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Review Article

Development of Anaerobic Reactor for Industrial Wastewater Treatment: An Overview, Present Stage and Future Prospects

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ABSTRACT

This paper reviews the development and evolution of anaerobic reactor for wastewater treatment. The successful application of anaerobic technology to the treatment of industrial wastewater is critically dependent on the development and type of anaerobic reactor used**.** Since the original design was developed, many modifications have been made in reactor design in order to enhance both the efficiency and reliability of the reactor. In this paper, the main alteration and modifications of anaerobic reactor would be documented.

Keywords: Anaerobic Baffled Reactor, Hybrid Reactor, Anaerobic Digestion, Wastewater

1. INTRODUCTION

An anaerobic process is a process where organic matters in wastewaters are converted to methane and carbon dioxide through a series of reactions involving a consortium of obligate and facultative anaerobic microorganisms [1]. Anaerobic systems can be categorized according to how the biomass is retained in the system and type of biomass they depend on. Systems where the bacteria grow and are suspended in the reactor liquid are called suspended-growth processes. Typically, suspended-growth systems have sludge that is considered to be flocculent or granular in nature-oftentimes both flocculent and granular sludge coexist in a reactor. Granular sludge exhibits high activity rates and settling velocities that reduce required reactor volumes and increase allowable organic loading rates.

Thus, these processes are considered to be a high-rate system. The factors that generate the formation of good granular sludge are complex and considerably researched both by investigators and vendors. These factors are varied but principally relate to loading condition, system configuration and wastewater characteristics. Usually, these systems retain granular sludge by employing specially designed often proprietary gas-liquid-solids (GLS) separation devices. Most delegate configurations include UASB (upflow anaerobic sludge blanket) and EGSB (expanded granular sludge bed) reactors.

Attached-growth processes make use of either fixed film or carried media (the latter suspended in the liquid) for the bacteria to grow and attach to. Attached-growth systems comprise fixed-film and fluidized bed reactors. In fluidized bed reactors, suspended carrier media such as sand are used to offer support surface for the microorganisms. Fixed film processes have bacteria reside on some type of more static support surface such as plastics rings, rocks, or media modules. Most representative configurations comprise the classical AF (fully packed anaerobic filter) and of historical value, fluid bed variants.

In a current development, e.g. hybrid anaerobic filters (HAF) as shown in Figure 1, combine suspended and attached-growth processes in a single reactor to take advantage of both biomass types. The hybrid reactor design combines a lower section functionally identical to an UASB and an upflow AF on top, the idea being to combine the strengths of each approach in a single tank [2]. Thus, the lowermost 30 to 50 percent UASB-like portion of the reactor volume is accountable for flocculant and/or granular sludge formation.The upper 50% to 70% of the reactor is filled with cross flow plastic media and also behaves as an anaerobic filter.

Advantages of the hybrid anaerobic reactor design include (1) granular sludge formation is not essential, i.e. flocculant sludge will perform satisfactorily and attain good stability at relatively high loadings and (2) biomass developed in the fixed media section add to the reactor's inventory [3]. The hybrid reactor has been principally suitable for treating wastewaters where granular sludge development is difficult such as some chemical industries wastes. The attached growth on the media in the upper portion of the reactor together with the development of a granular or flocculent sludge bed in the bottom section help add together significant biomass inventories which leads to increase process stability and higher removal. The cross flow media modules also function as effective gas-liquid-solids separator further enhancing biomass retention.

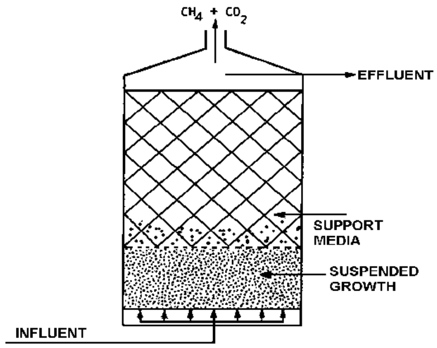

Fig. 1: Upflow Hybrid Anaerobic Filter [7]

The systems can be further qualified based on process rate, which were low-rate systems and high rate systems. Thus one can have low-rate with suspended-growth anaerobic system which includes bulk volume reactors and anaerobic contact reactors. Both these approaches are efficient at retaining flocculent (i.e. non-granular) sludge owing to lower organic and hydraulic loading rates than the high-rate systems. Particularly they are very well suited for industrial applications that do not granulate well or have higher than desirable amounts of troublesome constituents, example as high levels of organic and suspended solids.

2. HISTORY OF ANAEROBIC REACTORS

First conventional anaerobic digester was used in 1881 to liquidity the solid components of sewage. Then, in 1891 the first septic tank is build to retain solids in sewage and followed by development of the 'Imhoff' tank in Germany on 1905. In 1930s, digesters were started to be mixed and heated to improve the digestion of solids in the sewage. Few years later, in 1955, anaerobic contact process was developed to treat soluble organics and dilute wastewaters. Anaerobic reactors can be divided into conventional AD or high rate AD.

High rate anaerobic reactors include completely mixed anaerobic digester, anaerobic contact process, anaerobic sequencing batch reactor (ASBR), anaerobic packed bed or anaerobic filter, anaerobic fluidized and expanded bed reactors, upflow anaerobic sludge blanket (UASB) reactor and also anaerobic baffled reactor (ABR) [4].

2.1. Completely Mixed AD

Completely mixed reactors are reactor with no solids recycle in which the solid retention time, SRT equals the hydraulic retention time, HRT. Both wastewater and anaerobic bacteria are mixed together and allowed to react. Once the organic pollutant is reduced to desired level, then treated wastewater is removed. It can be operated in either batch or continuous mode and depends on the continuous growth of new biomass to replace that lost in effluent.

At least 10 days of HRT and SRT are required because of slow growing methanogenesis. This necessitates a reactor with a huge volume. Large volume requirements and wash-out of microorganisms in effluent pose serious problems and make ADs unsuitable for use with most industrial wastewaters. However, they can be used effectively for sludge treatment and for wastewaters that contain high organic matter and solids content.

2.2. Anaerobic Contact Process (ACP)

Link between high biomass concentration, greater efficiency and smaller reactor size is the idea of ACP as shown in Figure 2. Settling of anaerobic sludge in a settling tank and its return back to the reactor allows extra contact between biomass and raw waste. In ACP, due to sludge recycling, the SRT is no longer tied to the HRT. As a result, significant improvements in treatment efficiency can be achieved. Major problem is poor sludge settlement arose from gas formation by anaerobic bacteria in settling tank.

Gas formation problem can be minimized by employing vacuum degasification and applying thermal shock prior to sedimentation using flocculating agents in settling tank incorporating inclined plates into the settler design. Although simple in concept, individual units make ACP more complex than other high rate ADs. Absence of any internal fittings offers some advantages for the treatment of wastes having high solids content. Anaerobic contact reactors employ an external clarifier or vessel to settle solids and consequently recycle them back to the reactor tank.

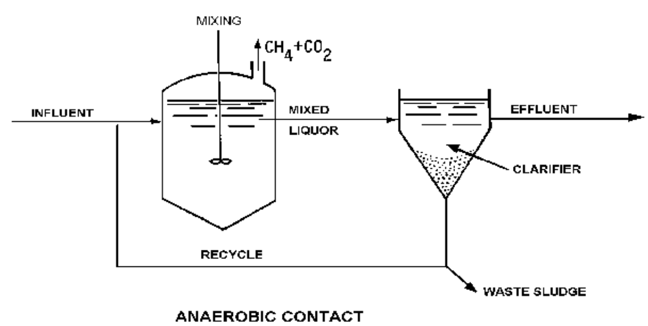

Fig. 2: Anaerobic Contact Reactor [7]

Typical configurations include large tanks due to the low hydraulic and organic loading rates employed in their design. Anaerobic contact systems are particularly efficient when granulation is difficult or wastewater contains higher than desirable amounts of troublesome constituents, such as suspended solids. Anaerobic contact alternatives are effective at successfully retaining flocculent, such as non-granular sludge, therefore permitting maintaining appropriate anaerobic biomass inventory levels.

2.3. Anaerobic Sequencing Batch Reactor (ASBR)

Anaerobic sequencing batch reactor (ASBR) process is a batch-fed, batch-decanted, suspended growth system and is operated in a cyclic sequence of four stages: feed, react, settle and decant. Due to significant time is spent in settling the biomass from the treated wastewater, reactor volume requirement is higher compared to continuous flow processes. Nevertheless, it requires no additional biomass settling stage or solids recycle. No feed short-circuiting is another benefit of ASBRs over continuous flow systems. Operational cycle-times for the ASBR can be as short as 6 hours if the biomass granulation is achieved.

2.4. Anaerobic Filter (Packed Bed)

Anaerobic filter (Fig. 3) is a fixed-film biological wastewater treatment process where fixed matrix (support medium) provides an attachment surface that supports the anaerobic microorganisms in the form of a biofilm. As wastewater flows upwards through this bed and dissolved pollutants are absorbed by biofilm, treatment occurs. Anaerobic filters were the first anaerobic systems that eliminated the need for recycle and solids separation while providing a high SRT/HRT ratio. Various types of support material can be used, such as sand, plastics, sand, reticulated foam polymers, stone, granite, granular activated carbon (GAC), and quartz.

These materials have exceptionally high surface area to volume ratios (400 m^2/m^3) and low void volumes. Its resistance to shock loads and inhibitions make anaerobic filter suitable for the treatment of both high strength and dilute wastewaters. Restrictions of anaerobic filter are mostly physical ones related to deterioration of the bed structure through a gradual accumulation of non-biodegradable solids. This leads eventually to short circuiting and channeling flow, and anaerobic filters are therefore unsuitable for wastewaters with high solids contents. Additionally, there is a relatively high cost due to the packing materials [5].

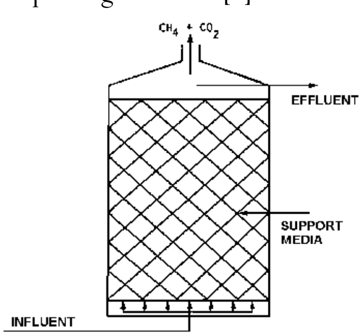

Fig. 3: Anaerobic Filter (Packed Bed) [7]

2.5. Fluidized Bed Reactor (FBR)

FBR is a biological reactor that accumulates a maximum active attached biomass thus far still handling fine suspended solids without blocking. By minimizing the volume occupied by the media and maximizing the surface area available for microbial attachment, a maximum specific activity of attached biomass may be achieved for a given reactor volume. A filter containing extremely small particles (0.5 mm) provides sufficient surface area to achieve these benefits. To attain fluidization of the biomass particles, units must be operated in an upflow mode. Rate of liquid flow and the resulting degree of bed expansion determines whether the reactor is termed expanded bed or fluidized bed system.

Expanded bed reactors have a bed expansion of 10% to 20% compared to about 30% to 90% in fluidized beds. In FBR, biomass is attached to surface of small particles (sand, anthracite, high density plastic beads, etc.) which are kept in suspension by upward velocity of liquid flow. Effluent is recycled to dilute feed waste and to provide sufficient flow-rate to keep particles in suspension. High degrees of mixing and large surface area of support particles that result from high vertical flows enable a high biomass concentration to develop an efficient substrate uptake. Biomass concentrations are usually around 15-40 g/l.

The most risk with FBR is the loss of biomass particles from the reactor following sudden changes in flow rate, particle density, or gas production. If flow is interrupted and the bed allowed settling, there is a possibility once flow is restarted for the entire bed to move upward in plug-flow rather than fluidizing. In practice, considerable difficulties were experienced in controlling the density of flocs and particle size due to variable amounts of biomass growth on particles. Therefore FBRs are considered to be complicated to operate.

2.6. Upflow Anaerobic Sludge Blanket (UASB) Reactor

The dilemma associated with anaerobic filters and FBRs has led to development of new unpacked reactors that still incorporate an immobilized form of particulate biomass. In 1970s, the concept of an unpacked high-rate reactor called UASB reactor was developed [6]. It is consider as the most widely used high-rate anaerobic system for industrial and domestic wastewater treatment worldwide.

UASB reactor is based on that anaerobic sludge exhibits inherently good settling properties, in which sludge is not exposed to heavy mechanical agitation. Sufficient mixing is provided by an even flow-distribution combined with a sufficiently high upflow velocity, and by agitation that results from gas production. Biomass is retained as granular matrix or blanket, and is kept in suspension by controlling the upflow velocity. Wastewater flows upwards through a sludge blanket located in lower part of reactor, while upper part contains a three phase separation system, which are the most characteristic feature of UASB reactor (Figure 4).

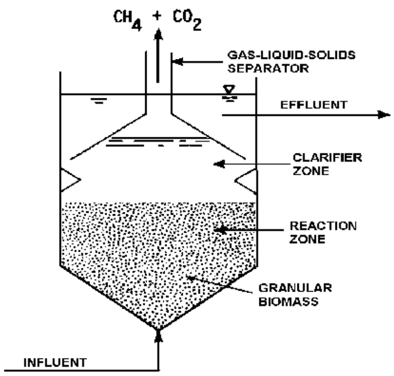

Fig. 4: Upflow Anaerobic Sludge Blanket Reactor [7].

It contributes the collection of biogas and also provides internal recycling of sludge by disengaging adherent biogas bubbles from raising the sludge particles. An advanced settling characteristic of granular sludge allows higher sludge concentrations and consequently permitted UASB reactor to achieve much higher OLRs. Granular sludge development is now observed in UASB reactors treating different types of wastewater.

2.7. Anaerobic Baffled Reactor (ABR)

ABR was first developed in early 1980s, and consist of compartments (up to 8) in one reactor which is baffled to force the incoming wastewater up through a series of sludge blankets, thereby minimizing the loss of biomass. ABR are widely used in wastewater treatment plant to remove heavy sediment solids with the intention that the carryover wastewater will have lower COD level before going to next step of processes. A typical construction of the tank or reactor usually comprises of different compartments with various outlet levels and having a series of arranged baffles.

Fig. 5 shows an anaerobic baffled reactor (ABR) with several compartments that is designed to reduce the suspended and organic matter in the wastewater by about 70%. Raw wastewater enters the ABR tank through the inlet tubes, which directs the flow to the bottom of the first compartment. Owing to the nature of wastewater under anaerobic conditions, granulated sludge blanket is formed. As the wastewater flows up throughout the sludge granules, the solids are trapped in the sludge blanket where anaerobic bacteria consume the organics as their food.

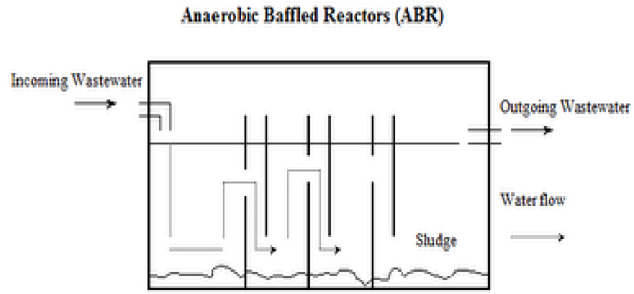

Fig. 5: Anaerobic Baffled Reactors [1].

Consequently, partially clarified effluent flows up over the baffle to the next compartment where the same action is performed. In each subsequent compartment, the effluent is clarified further until the last compartment, where the biochemical oxygen demand level is greatly reduced and the anaerobic effluent is relatively free of suspended solids. The technology is relatively simple to operate, inexpensive, does not require electricity, and can be constructed with local materials and labor [7].

ABRs are relatively simple to design in which some designers use transfer openings in the baffle walls to direct the flow from one compartment to the next [5]. Other designers use pipes that accumulate the effluent from the top of one compartment and deliver it to the bottom of the next compartment. With any design, it is important to ensure that pipe or transfer openings are set level to avoid short circuiting.

As illustrated in Fig. 5, the incoming wastewater is usually diverted to the tank from an elevated pipeline preferably using only gravitational force to less create unnecessary turbulence inside the reactor. As wastewater starts to buildup and increase in level, the carryover water will start to overflow to the next compartment while leaving heavy solids behind to settle at tank bottom. Usually this method is effective especially for agriculture wastewater and household discharge whereby high amount of heavy solids can be expected. One of the advantages of using this system is that it requires low level of maintenance due to no mechanical moving parts and the baffles position is already fixed without needing further adjustment.

3. ANAEROBIC BAFFLED REACTOR (ABR) DEVELOPMENT

The first ABR was developed by Fannin, *et al.* [8, 9] who added vertical baffles to reactor treating high solids kelp slurry to enhance the reactor's ability by maintain slowly growing methanogenesis, which were being replaced by the influent solids. Methane level increased from 30% to over 55% with a methane yield of $0.34 m^3.kg\ VSS^{-1}$ after the baffled were added at constant loading rate of 1.6 kg COD m^{-3} d^{-1}. Later, Bachmann, *et al.*; Wu and Smith [10,11] compared the performance of two baffled reactor before and after narrowing the downflow chambers and slanting the baffled edges. This modified design showed improved methane production rates and reactor efficiency, however a decreased in the methane content of the biogas was noted.

In order to remove nitrogen in the ABR, Barber and Stuckey [12,13] incorporated nitrifiers immobilized in polyvibyl alcohol (PVA) beads in the aerated seventh compartment of an eight compartment reactor, while Rostron, *et al.*[14] use Kaldnes particles in the last compartment to reduce any solids loss caused by aeration. Only 50% of the incoming ammonia was nitrified due to the bead structure and mass transfer problems. With recycled effluent, almost all the nitrate/nitrite (~96%) was reduced to nitrogen gas, and there was small increase (~5%) in chemical oxygen demand (COD) removal over the ABR.

Similar to this approach is the development of the carrier ABR (CABR), in which a medium is added (eg bamboo rings, coke particles) to some or all of the ABR compartments to provide a surface for bacteria to grow on and to avoid the washout of biomass in essence a series of upflow anaerobic filters [15-18]. This adjustment seems to help during shock loads and results in good performance under most conditions.

Another modification of the ABR is to seed the reactor with granular UASB sludge during startup. Grobicki [19] had noticed that granules forming under certain conditions in the ABR, but it were not predictable. Freese and Stuckey [20] studied the effect of starting up an ABR with suspended biomass and granules. It was found that using granules resulted in a far faster start up, but the nutrient deficiencies resulted in poor granules and that if the feed was changed from carbohydrate to protein/carbohydrate then "fuzz" developed on the granules preventing gas escape and they were washed down and out of the reactor. The concept of a granular-bed ABR (GRRABR) was then developed where the acidogenics tended to be suspended while the methanogenesis were immobilized in the granules [21-23].

The evolution of the ABR resulted in similar manifestations of the design, the periodic ABR (PABR) was continuously developed [24-26]. This design used a concentric circular reactor where the chambers are comparable to an ABR with baffles, but it can be fed into any chamber from 1 to 8. The authors claim that this mode of operation allows the PABR to be operated as a UASB, ABR or a combination in the middle, and thus it is best suited to handle time-varying loads at maximum conversion rates. Similar in design is the anaerobic migrating blanket reactor ABR (AMBR) where three CSTR compartments are fed so that the feed and exit points can be varied over time [27-29]. While marginally better than a UASB or standard ABR under some conditions, these types of reactors lose some of the advantages of the ABR, such as separation of the various anaerobic trophic groups.

4. MODIFIED HYBRIDIZED ANAEROBIC INCLINING BAFFLED (MHAI-B) REACTOR

The development of effective and simple methods for treatment of wastewater is a challenging task to environmental engineers and scientists. Therefore, a novel modified hybridized anaerobic inclining-baffled (MHAI-B) bioreactor which is a combination of regular suspended-growth and fixed biofilm systems together with the modification of baffled-reactor configurations seems to be a good candidate to anaerobic baffled reactor development. The most significant advantages of this design was its ability to nearly perfectly realize the staged multi-phase anaerobic theory, allowing different bacterial groups to develop under more favorable conditions, low costs and without the associated control problems. Other advantages include reduced sludge bed expansion, no special gas or sludge separation required and high stability to organic and hydraulic and toxic shock loads. The compartmentalization MHAI-B bioreactor results in a buffering zone between the primary acidification zone (downflow chamber) and active methanogenesis zone (upflow chamber). MHAI-B bioreactor will behave partly as a fluidized bed reactor similar to up-flow anaerobic sludge blanket (UASB) reactor and it also act as an activated sludge reactor as well as trickling submerged fixed film reactor. This MHAI-B bioreactor combines suspended- growth and attached-growth processes in a single reactor to take advantage of both biomass types.

5. CONCLUSION

All design of anaerobic digester show that it is capable to treat a variety of wastewaters of varying strength. The physical structure of the reactors allows various modifications to be made that providing the capability to treat wastewaters that currently require at least two separate units, therefore substantially reducing capital costs.

6. ACKNOWLEDGEMENTS

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