids were present in the effluent as expelled sludge particles. The sludge mass tended towards a constant value, equivalent to an average sludge concentration of 24 g TSS l^{-1}, but it took 6 months to build up this sludge mass. Insofar as construction is concerned, there is also a definite advantage for the UASB-ST reactor. The unit has a much smaller

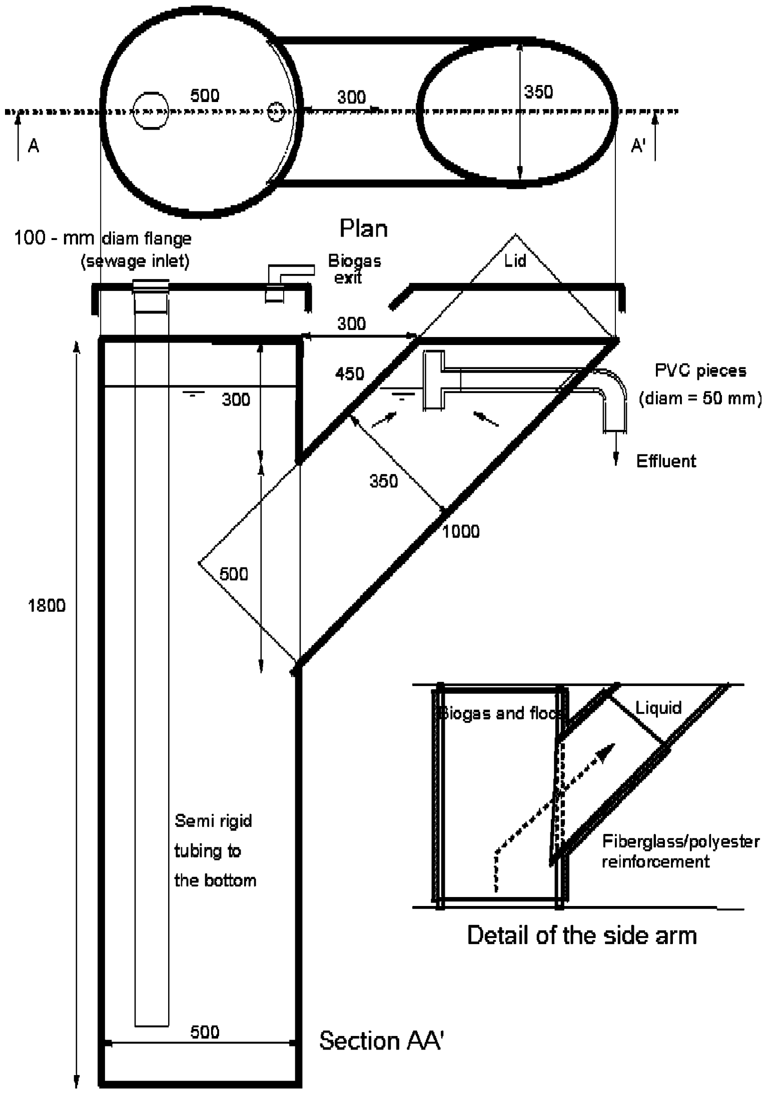

Figure 6. Schematic representation of the single family UASB reactor. Measurements are in millimeters.

"foot print" and hence can be accommodated more easily in almost any form and size of the available space. It is interesting to note that the UASB-ST must not be desludged: the very presence of the sludge mass is the guarantee that the anaerobic treatment will be efficient. This gives the unit another important advantage over the classical ST.

3.3. *Fixed film fluidized bed (FB) and expanded bed (AAFEB)*

In the fixed film fluidised bed (Figure 7) system, introduced by Jeris (1982), the carrier consists of a granular medium, which is kept fluidized as a result of the frictional resistance of the waste flow. As granular medium initially sand was used, but later on media with a lower density were used, like anthracite and plastic materials, in order to reduce the pumping costs. In practical applications considerable difficulties have been experienced in controlling the particle size and the density of the particles, consequently to maintain a stable process performance. The anaerobic attached film expanded bed (AAFEB) reactor differs from the fluidised bed concept, by the much lower upflow velocities applied; the sludge bed is only expanded by 10 to 20%

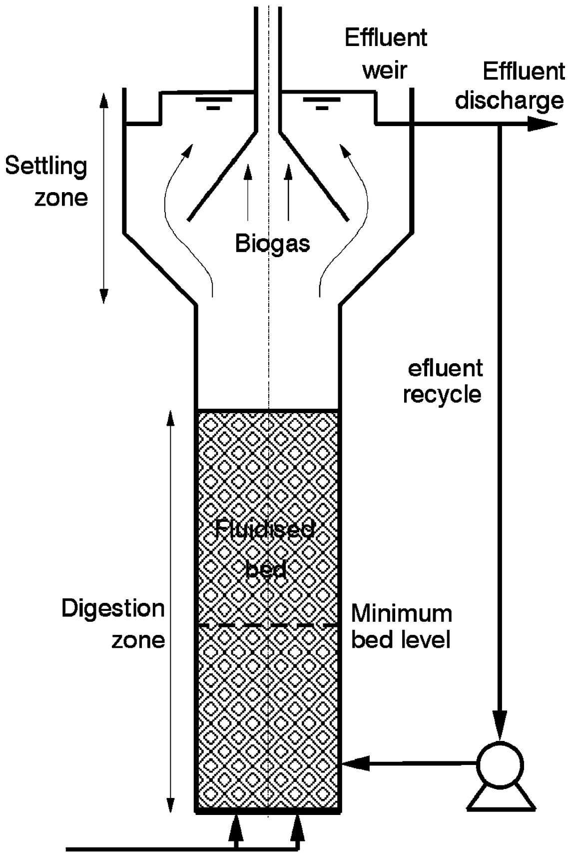

Figure 7. Schematic representation of a fluidised bed anaerobic reactor.

(Jewell et al. 1981). So far, there are no full-scale installations for sewage treatment using such reactors. Pereira et al. (1999) operated a 15-m height small-scale (32 m^3) AAFEB with granular activated carbon during 13 months, treating raw sewage. From this work and other experimental results from pilot and bench scale studies, the organic matter removal efficiency was obtained as a function of the retention time. The experimental data obtained by several research workers using the fluidised or expanded bed configuration are presented in Figure 9b.

3.4. *Other anaerobic reactor configurations*

New or modified anaerobic reactors for the treatment of domestic sewage have been studied, some being strongly based on the UASB concept and others not. Nevertheless, their resulting configurations are meant to obtain intense mixing and contact, and retention of high active biomass. In general, such reactors include devices to improve the influent distribution, use of effluent and gas recirculation, special devices for separation of solids and gases from the liquid, several support materials, and so on. In this category may be included the horizontal compartmented reactor with baffles, the rotating disks, the anaerobic sequential batch reactor (ASBR) and the horizontal anaerobic immobilized sludge (HAIS) reactor. So far these systems have not yet been installed at full-scale. They have been studied at small scale as options for sewage treatment as well as industrial wastewater treatment. In Brazil, studies on such reactors and many others have been conducted within a research program (Prosab) on domestic sewage treatment (Campos 1999; Chernicharo 2003).

The horizontal compartmented reactor separated by vertical baffles results in a tank with chambers in series, where the liquid flows successively from one to another chamber in a upflow mode by using vertical pipes (Figure 8a). The operation is similar to a UASB-ST in series, but without a solid-liquid separator. It is aimed for small communities and can be built without cover. An HRT of 12 h or higher is recommended and the first experiments showed good performance even in low temperature regions (Orozco 1988; Povinelli & Campos 2000).

Similarly to the aerobic version, the anaerobic rotating disks reactor uses plastic porous and light materials for the development and attachment of the microorganisms in submerse parallel disks on an axis driven by an external motor. The liquid flows horizontally through the reactor and the disks rotating movement results in good mixing and contact. This concept is aimed to overcome the problems of sludge separation and preferential flow that occurred in the UASB and in the anaerobic filter, especially at low temperatures and low influent COD concentrations. Nevertheless, the system shows the weak points of fixed film reactors: the biomass and the distribution of the influent are not easily controlled.

After the work of Dague et al. (1966), the ASBR has received increased interest due to its potential use in the practice of wastewater treatment, especially when receiving low concentration effluents like domestic sewage and even in the case of temperate or cold regions. The batch mode operation consists of 4 basic steps, filling with influent, reaction, settling and emptying the clarified effluent from a tank. Some attributed advantages include the good treatment efficiency (BOD and TSS), development of active and dense biomass, and with good settling characteristics, and operational flexibility in the case of high variation of the influent flow. In general the total volume required for the tanks is higher compared with that of conventional continuous tanks, but there is no need of a separate settler.

Another fixed film reactor developed by Foresti et al. (1995) is the horizontal anaerobic immobilized sludge reactor (Figure 8b) where the flow is across a long and narrow tube filled with light polyurethane foam cubes of high specific superficial area and of relatively low cost. In this way, a near piston flux can be achieved and a very high fixed biomass is retained by applying low HRT resulting in relatively high organic loading (Zaiat et al. 2000).

3.5. *Full scale application of anaerobic treatment*

In Brazil, hundreds of anaerobic treatment units have been implemented and many more are under construction or at the design stage. These systems are scattered over the whole country and have found particular wide application in the subtropical south. The vast majority of anaerobic systems is composed of UASB reactors and its variants. The size of the plants varies from small on site one-family systems (5 inhabitant equivalents) to very large communal units (1,000,000

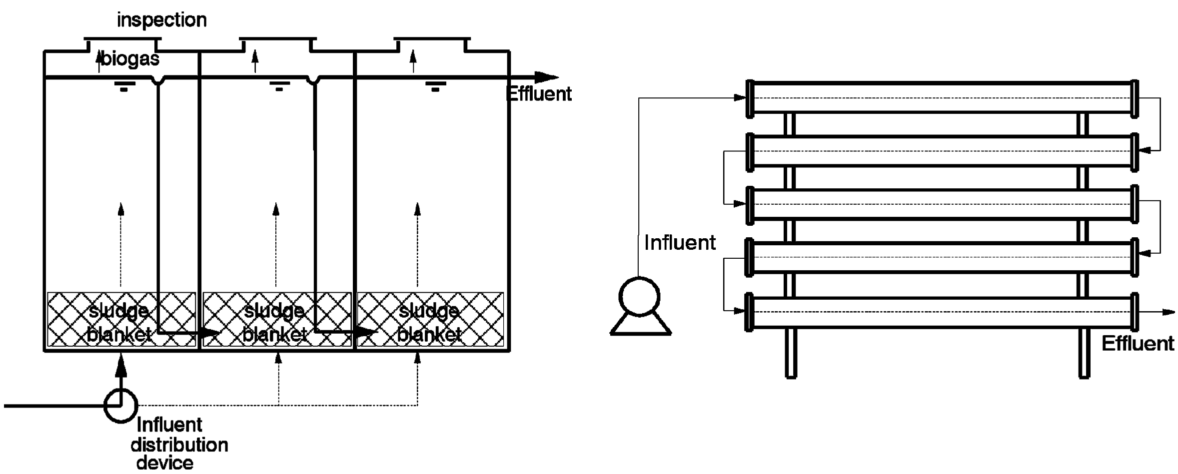

Figure 8. Schematic representation of (a) horizontal compartmented reactor with baffles, left; and (b) horizontal anaerobic immobilized sludge reactor (HAIS), right.

inhabitant equivalents). Retention times in the plants are usually in the range of 6–10 h. Some anaerobic reactors are followed by post treatment units. Aerobic systems (activated sludge or biological filters) and polishing ponds have been most frequently applied.

4. Performance comparison of anaerobic treatment systems

The most important parameters to compare the performance of anaerobic treatment systems are efficiency and costs. The efficiency can be conveniently expressed in terms of the removal efficiency of the organic influent material. In practice the concentration of the organic material is usually expressed in terms of COD. Since anaerobic treatment systems are simple with little or no mechanized parts, the investment costs to a large extent are determined by the volume, which in turn is given by the flow to be treated and the hydraulic retention time. Thus, in order to compare the performance of the different anaerobic systems, it is important to evaluate the COD removal efficiency as a function of the sewage retention time. In Figure 9 the experimental data of the COD removal efficiency are plotted as a function of the liquid retention time for 4 different anaerobic treatment systems. The log–log scale was used because the experimental data presented by different research workers exhibit very considerable spread. However, the existing data do indicate that there is a tendency for an increasing efficiency with increasing retention time. The spread is to be expected since not only the treatment units are different but also the origin of the wastewater (degree of separation of rainwater and industrial contribution, retention time in sewerage network) and operational conditions such as temperature, weather conditions and the sludge age. Also it was not always clear if raw or settled effluent was used for the calculations. The available experimental data seem to suggest a log–log relationship between the removal efficiency and the HRT for all of the anaerobic treatment systems for which a reasonable amount of experimental data from full-scale plants is available. Table 1 shows the empiric relationships derived from the experimental data for 5 different types of anaerobic reactors. Figure 10 shows the tendency of all evaluated anaerobic treatment systems as a function of the liquid retention time, in accordance to the obtained empirical expressions (Equations 1–5 in Table 1).

It is important to stress that the liquid detention time of a certain anaerobic treatment system is by no means an unequivocal parameter to estimate the treatment efficiency. Cavalcanti (2003) has clearly shown that by introducing a more efficient phase separator in a UASB reactor, it was possible to increase the treatment efficiency, when the liquid retention time was kept constant. This was achieved because the improved phase separator allowed to retain a larger sludge mass in the reactor, so that in effect the sludge retention time (SRT) or sludge age (the ratio between the reactor sludge mass and the daily produced excess sludge) was increased. Calvalcanti (2003) also confirmed that indeed the sludge retention time and not the liquid retention time is the fundamental parameter of anaerobic treatment processes.

Even though the sludge age is at least in principle a more important parameter than the liquid retention time, the latter has more practical applicability. The problem is that the sludge age cannot yet be used to design an anaerobic waste water treatment plant. Anaerobic digestion theory is not yet developed sufficiently to relate *a priori* the sludge age to reactor size. Apart from the complex biological processes that determine the sludge production rate, other factors such as the mechanical sludge properties (notably settleability, but also degree of granulation, tendency to flocculate), liquid currents, intensity of energy dissipation from rising biogas bubbles, as well as design in features of phase separator and filter medium, influence the maximum sludge hold-up and hence the sludge age. It is not yet possible to predict the sludge hold-up in any of the discussed anaerobic treatment systems. Thus, to know for example, that it is desirable to have a sludge age of say 50 days for efficient anaerobic sewage treatment, is not a sufficient basis to design a treatment plant that will effectively exhibit the required treatment efficiency. Since it is not yet possible to use the sludge age to design anaerobic wastewater plants on a rational basis, a different approach is normally used: from observed empiric relationships between efficiency and liquid retention time in anaerobic plants similar to a unit to be designed, the required

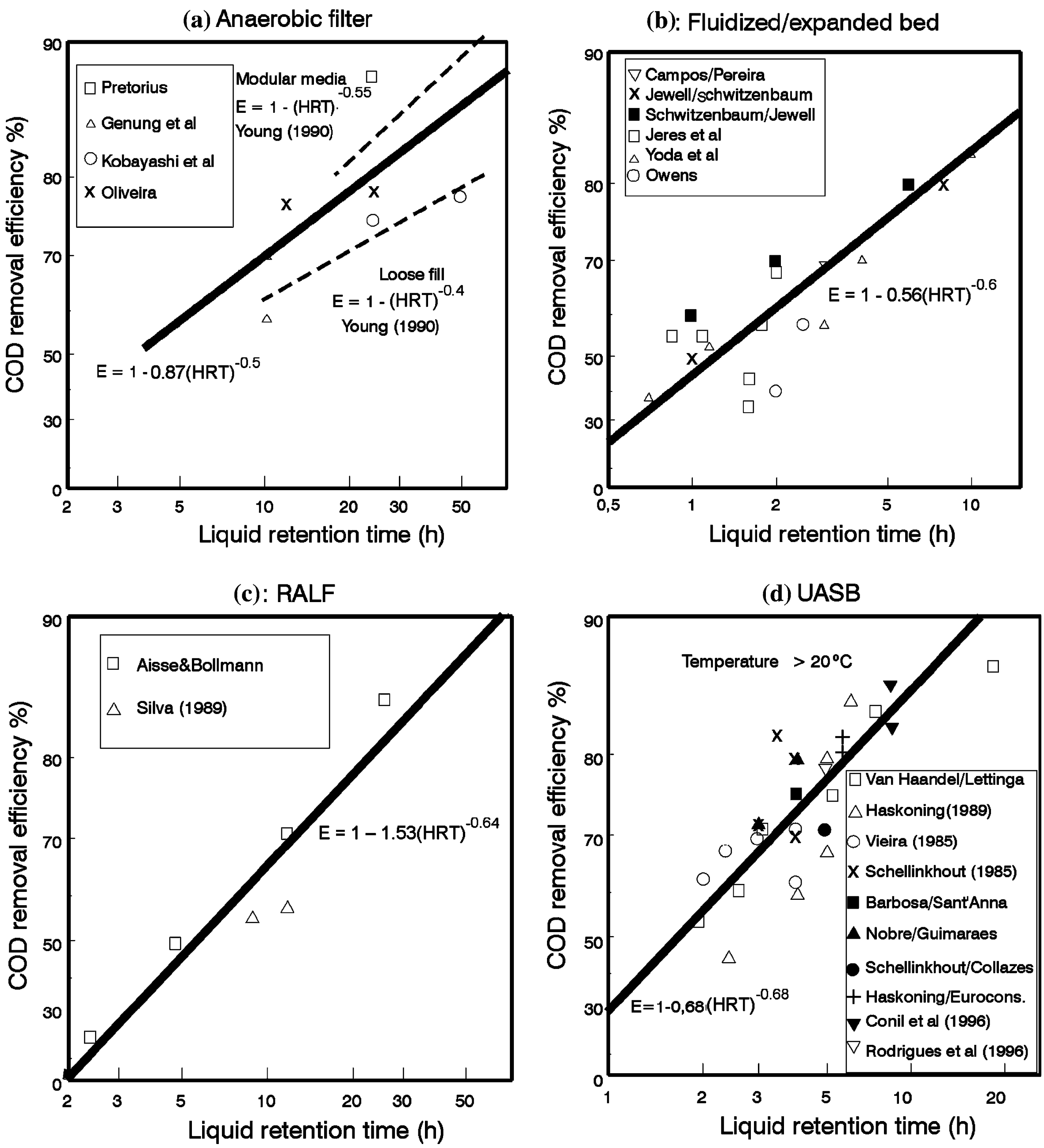

Figure 9. Experimental data of the COD removal efficiency *E* (%) in anaerobic treatment systems of raw sewage, as a function of the liquid retention time HRT (h): (a) anaerobic filter; (b) fluidized and expanded bed; (c) RALF; and (d) UASB.

liquid retention time for some particular treatment efficiency is estimated; and the design of the plant is made on this "best estimate" of the liquid retention time.

As the spread in available experimental data is large, clearly the actual efficiency in any particular treatment system can deviate significantly from value predicted by the empiric expressions. At any rate some important points can be made from an analysis of Figures 9 and 10: (i) for temperatures above 20 °C, a COD removal efficiency exceeding 80% is possible for

Table 1. Empirical expressions for the COD removal efficiency E (fraction), as a function of the liquid retention time HRT (h) for different types of anaerobic reactors

Reactor type	COD Removal Efficiency (E)	Equation
Anaerobic pond*	$E = 1 - 2.40\ (\mathrm{HRT})^{-0.50}$	(1)
Anaerobic filter	$E = 1 - 0.87\ (\mathrm{HRT})^{-0.50}$	(2)
UASB	$E = 1 - 0.68\ (\mathrm{HRT})^{-0.68}$	(3)
RALF	$E = 1 - 1.53\ (\mathrm{HRT})^{-0.64}$	(4)
Fluidized bed	$E = 1 - 0.56\ (\mathrm{HRT})^{-0.60}$	(5)

* BOD removal efficiency.

the systems considered, but the required retention times differ significantly according to the system (Table 1); (ii) in the range of practical interest, the performance of a UASB reactor and a fluidised or expanded bed reactor tend to be similar with the same retention time: (iii) the performance of a well designed conventional UASB system is much superior to that of the RALF reactor operated at the same retention time; and the removal efficiency of an anaerobic pond is very much inferior to all other considered anaerobic systems, even when BOD instead of COD is considered (the BOD removal efficiency is always higher than the COD removal efficiency).

5. Combined anaerobic reactor systems

5.1. *Two-stage systems*

When treating a wastewater with a large particulate organic fraction like sewage, it may be advantageous to apply a two-stage anaerobic process. In the first stage the particulate organic matter can be entrapped and partially converted into soluble compounds, which then are digested in a subsequent stage. The hydrolytic reactor of the first stage will typically contain a flocculent sludge and be operated at a relatively low upflow velocity. Particulate influent matter can be adsorbed on the flocs and partially reintroduced back into the liquid phase after hydrolysis, and then leave the reactor. Almost no methanogenesis will occur in the hydrolytic reactor, because the environmental and operational conditions are not very adequate. Moreover, the development of acid fermentation may tend to decrease the pH to a value below the optimal methanogenic range. Also, due to the accumulation of solids in the first reactor and the fact that only part of the entrapped matter will be hydrolysed, there is a need to discharge excess sludge from the reactor at a relatively high frequency. Consequently, the sludge age will remain relatively low and the slow

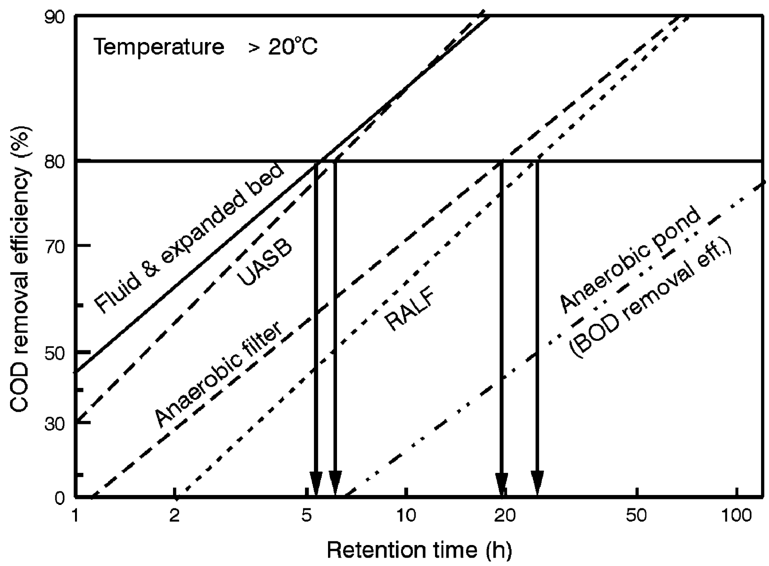

Figure 10. Tendencies of the COD removal efficiency E (%), as a function of the liquid retention time HRT (h) in accordance to the empirical expressions (Equations 1 to 5).

growing methanogens cannot develop well. Due to the fact that part of the suspended matter adsorbed in the hydrolytic reactor, notably the biodegradable matter, will return into the liquid phase, the removal efficiency of the suspended solids will be higher than that of the organic matter. Therefore, since the effluent of the first reactor will contain predominantly dissolved organic matter, its characteristics are appropriate for treatment in an EGSB or UASB reactor.

A drawback of the two-stage system can be the high solids accumulation in the first reactor, which will occur when the hydrolysis rate becomes low, as is the case at low temperatures. Under such conditions, the sludge retention time may become too low to achieve a sufficiently high degree of liquefaction to stabilize the excess sludge. Even in that case, however, it is still possible to obtain a satisfactory excess sludge quality by applying sludge stabilisation in a separate heated digester. With this auxiliary hydrolysis digester, the stabilised sludge can be separated in a liquid-solid separation step; and the resulting liquid phase, enriched with soluble organic matter can be mixed back with the regular effluent of the unheated hydrolytic reactor, and then treated in the second methanogenic reactor.

The two-stage anaerobic sewage treatment system with an auxiliary sludge digester is shown in Figure 11. On the left hand side the flow sheet of the treatment system is shown. If it is assumed that the hydrolytic reactor retains a fraction Y of the influent COD and that a fraction X of these solids is hydrolysed, then the COD fraction that leaves the hydrolytic reactor is $1-[Y(1-X)]$. The remaining fraction $[Y(1-X)]$ is composed of solids that can be discharged into the external digestor, which is presumably heated. If the hydrolysis efficiency in this digestor is E, a fraction $E\ [Y(1-X)]$ is solubilised and can be sent to the methanogenic reactor, whereas the remaining fraction $(1-E)[Y(1-X)]$ is discharged as stabilised sludge. If there is a methanogenic efficiency Z in the final reactor, the digested COD fraction will be a fraction Z of the sum of the solubilised COD fractions from the hydrolytic reactor and the external digester: $1-[(1-E)Y(1-X)]$. The COD fraction in the final effluent would be $(1-Z)[1-(1-E)Y(1-X)]$. The numerical values of the variables E, X, Y *and* Z will depend on the operational conditions of the three reactors (particularly the sludge age) and the influent characteristics (particularly the temperature).

Much research will be required to find the optimal conditions for maximum methane efficiency, low residual organic material concentration and low production of stable sludge for minimum costs. From the above it seems that the influent COD in treatment system is divided into three fractions: (i) methanised, (ii) discharged as sludge and (iii) remaining in the effluent. The curves in Figure 11 (right) indicate the magnitude of the three fractions as a function of the operating temperature. At high temperatures

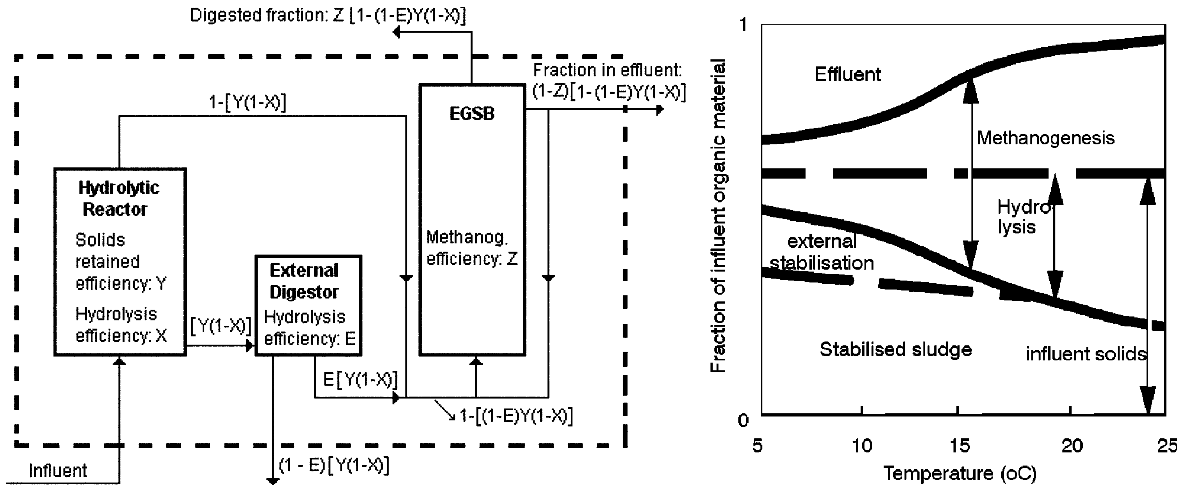

Figure 11. Two-stage anaerobic sewage treatment.

most of the biodegradable material is transformed into methane, whereas the effluent COD represents basically the non-biodegradable and soluble influent COD, which cannot be removed in the anaerobic reactor. The COD fraction discharged as sludge is comprised of biological sludge (bacterial mass) and non-biodegradable and particulate influent COD that is flocculated in the treatment system. As the temperature decreases, an increasing fraction of biodegradable influent COD is not converted into methane but instead discharged in the effluent as soluble biodegradable material or in the sludge as particulate biodegradable material.

The current anaerobic reactor configurations can be combined and used for the objectives of hydrolyse-acidification and methanogenesis in a two-stage system. The first stage reactor would mainly serve for entrapping, hydrolysing and acidifying the suspended solids of the domestic sewage, especially in the case of high COD concentration. To obtain the desired separation, a difficulty would be the control of the sludge retention time in order to avoid methane production in the first reactor. Consequently, excess less stabilised sludge discharge should be more frequent in order to maintain a low SRT. Another difficulty would be the possible flotation of the accumulated solids. Some alternatives studied include the use of two UASB reactors in series, an AF and a UASB, and a UASB-ST and a UASB.

Halasheh (2002) operated two UASB reactors fed with raw sewage at HRT of 8–10 h in the first stage reactor. The result showed a COD removal efficiency of 50 to 60% without much variation between summer time (25 °C), and winter time (18 °C). A confirmed problem was the need for further stabilization of the sludge produced in the first reactor, especially during the winter time. A combination of an AF with polyurethane foam media and a UASB was conducted at 24 °C, with HRT of 4.6 and 23 h, respectively. A COD removal efficiency of 71% was obtained in the AF which produced excess sludge that also needed further stabilization, since the ratio of total volatile solids to total solids was 0.68. The SRT was 19 days and good acidification level occurred in the AF reactor. The ratio of volatile fatty acids to soluble COD increased from 33% in the influent to 62% in the effluent.

In a UASB-ST reactor, an improvement of the conventional septic tank usually installed for on-site treatment, the long SRT improves the retention of viable sludge. This is an important factor in the case of low temperatures, since the removal of solids and conversion of non-acidified organic matter can be enhanced. Therefore, the resulting dissolved compounds can then be better removed in the second stage reactor. Luostarinen and Rintala (2005) evaluated the feasibility of a system with a UASB-ST and UASB reactors at low temperature (10–20 °C) for on-site treatment of black water at an HRT of 4.4 days and 1.4 days, respectively. The two-stage reactor system for all temperature ranges achieved a high COD and TSS removal efficiency of above 90%. Stabilisation of reactor sludges was also incomplete.

5.2. *Two-step systems*

Some combined anaerobic reactors have been studied with the objective of achieving good performance for the hydrolytic and methanogenic reactors. Nevertheless, other combinations are merely sequential anaerobic reactors in which a post-treatment step, to polish off the first reactor effluent, is left to the second reactor. A classical example is the septic tank with anaerobic filter. Some other options of combined anaerobic reactor are the UASB and AF, and the UASB and EGSB.

In the classic ST-AF system, settleable solids are removed in the first tank and the organic fraction will partly be digested at the bottom. The soluble organic fraction will be treated in the AF, since the configuration is not indicated for raw sewage due to possible frequent clogging problems in the media. Only organic matter can be removed in this system, the removal of coliforms is not high and depending on the AF media helminth eggs can be significantly retained.

The use of a UASB reactor instead of the classic septic tank in a UASB-AF system has been shown advantageous in several ways. Nevertheless, the UASB effluent may contain a considerable suspended solids concentration due to sludge particles being discharged from the reactor. Coelho et al. (2002) have shown that the improvement by applying post treatment in an AF is insignificant. Experimental results compared with single UASB for the same operational

(HRT and organic loading rate) conditions showed that there is little difference favouring the UASB-AF reactors in terms of COD removal. However, by using a plastic media of small size electro ducts (1–2 cm) in the AF, the number of helminth eggs in the effluent of the UASB-AF was almost nil, which is important in the case of wastewater reuse (Andrade Neto 2004; Pimenta et al. 2005).

The EGSB can be used as polishing reactor of UASB or any other anaerobic effluent, since it is indicated for low strength wastewater and low temperature, for which conditions a very high intense mixing and contact biomass-wastewater is a fundamental factor to be achieved. It is important that effluent enters the EGSB reactor predominantly in dissolved form, either acidified or non-acidified, due to its characteristics of high upflow velocity that is unfavourable for retaining suspended solids. Even with flocculent sludge but consisting of dense biomass, the results in a pilot-scale polishing reactor for UASB domestic sewage effluent showed good removal efficiency in terms of COD and suspended solids (Kato et al. 2003).

5.3. *Other combined systems: anaerobic and non-anaerobic systems*

Despite the occasional use of combined anaerobic reactors alone, probably the most applied alternative for post-treatment is the combination of a modern anaerobic treatment reactors in series, in which most of the settleable solids and a large fraction of the organic material are removed, and a high rate aerobic system to treat the anaerobic effluent substantially free from settleable solids and with a low organic material concentration (Guimarães et al. 2003). Other options are application of polishing ponds for residual organic material removal and disinfection (Cavalcanti 2003). Aerobic post-treatment can be used with several reactors. Activated sludge (in continuous or sequential batch mode), aerated lagoons, trickling filters, submerged aerated filters and biodiscs are some examples. Post-treatment can also be applied for the removal of some components that cannot be removed by anaerobic digestion. In this respect the anamox process for the removal of nitrogen is an example of a new development, in which autotrophic ammonium oxidation with nitrite occurs. These and other options for post-treatment will be discussed in a following article.

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