STUDY THE PERFORMANCE OF THE PERIODIC ANAEROB
BAFFLED REACTOR (PABR) AT DIFFERENT SWITCHING
FREQUENCIES UNDER THE STABLE PERIODIC STATE (SPS)
CONSTANT HYDRAULIC RETENTION TIME AND AT CONSTA
FEED STRENGTH

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CERTIFICATE

Certified that the dissertation entitled ***performance of the periodic anaerobic baffle reactor (PABR) at different switchin frequencies under stable periodic state (SPS at constant hydraulic retention time and a constant feed strength*** " is being submitted b Mr. Sanjay Kumar Singh in the partia fulfillment of the requirement of the degre of master of engineering in environmenta engineering of Delhi College of Engineering Bawana road, Delhi is a record of candidate' own work carried by him under my supervisio and guidance .

This is further certified tha the work presented in this thesis has not bee submitted for the award of degree anywhere.

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ABSTRACT

The most common bioreactor type used for anaerobic digestion is the Continuously Stirred Tank Reactor (CSTR). The main problem of this reactor type i.e. the fact that the active biomass which continuously removed from the system, leading to long retention time, has been overcome in a number of system based on immobilization of active biomass. Two representative types are the up flow Anaerobic Sludge Blanket Reactor (UASBR) and the Anaerobic Baffled Reactor (ABR). The success of these reactor systems rest on the highly flocculated, well settling, compact methanogenic sludge granules which develop in these reactors. A novel reactor type named Periodic Anaerobic Baffled Reactor (PABR) has been designed, offering the following major advantage: it may be operated as an ABR, a UASBR or at an intermediate mode. The PABR hydraulic behavior has been characterized using residence time distribution experiments at different retention times. Simulating the PABR behavior, the dependence of the reactor of the reactor performance on the switching frequency is determined as a function of the retention time. In particular, it is found that for high retention times the ABR mode is superior, whereas for low retention times, the UASBR mode should be preferred. In order to establish the accuracy of the predictions of the simulation study , the PABR behavior was experimentally verified using three different stable periodic states.

<u>KEYWORDS</u>

Anaerbic; Baffled Reactor; Periodic; Up flow Anaerobic Sludge Blanket

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PERIODIC ANAEROBIC BAFFLED REACTOR - A NOVEL SYSTEM for TREATMENT of Dairy waste

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1.1 INTRODUCTION

The most common configuration used for the anaerobic treatment of wastewaters is the Continuously Stirred Tank Reactor (CSTR) (Nyns and Thomas, 1997). The main problem of this reactor type, i.e. the fact that the active biomass is continuously removed from the system leading to long retention times, has been overcome in a number of systems based on immobilization of the active biomass. However, such systems set up demands on the amount of particulate materials that can be present and are only suitable for readily hydrolysable wastewaters. A typical such reactor (Lettinga *et al.,* 1980) is the up flow Anaerobic Sludge Blanket Reactor (UASBR). In the UASBR the microorganisms are kept in the reactor due to the production of the highly flocculated, well settling, compact sludge granules, which develop. Granular UASBRs are the system of choice for low to medium - high strength waste waters containing low or easily hydrolysable solids.

The Anaerobic Baffled Reactor (ABR), initially developed by McCarty and Coworkers (Bachmann *et al.,* 1982, 1985) consists of a series of baffled compartments where the wastewater flows upward through a bed of Anaerobic Sludge. The ABR does not require the sludge to granulate in order to perform effectively, although granulation does occur over the time. Experiments with lab-scale reactors have shown that the ABR is very stable under hydraulic shock loads, being able to tolerate shocks of 0.5 - 1 h retention time for 2-3hrs (Grobicki and Stuckey, 1991, 1992). The ABR has many potential advantages, i.e. stability under hydraulic shock loading, low sludge generation, low capital and operation costs coupled with mechanical simplicity. From a reactor design point of view UASB reactor resembles a well-mixed reactor, whereas an ABR resembles a plug-flow reactor.

A novel reactor type, the Periodic Anaerobic Baffled Reactor (PABR) consists of two concentric cylinders. The PABR is constructed with Perspex Sheet. The area between the cylinders is compartmentalized so that the reactor resembles an ABR with the compartments arranged in a circular manner (Fig 1a). The liquid comes in the digester at the down flow section of feeding (first) compartment, comes up at the up flow section of the same compartment and passes into the next (second) compartment through the outer tubing. The same procedure is repeated until the effluent compartment, which is the fourth one in counter clockwise order. For instance, when A is the feeding compartment (Fig. 1b), D will be the effluent one and valves 1,3,6,9,11 will be switched on while valves 2,4,5,7,8,10,12 will be switched off. Likewise, whenever the feeding compartment is B, C or D, the effluent one will be the A, B or C respectively. The feeding and effluent compartments are periodically changed by proper switching (on or off) the twelve valve of outer tubing. Consequently, during a period of operation each compartment serves as the feed compartment for one-fourth of the time, and as a harvesting (effluent) compartment for one-fourth of the time. In the extreme of zero switching frequency (no switching) the reactor behaves as a simple ABR. In the other extreme (infinite frequency) the compartments become identical so that the reactor should behave like a UASBR. By setting the frequency, a great flexibility may be added, taking advantage of the optimal reactor configuration (UASBR, ABR or Something in between) depending on the loading conditions.

The novel reactor offers the following major advantages:

1. It may be operated as an ABR, a UASBR or an at an intermediate mode by varying the switching frequency. Preliminary investigation (described in the sequel) have demonstrated that:

   (a) The UASBR mode has higher performance for small retention time (high loading rates)

   (b) The ABR mode has higher performance for high retention time (low loading rates)

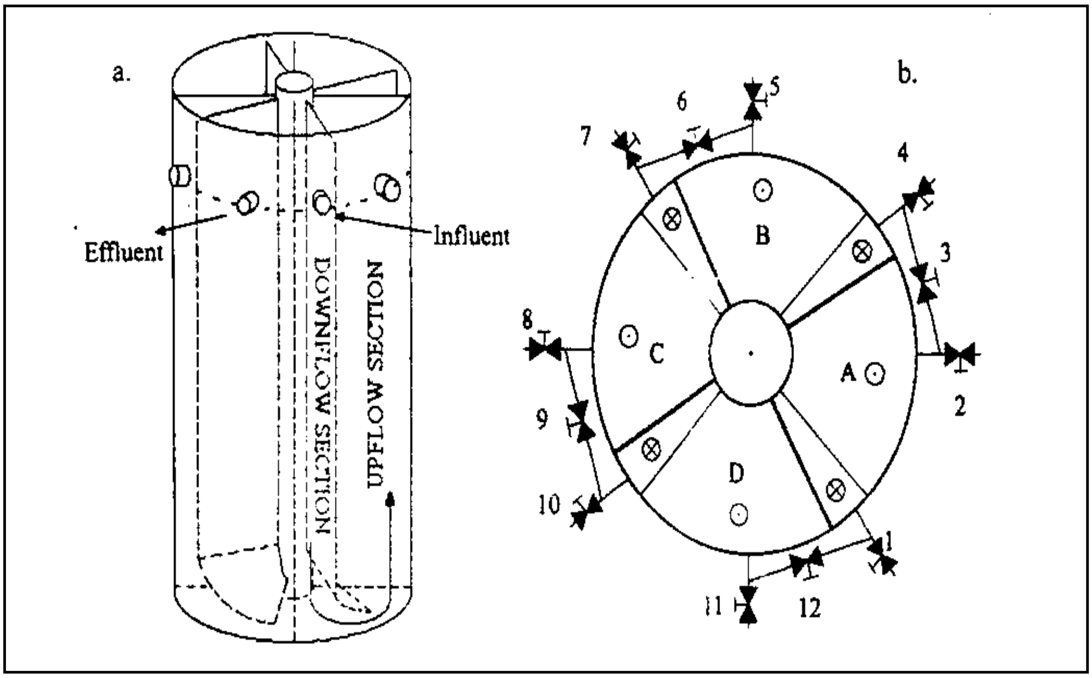

Fig. 1. (a) Front view of a four compartment: (b) Top view of a four compartment PABR. 1-12 valves, º ○ Upflow , ⊗ Downflow

PERIODIC ANAEROBIC BAFFLED REACTOR (PABR)

FIGURE. 1 (a) & (b)

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Consequently, the PABR is best suited for handling time varying loading rates, since it allows for maximal conversion rates at all times. The expected reactor behavior has been simulated with an appropriate mathematical process model and the bioreactor performance has been experimentally tested.

2.The inner cylinder may be used as a heat exchanger for maintaining the reactor under mesophilic (35° C) or thermophilic (50° C) conditions. In addition, the heat losses from the outer surface are minimized, since the reactor has minimal outer surface area per unit volume when compared with a rectangular shape ABR.

The fact that the PABR has residence time distribution equivalent to four well mixed reactors in series (Skiadas and Lyberatos, 1998) allows simulation of the PABR, using kinetic models that were developed for the anaerobic digestion in Continuously Stirred Tank Anaerobic Digesters. Simulation employing the model of smith *et al.,* (1988) (acido-genesis of glucose and methanogenesis are taken into account considering unionised volatile fatty acids (VFAs) concentration as a key parameter and methanogensis as the rate limiting step) showed that: (a) for large values of organic loading, the PABR is expected to perform better when operated at a high frequency of switching feed point, namely it behaves as a UASBR; and (b) for smaller values of the organic loading the PABR should be operated at smaller frequencies approaching that of an ABR (Skiadas and Lyberatos, 1998). In addition, when a PABR is operated without switching of the feeding point (namely as an ABR), it fails when a relatively high step increase in the Hydraulic Retention Time (HRT) is imposed.

The PABR, when operated with periodic switching of the feeding point, is able to approach a stable periodic state (SPS) when exposed to same step change (Skiadas and Lyberatos, 1998). The above simulation predicted that for a four day HRT and 16 g/l influent Chemical Oxygen Demand (COD) concentration, the PABR performance in SPS was optimum when operated at the UASBR mode (high switching frequency) with 12 g/l effluent COD concentration and 2.4 g/l biomass concentration. In contrast, experiments with a 15 l PABR, fed with a glucose - based synthetic wastewater of the same influent COD concentration varying between 31 and 57 g/l (Skiadas, 1998). The difference between the model prediction and the experimental results is attributed to the high biomass retention in the compartments of the PABR, that a simple CSTR model neglects.

1.2. Objective

To study the performance of the Periodic Anaerobic Baffled Reactor (PABR) in counter clockwise sequential at different switching frequencies under stable periodic state (SPS) at constant hydraulic retention time (HRT=12h) and at constant feed strength.

Chapter 2

2.1 GENERAL

India has emerged as one of the world's largest producer and fastest growing markets for milk products. With an annual growth of over 5%, the country's milk production in 1996-97 exceeded 203 million lpd (74.3 million tones per year, Dairy India-97). In a typical Indian dairy handling about 3,00,000 to 4,00,000 litres of milk in a day, large quantity of wastewater originates due to their different operations. The organic substances in the wastes either in the form in which they were present in milk, or in a degraded forms due to their processing . As such, the dairy wastes, though biodegradable, are very organic in nature.

The dairy waste is organic in nature. This is slightly alkaline when fresh. When these wastes are followed to go into the stream without any treatment, a rapid depletion of the dissolved oxygen content of the stream occurs, along with sewage fungi covering the entire bottom of the stream and submerged parts of the hydraulics structures within it. The waste is said to be harboring, occasionally, the bacteria responsible for tuberculosis. At certain concentrations, the dairy waste is found to be toxic to fish also.

As evident from COD/BOD ratio, the dairy waste can be treated efficiently by biological growth. Therefore, it is amenable to anaerobic lagoon treatment giving a BOD reduction of 90% at an organic loading of 0.48 kg COD/cum/day with a retention time of 7 days and a depth in the order of 3 meters.

2.2 WASTEWATER TREATABILITY STUDIES

Determination of Treatability and the kinetic constants are the essential steps in the design of waste treatment plants. In dealing with typical domestic and municipal sewages, laboratory studies are not essential for developing design criteria. However, in the case of certain industrial waste followed by pilot plant studies to evaluate more specifically any operating problems before a full scale unit is designed. Wastewater treatability studies are especially important where new treatment methods are being proposed. Therefore, the engineer must understand the general approach and methodology in:

⇨ Assessing the treatability wastewater

⇨ The conduct of laboratory and pilot-plant studies, and

→ The translation of design experimental data into design parameters

2.3 REVIEW OF LITERATURE

Among the various industrial wastewaters, the amount of dairy wastewater has increased manifolds due to the increased production of dairy products and due to the awareness among the people regarding its nutritive food value. Dairy processing industry in India has developed rapidly, since 1950. There are 428 plants public and private sector units producing 74.3 million tones of milk producing annually (Dairy India-1997). Large volume of the water are normally used in dairy processing plants. The volume of the effluent from dairy plant is related to the products being produced (Forbes, 1974, Metcalf and Eddy, inc, 1972). The total amount of readily biodegradable waste produces each year from industry from dairy food processing is extremely high. The waste is highly organic in nature (Forbes, 1974, Metcalf and Eddy, inc., 1972) but the concentration of the organic matter differs in various plants. Effluents from cheese making, condensing, etc., are generally highest in organic matter, while those from bottling, drying and other processing effluents are generally low in organic content (Warner, 1976). The waste essentially consists of a solution of milk, milk products and cleaning material (Brown and Pico, 1979). Due to their organic composition, dairy effluents are readily treated by biological processes (Warner, 1976). The treatment processes is determined by flow rate, waste strength and stream conditions. Various methods are used for treatment of dairy effluents, such as filtration (Muers, 1968; Wheatland, 1960), extended aeration (Mortesen, 1977), chemical treatment such as electro-coagulation and precipitation (Foolfarov and kalinia-shuvalova, 1977), followed by electro-flocculation and precipitation (solymos, 1976), physical methods such as activated carbon adsorption (IKI, 1979); anaerobic (Bachmann and Blane, 1985,. Birks and Hynek, 1971: Bulk et al, 1982), and aerobic treatment (Garrison et al, 1983; Meij milk products co. Ltd, 1984).

The wastewater is highly proteinatious and can be effectively treated by the anaerobic process. Van den berg and Kennedy (1983) have treated the dairy waste successfully by the stationary fixed film reactors. They reported a COD reduction of 95% at high loading rate for whey. Taori (1982) carried out work on the treatment of original dairy wastewater by two phase anaerobic packed bed up flow filter (Pilot Scale), and concluded that the system worked well and had the capacity to take up higher loading with fairly stable performance. He could achieve a COD and BOD reduction of 90% and 96.5% respectively with 13.2-day detention time (organic loading of 1.2 kg COD/ m^3/day). The methane content of the gas has been reported to around 72%. The anaerobic reactors are particularly useful for strong organic waste with low solids content like dairy wastewater. Further, it provides a novel way of waste treatment through its characteristics properties of low hydraulic retention time (HRT) and solids retention time (SRT). Intensive investigation was carried out by Jayashree Venkataraman (1988) using anaerobic packed bed reactor, attached bed reactor and two-stage anaerobic.

2.4 APPLICATION OF ANAEROBIC TECHNOLOGY FOR THE TREATMENT OF INDUSTRIAL WASTEWATER

The successful application of anaerobic technology to the treatment of industrial wastewater is critically dependent on the development, and use, of high rate anaerobic bioreactors. These reactor achieve a high reaction rate per unit reactor volume (in terms of kg COD/m^3/day) by retaining the biomass (Solids retention time, SRT) in the reactor independently of the incoming wastewater (Hydraulic Residence Time, HRT), in contrast to continually Stirred Tank Reactor (CSTRs). Thus reducing reactor volume and ultimately allowing the application of high volumetric loading rates, e.g. 10-40 kg COD/m3/day (Iza et al., 1991). High rate anaerobic biological reactors may be classified into three broad groups depending on the mechanism used to achieve biomass detention, and these are fixed film, suspended growth, and hybrid. There are currently 900 full-scale installations in the world today (Habets,1996) and they are distributed as follows: Up flow Anaerobic Sludge Blanket (UASB-Suspended growth) 67% (Lettinga et al., 1980); CSTR 12%; Anaerbic Filter (AF-fixed film) 7% (Young and McCarty, 1969); others 14%. The highest loading rates achieved during anaerobic treatment to date are attributed to the "Anaerobic Attached Film Expended Bed" (AAFEB) reactor (120 kg COD/m3/day, Switzenbaum and Jewell (1980)), but its inherent complexity and high operating costs limits its practical use on wide scale.

Around the same time as Lettinga developed the UASB, McCarty and co-workers at Stanford notice that most of the biomass present within an anaerobic Rotating Biological Contactor (RBC, Tait and Freidman (1980)) was actually suspended, and when they removed the rotating discs they developed the Anaerobic Baffled Reactor (ABR, McCarty (1981)). However, baffled reactor units had previously been used to generate a methane rich biogas as an energy source (Chynoweth et al., 1980). Although not commonly found on a large scale, the ABR has several advantages over other well-established systems, and these are summarized below.

Advantage associated with the anaerobic baffled reactor.

→ Construction

1. Simple design
2. No moving parts
3. No mechanical mixing
4. Inexpensive to construct
5. High void volume
6. Reduced sludge bed expansion
7. Low capital and operating costs

→ Biomass

1. No requirement for the biomass with unusual settling properties.
2. Low sludge generation.
3. High solids retention time.
4. Retention of biomass without fixed media or a solid settling chamber.
5. No special gas or sludge separation required.

→ Operation

1. Low HRT
2. Intermittent operation possible
3. Extremely stable to hydraulic shock loads.
4. Protection from toxic materials in influent.
5. Long operation time without sludge wasting.
6. High stability to organic shocks.

Probably the most significant advantage of the ABR is its ability to separate acidogenesis and methanogenesis longitudinally down the reactor, allowing the reactor to behave as a two phase system without the associated control problems and high costs (Weiland and Rozzi, 1991). Two-phase operation can increase acidogenic and methanogenic activity by a factor of up to four as acidogenic bacteria accumulate within the first stage (Cohen et al., 1980,1982), and different bacterial groups can develop under more favourable conditions. The advantages of two-phase operation have been extensively documented (Pohland and Ghosh, 1971; Ghosh et al., 1975; Cohen et al., 1980, 1982). These benefits have catalysed the development of other staged reactor configuration, such as the "multiplate Anaerobic Reactor " (El-Mamouni et al., 1995), " Upflow Staged Sludge Bed (USSB)" (Van Lier et al., 1994, 1996) and the "Staged Anaerobic Filter" (Alves et al., 1997), all of which have showed considerable potential for wastewater treatment. Disadvantages of the baffled reactor design at pilot/ full-scale include the requirement to build shallow reactors to maintain acceptable liquid and gas upflow velocities, and problem with maintaining an even distribution of the influent (Tilche and Vieira, 1991).

2.5 REACTOR DEVELOPMENT

The ABR is a reactor design which uses a series of baffles to force a wastewater containing organic pollutants to fiow under and over (or through) the baffles as it passes from the inlet to the outlet (McCarty and Bachmann, 1992). Bacteria within the reactor gently rise and settle due to flow characteristics and gas production, but move down the reactor at a slow rate. However, in order to improve reactor performance several modifications have been made. The main driving force behind reactor design has been to enhance the solids retention capacity, but other modifications have been made in order to treat difficult wastewaters (e.g. with a high solids content, Boopathy and Sievers (1991)), or simply to reduce capitals costs (Orozco (1997)). A summary of the main alterations is shown in Table 1.

TABLE 1

Sl.No.	MDIFICATION	PURPOSE	Reference:
1	Addition of vertical to a plug flow reactors	Enhances solids retention to allow better substrate accessibility to methanogens	Fannin et al., 1981
2	a) Down flow chambers narrowed b) slanted edges on baffles (40-45^0)	a) Encourages cell retentions in upflow chambers b) Routes flow towards center of compartment encouraging mixing	Bachmann et al., 1983
3	a) settling chamber b) Packing positioned at top of each chamber c) Separated gas chambers	a) Enhances solids retention b) Prevent washout of solids c) Ease and control of gas measurement, provides enhanced reactor stability.	Tilche and Yang, 1987
4	Enlargement of first chamber	Better treatability of high solids wastewater	Boopathy and Sievers, 1991

2.6 REACTOR HYDRODYNAMICS

2.6.1 Flow Patterns

The hydrodynamics and degree of mixing that occur within a reactor of this design strongly influence the extent of contact between substrate and bacteria, thus controlling mass transfer and potential reactor performance. In 1992, Grobicki and Stuckey conducted a series of residence time distribution studies by tracking the fate of an inert tracer (Li^+) in the effluent of a number of baffled reactors (4-8 chambers), both with and without biomass, at various HRTs, and incorporated the data into "Dispersion" and "Tank In series" models previously described by Levenspiel (1972). The models provided a useful method to calculate the degree of mixing and amount of unused volume (known as "dead space") within the reactor. They found low levels of dead space (< 8% hydraulic dead space in an empty reactor) in comparison with other anaerobic reactor designs e.g. 50-93% in an anaerobic filter and > 80% in a CSTR.

Dead space increased to 18% on the addition of 8g VSS/l, however, no direct correlation between hydraulic dead space and HRT could be drawn. AT low HRT , the presence of biomass had no significant effect on hydraulic dead space, which was found to be a function of flow rate and number of baffles. This contrasted with biological dead space, which was found to be a function of biomass, gas production, and flow rate, and which increased with increasing flow rates. At high loading rates caused by low HRT, gas production as well as increased flow rates kept sludge beds partly fluidized. Therefore, the contradictory effects of hydraulic and biological dead space prevented a correlation being derived between HRT and overall dead space. Biological dead space was established as major contributor to overall dead space at high HRT, but its effect decreased at lower HRT since gas production disrupted channeling within the biomass bed. Severe channeling, caused by large hydraulic shocks, was found to be beneficial, since most of the biomass was not entrained in the flow, and this resulted in low washout and a fast recovery in the performance (Grobicki and Stucky, 1992; Nachaiyasit and Stucky, 1997c). Nevertheless, investigations of the hydrodynamics, which are probably important, and these include biogas mixing effects; viscosity changes due to extracellular polymer production and the biomass particle size.

2.6.2 Effects of Effluent Recycle

Recycling of the effluent stream tends to reduce removal efficiency because the reactor approaches a completely mixed system, and therefore the mass transfer driving force for substrate removal decreases despite a small increase in the loading rate.

Chynoweth et al., (1980) observed a positive effect caused by recycling twenty percent of the effluent, when the methane yield was increased by over 30%. The addition of a recycle stream was also found to alleviate the problem of low pH caused by high level of volatile acids at the front of the reactor, and discourage gelantinous bacterial growth at the reactor inlet for the treatment of complex protein carbohydrate wastewater (Bachmann et al., 1983). Another benefit of recycle is the dilution of toxicants and reduction of substrate inhibition in the influent (Bachmann et al., 1985; Grobicki and Stuckey, 1991).

From the theoretical consideration, recycle should have a negative effect on reactor hydrodynamics by causing increased mixing (which encourages solids loss, and disrupts microstructures of bacteria living in symbiotic relationships (Henze and Harremoes, 1983)) and enhancing the amount of dead space (Grobicki and Stuckey, 1992; Nachaiyasit, 1995).

Mixing caused by recycle has also been found to cause a return to single phase digestion, therefore the benefits arising from the separation of acidogenic and methanogenic phases are partially lost. Bachmann et al., (1985) noticed that methanogenic activity was more uniformly distributed over the whole reactor after recycle was used. The consequences of this observation are scavenging bacteria (such as methanosaeta) will end up at the front of the reactor. Where harsh conditions of high substrate concentration, high hydrogen partial pressure and low pH will make them relatively inactive, and poorly scavenging acid producing bacteria pushed towards the rear of the reactor will be starved since less substrate will be available. Nachaiyasit (1995) discovered a fall in both gas production and methane composition down the reactor when the recycle ratio was increased.

The overall benefits of recycle are unclear and ultimately it use will depend on the type of waste being treated. If pH problems are severe, the influent has high levels of toxic materials, or high loading rates preferred then recycle will be beneficial.

2.7 REACTOR PERFORMANCE

The overall objective of the start-up is the development of the most appropriate microbial culture for the waste stream in question. Once the biomass has been established, either as a granular particle or a floc, reactor operation is quite stable.

Initial loading rate should be low so that slow growing micro-organism are not overloaded, and both gas and up flow velocities should be low so that flocculent and granular growth is encouraged. In order to stimulate the growth of methanogenic archea, pluses of methane precursors (acetate and/or an acetate/formate mixture) were added directly before raising loading rates and these were effective in minimizing the shock caused by a sudden increase in organic loading. Alternative methods to prevent failure include the adjustment of pH in the first compartment (Grobicki, 1989). A recent study (Barber and Stuckey, 1997) has shown that maintaining an initially long detention time (80h) which is reduce in a stepwise fashion during which time substrate concentration is kept constant, provides greater reactor stability and superior performance than the reactor started with a constant and low detention time coupled to a stepwise increase in substrate concentration. These finding were linked to better solids accumulation, promotion of methanogenic populations, and faster recovery to hydraulic shocks in the reactor started at the longer retention time.

2.7.1 Treatment Applications

This section reviews the performance of the baffled reactor while treating a variety of wastewater, in particular, low and high strength, low temperature, high effluent solids and sulphate containing waste.

Low strength treatment:- Various authors have treated low strength wastewaters effectively in ABR. Dilute wastewaters inherently provide a low mass transfer driving force between biomass and substrate, and subsequently biomass activities will be greatly reduced according to Monod Kinetics. As a result, treatment of low strength wastewaters has been found to encourage the dominance of scavenging bacteria such as Methanosaeta in the ABR (Polprasert et al., 1992). Hassouna and Stuckey (1998), have shown that no substantial change occurred in the population of acid producing bacteria down the length of a reactor treating dilute waste, indicating the lack of significant population selection at low COD concentrations.

It appears that biomass retention is enhanced significantly due to lower gas production rates suggesting that low hydraulic retention times (6-2h) are feasible during low strength treatment. Orozco (1988) noted decreasing overall gas production with increasing HRTs, and this implied possible biomass starvation in later compartment at longer retention times. Another important consequence of low retention times when treating dilute wastewaters is an increase in hydraulic turbulence, which can lower apparent Ks values (Kato et al., 1997) thus enhancing treatment efficiency

Witthauer and Stucky (1982) observed irregular COD removal in baffled reactors run at low loading rates and long retention times when treating dilute synthetic grey water. These problems were associated with low sludge blankets (inoculum contained less than 3g VSS/l) caused after long periods of biomass settling. Channels were formed within low blanket and this resulted in low gas productivity in most of the sludge blanket except for around the channels. Hence, biogas mixing was greatly reduced and this resulted in minimal biomass/ substrate transport. In contrast, anaerobic filters, operated under the same conditions, outperformed the baffled reactors, even after their suspended biomass was washed out in hydraulic shock experiment.

2.7.2 High strength treatment

Where as low retention times are possible and even necessary for dilute wastewaters, the opposite applies when treated concentrated waste. This is mainly due to the high gas mixing caused by improved mass transfer between the biomass and substrate. This will result in high biomass wastage, and has led to modifications in the reactor design in order to enhance solids retention.

According to kinetic considerations, high substrate concentration will encourage both fast growing bacteria, and organisms with high Ks values, and the methane production will be derived mainly from acetate deccarboxylation by methanosarcina species and hydrogen scavenging methanogens (such as methanobrevibactor and methanobacterium). Subsequently methanosarcina species was observed as dominant bacterial species in bioflocs formed during high strength treatment (Boopathy and Tilche, 1991).

2.7.3 Low temperature treatment

At low/ambient temperature Van Lier et al., (1996), found significant advantages with respect to reactor performance for staged reactors when compared with completely mixed systems. The vast majority of work done so far on baffled reactor conducted in the mesophilic temperature range. Howevers the baffled reactor has been run as low as 13^0c (Orozco,1988), although the most extensive study at low temperatures in the baffled reactor was carried out by Nachaiyasit and Stuckey (1997a).

Generally, biochemical reactions double in relative activity for every 10^0c increase in temperature in accordance with the Van , t Hoff rule over a restricted temperature range. In spite of this, Nachaiyasit (1995), found no significant reduction in overall COD removal efficiency when the temperature of an ABR was dropped from 35 to 25^0c with steady state reached after only two weeks. However, lower catabolic rates caused by elevated Ks values (according to Arrhenius Kinetics) at the front of the reactor caused a shift in acid production towards the rear, although overall removal was unaffected. An increase in VFA production caused a simultaneous reduction in pH and an initial increase in gas phase hydrogen that quickly returned to below background levels. The deeper penetration of the VFAs down the reactor should potentially improve the growth yields of the Methanogens in the latter compartments. The results showed that slower growing organisms exhibited a greater sensitivity to a fall in temperature compared to bacteria with faster growth kinetic and this is in accordance with literature findings (Cayless et al., 1994; Kotsyurbenko et al., 1993; Speece, 1996). Similar high treatment efficiencies at ambient temperature have also noted for a medium strength phenolic wastewater (Holf et al., 1997).

Nachaiyasit and Stucky (1997a) further reduced the temperature to 15^0c, and a fall in overall efficiency of 20% was noted after one month. Changes in performance down the reactor occurred over a long period of time in contrast to CSTRs. This is advantageous since the slow response would inherently provide more protection to shocks than in other reactor systems. However, despite the fact that the reactors were kept for long periods of time at reduced temperatures (12 weeks) their performance did not improve despite the increased intermediate acid concentrations, which according to Monod Kinetics should encourage more biomass growth to compensate for the increased substrate levels. This may be due to the fact that Ks increase substantially as temperature falls, (Lawrence and McCarty, 1969) leaving low level of VFAs that cannot be degraded.

This study also found that the fraction of VFAs in the effulent in terms of COD had reduced significantly. VFAs contributed to approximately a third of the COD at 15^0C and twothirds at 25^0C, indicating that the production of refractory material termed as soluble microbial products (SMPs) Rittmann et al., (1987) increased substantially at lower temperatures. In conclusion, the work found that a combination of decreased catabolic rates, increased Ks, and higher levels of refractory material caused inferior performance at 15^0C, but that a drop in temperature from 35^0C to 25^0C had negligible effects on overall performance despite predictions from Van 't Hoff rule. This has been observed before in bioflim/floc-based reactors where mass transfer limited biomass activity (Hickey et al., 1987).

2.7.3 High solids treatment:

In early work, Chynoweth's group in Illinois (1980, 1981) used baffled reactors to generate methane from sea kelp as an alternative energy source. Although the COD of the kelp was not quoted, the feed contained 15% total solids which were ground and chopped. Practical problems associated with feeding solids were overcome by applying the substrate by syringe. During a particular run, significant solids build up was observed in the first compartment after two weeks of operation. The solids build up reduced microorganism contact with substrate therefore minimizing hydrolysis and subsequent bioconversion. Performance was significantly improved after manually agitating the reactor for a short time period. Solids material was also found to physically displace biomass within the reactor indicating that modifications to the ABR would required for high solids treatment.

2.7.4 Sulphate treatment:

Fox and Venkatasubbiah (1996), investigated the effects of sulphate reduction in the ABR by treating a sulphate containing pharmaceutical wastewater up to a final strength of 20g-COD/l, with a COD: SO4 ratio of 8:1. At steady state, 50% COD removal and 95% sulphate reduction was possible with a detention time of 1 day. Reactor profiles showed that sulphate was almost completely reduced to sulphides within the first chamber, and a concomitant increase in sulphides levels down the reactor indicated that sulphate redirected electron equivalents to hydrogen sulphides in preference to methane.

After altering the COD : SO4 ratio by adding glucose, isopropanol and sulphate, the authors noted a fall in potential sulphate reduction from >95% at COD: SO4 150:1 to <50% at COD: SO4 24:1. Increasing sulphate concentrations with glucose and isopropanol present showed inhibition of sulphate reduction caused by elevated sulphides concentrations.

2.8 BIOMASS CHARACTERISTICS AND RETENTION CAPABILITY

2.8.1 Bacterial population

With the unique construction of the ABR various profiles of microbial communities may develop within each compartment. The microbial ecology within each reactor chamber will depend on the type and amount of the substrate present, as well as external parameters such as pH and temperature. In the acidification zone of the ABR (front compartment(s) of the reactor) fast growing bacteria capable of growth at high substrate levels and reduced pH will dominate. A shift of slower growing scavenging bacteria tha grow at higher pH will occur towards the end of the reactor.

Various techniques have been applied to described the population dynamics within the ABR, and the results are summarized in the Table 2

TABLE 2

Sl.No	OBSERVATIONS	TECHNIQUE	REFERENCE
1	Methanosarcina predominant at front of reactor with Methanosaeta found towards rear.	SEM, TEM, LLM	Boopathy and Tilche 1991, 1992; Tilche and Yang, 1987; Garuti et al., 1992; Yang et al., 1988
2	Active methanogenic fraction within biomass highest at front of reactor and lowest in last chamber	ATA	Bachmann et al., 1985; Orozco, 1989
3	Bacteria resembling propionibacterium, syntrophobacter and methanobrevibacter found in close proximity within granules methanoseta and colonies of syntrophomonas also observed	TEM	Grobicki, 1989
4	Large numbers of methanobacterium at front of ABR along with methanosarcina covered granules; subsequent chambers consisted of methanosaeta coated flocs	EP	Tilche and Yang, 1987
5	Virtually all biomass activity (>85%) occurred in the bottom third of each compartment where biomass was concentrated; highest activity (92%) found in the bottom of first chamber	ATPA	Xing et al., 1991
6	Mainly methanosaeta observed with some cocci: no methanosarcina observed	SEM	Holt et al., 1997
7	Irregular granules with gas vents	SEM	Polprasert et al., 1992

	covered by single rod shaped bacteria; no predominant species observed		
8	Bacteria resembling Methanobrevibacter, methanococcus, and Desulfovibrio found	ATPA, SEM, EP	Boopathy and Tilche, 1992
9	Wide variety of bacteria observed at front of reactor	SEM, TEM	Boopathy and Tilche, 1991; Barber and Stuckey, 1997

Abbreviations; ATA=Anaerobic Toxicity Assay, ATPA= ATP analysis
EP= (phase contrast) Epifluorescene Microscopy,
LLM= Light Level Microscopy, SEM= Scanning Electron Microscopy
TEM= Transmission Electron Microscopy

By far the most common observation involved the shift in population of the two acetoclastic methanogens methanosarcina species and methanosaeta species. At high acetate concentrations methanosarcina outgrow methanosaeta due to fast growth kinetics (doubling time 1.5d compared with 4d for methanosaeta), however, at low concentrations methanosaeta is dominant due to its scavenging capability (Ks = 30mg/l compared with 400mg/l for methanosarcina (Gujer and Zehunder, 1983)).

Tilche and Yang (1987) and Yang et al., (1988) compared the performance and bacterial populations of an anaerobic filter and a hybridized baffled reactor (HABR) at pilot scale treating molasses wastewater with maximum loading rates of 10.5 and 5.5 kg-COD/m3/d for the anaerobic filter and HABR respectively. The major findings of the study were: a large concentration of methanosarcina at he front of the baffled reactor which shifted to methanosaeta towards the rear, compared with a domination of methanosaeta in the filter reactor, and hydrogen scavenging methanobacterium were observed at the front of the baffled reactor using epifluorescence microscopy.

Explanations were offered to described the lack of methanosarcina in the filter reactor. Firstly, the acetate loading in the first chamber of the HABR was 1000mg/l that might be close to the apparent Ks value for the methanosarcina and therefore may have favoured its growth. In contrast, acetate levels were 10 times lower in the filter reactor and therefore methanosaeta had a kinetic advantage and dominated in the reactor. Secondly, lower superficial gas production rates in the baffled reactor (5m/d in the first compartment of the HABR compared with 9m/d in the filter) resulted in lower gas turbulence, and therefore fewer washouts of bioflocs compared with anaerobic filter. Hydrogen levels were also measured, and the highest concentrations (4e-4 atm) were noted in the first chamber of the baffled reactor, and this may explain the presence of methanobacterium. The results were subsequently supported by Polprasert et al., (1992) where acetate concentrations as low as 20mg/l enabled the domination of methanosaeta like bacteria through a four-compartment reactor.

2.8.2 Biomass activity

Tilche and Yang (1987) and Yang et al., (19880 also discovered that 70% of all methane produced in the HABR came from first compartment, despite having only 10% of the VSS present within the reactor, and these findings supported previous work (Bachmann et al., 1985; Orozco, 1988). Bachmann used a procedure based on the Anaerobic Toxicity Assay (ATA, owen et al., (1979)) and discovered that the active fraction of acetate utilizing methanogens as a percentage of the total VSS varied from 5.7 to 1.8%, with the largest value obtain at the front of the reactor and the lowest at the rear. In a study involving an 11-compartment open top baffled reactor treating 500mg/l sucrose at low temperature (13-16^{0}C), Orozco (1988) quoted activities of 1.43g-COD-CH4/m3 in the first seven chambers and o.72 in chambers 7 to 11.

Xing et al., (1991), and Boopathy and Tilche (1992) used ATP analysis to determine the relative position of the most active bacteria. Samples were taken from top, middle and bottom of all three chambers from a reactor with aworking volume of 150l treating molasses wastewater at a loading rate of 20kg-COD/m3d. The results showed that at least 85% of activity came from bottom of the each compartment with the highest activity (92%) measured at the base of the first compartment. However opposite trend was found in a study treating slaughterhouse wastewater (Polprasert et al., 1992). The reason for this may lie in the concentration of intermediates, especially acetate, at the front of the reactor. In studies where methane activity was higher in the front compartments (Bachmann et al., 1985; Tilche and Yang, 1987; and Yang et al., 1988), acetate concentrations were relatively high and therefore provided the best environmental conditions for the growth of methanosarcina which can grow quickly even at pH values as low as 6 (Speece, 1996). Another source of methane would be from hydrogen scavenging bacteria such as methanobacterium (Tilche and Yang, 1987) and methanobrevibacter, which would be stimulated by the higher hydrogen concentrations; the net effect would be a high methanogenic activity. In contrast, with dilute wastewaters, where acetate levels are low in the front compartment (as in the work by Polpraster et al.,), the likely scenario is that methanosaeta would dominate. However, this species grows at a far slower rate compared to methanosarcina and is also far more sensitive to environmental conditions such as reduced pH. This would encourage the growth of acid producing bacteria that would inevitably lead to a reduction in methane potential.

Hassouna and Stuckey (1998) showed a shift in the activity of acid producing bacteria down the length of an eight compartment baffled reactor. Using the method of Owen et al., (1979), aliquots were removed from each compartment of ABRs treating a range of substrate concentrations. In the foremost compartments a glucose spike was readily converted to volatile acids within a few hours and this contrasted with the results from subsequent compartments, which show virtually no degradation of the spike.

2.8.3 Granulation (and flocs sizes)

Although granulation is not necessary in the ABR for optimum performance, unlike suspended systems such as the UASB, various report have noted the appearance of granules in the reactor. Boopathy and Tilche (1991) started up HABRs (the inoculum contained 4.01 g VSS/l) with a low initial loading rate (0.97 kg-COD/kg VSS d) and liquid up flow velocities belown0.46 m/h, in order to encourage the growth of flocculent and granular biomass. Subsequently, stable granules of 0.5mm appeared after one month in all chambers of the reactor and they were reported to be growing although no data was given; microscope studies subsequently showed that the granules were comprised primarily of acetoclastic methanogens. Similarly, Tilche and Yang (1987) found methanosarcina coated flocs held together by fibrous bacteria resembling methanosaeta. The flocs, which were formed after one month, were small with diameters less than 1.5mm and were weak.

Boopathy and Tilche (1992) noticed similar particles of both types described above, which grew from 0.5mm after one month to 3.5mm after three month in a hybrid reactor. Granules, which were made from methanosarcina clusters, were of low density and full of gas cavities and therefore lifted to the surface of the reactor due to high gas and liquid velocities during the high loading. There was a little difference in particle size throughout the reactor when molasses alcohol stillage wastewater was treated. However, two weeks after the substrate was altered to raw molasses with a ten-fold increase in inlet COD a profile emerged which showed a steady decrease in particle size down the reactor. In addition, the sludge weight increased from < 600 to 900g in the first compartment within the same periods (Xing et al., 1991). Orozco (1988) reported a similar decrease in granule size from 5.4mm in the first chamber down to 1.5mm in the last chamber of a reactor treating dilute carbohydrate w waste. However, on a laboratory scale, (Barber and Styckey, 1997) floc size seemed to grow to a maximum near the centre of an eight-compartment reactor and then reduce towards the rear. Typical floc sizes were 100, 230 and 17500m in the front, middle and rear compartment respectively. The floc size was a function of both gas production and COD concentrations, with the largest particles growing when COD concentrations wer sufficiently high to support growth, and gas production low enough to avoid floc breakage.

2.8.4 Solids retention capability

By using a chromic oxide sequi tracer in a high solids swine wastewater (51 g/l), Boopathy and Sievers (1991) managed to measure the solids retention time for two hybrid reactors running at a hydraulic retention time of 25d compared with 22d for a two-compartment unit. The two-compartment reactor had a larger initial chamber, and this provided a natural filtering action that enables it to lose fewer solids to the effluent. Despite this, the three-compartment reactor was found to be more efficient at converting the trapped material into methane on the basis of cellulose, lipid and protein measurements.

In a comparative study, Orozco (1998) calculated the minimum solids retention time required to achieve certain removal efficiencies in baffled and UASB reactors under the same loading conditions, and concluded that the solid residence time in the UASB would have to be approximately 40% higher than the ABR in order to achieve the same removal rate. By assuming a series of perfectly mixed reactors, Grobicki and Stuckey (1991), calculated the solids retention times, biomass yield, and washout of biomass under several system experimental conditions. Solids retention times varied from 7 to 700d (5<80h) and large deviations in the results were attributed to varying degrees of granulation. Although a strong correlation was found to exist between the solids retention time and HRT, the caution should be exercised when using the calculated figures due to the assumptions of perfectly mixed behaviour. Solids retention times of 300d were reported by Garuti et al., (1992) using a 350l reactor with a 15h retention time and this figure is far higher than those calculated by Grobicki and Stuckey (1991) under similar conditions. Also reported that the observed yield were very low (approximately 0.03 kg VSS/kg COD), which implies constant biomass concentration profiles over time, but these finding are in contrast to other researchers (Boopathy and Tilche, 1991; Xing et al., 1991).

Boopathy et al., (1988) discovered that increasing the loading rate from 2.2 to 3.5 kg COD/m3d made no significant difference to the amount of solids lost to the effluent, with a maximum of 0.5g/l occurring during start-up. These results were virtually negligible effluent VSS was found with loading rates between 6 and 12.5 kg COB/m3d. However, a linear increase up to 17g VSS/l at high loading rates (28 kg COD/m3d) was observed. A similar correlation was also found to exist between the Sludge Volume Index (SVI) and the total solids lost from a pilot scale reactor (Garuti et al., 1992). Finally, in recent study, Barber and Stuckey (1997) found that twice as many solids were lost during start-up by reactor running at a low HRT of 20h compared with one which was run on the same feed at long retentions times (80-40-20h), and this was linked to inferior COD removal since biomass accumulated faster in the reactor run at longer times.

2.9 FUTURE PROSPECTS FOR THE ABR

The ABR shows promise for industrial wastewater treatment since it can withstand severe hydraulic and organic shock loads, intermittent feeding , temperature changes, and tolerate certain toxic materials due to its inherent two-phase behavior. Despite comparable performance with other well-established technologies, its future use will depend on exploiting its structure in order to treat wastewaters, which cannot be readily treated. Outlined below is a possible processes that are feasible in the ABR.

2.9.1 In situ aerobic polishing

An aerobic polishing step can be inserted within an ABR with no detrimental effect on the reactor performance. This is due to the fact that "aerophobic" methanogens can remain active even oxygen is present, and whilst inside immobilized aggregates methanogenic archea are well shielded from oxygen by layer of facultative bacteria (Lettinga et al., 1997). Also, processes which inherently require both anaerobic and aerobic treatment (or detoxification) can be dealt within a single reactor unit, such as black hemp liquors, wood extractives, coal processing industry, petrochemical, and textile dye wastewaters (Lettinga et al., 1995) thus significantly reducing capital costs

2.9.2 Total nitrogen removal

To treat ammonia-containing wastewaters with an anaerobic/aerobic baffled reactor for total nitrogen removal. Ammonia present in the wastewater passes through the anaerobic compartments largely unmetabolised, and is then oxidized to form nitrates and nitrites at the rear of the reactor. These can be recycled to the anaerobic section where they act as alternative electron acceptors and are reduced to nitrogen.

2.9.3 Complete sulphur removal

Sulphate is reduced at higher redox potentials than that at which methanogenesis begins (Henze and Harremoes, 1983), and will therefore converted to hydrogen sulphides at the front of a baffled reactor at the expense of methanogenesis (Fox and Venkatasubbhiah, 1996). Micro-aerobic polishing could be achieved within an aerobic stage to produce elemental sulphur, which could be recovered eliminating the need of a separate trickling filter unit.

2.9.4 Enhancement of two-phase properties (better pH and temperature control)

The optimum pH for a two-phase system has been widely quoted to be approximately 5 (Ghossh et al., 1975; Aivasidis et al., 1988; Speece, 1996). This implies that less buffering would be required in a baffled reactor since the pH is routinely above 6 in the first compartment. Alternatively, buffering and /or nutrients could be added separately in latter compartments to provide optimal conditions for scavenging methanogens.

2.10 RECOMMENDATIONS

The physical structure of the reactor allows various modifications to be made, such as an in situ aerobic polishing stage, resulting in providing the capability to treat wastewaters that currently require at least two separate units, therefore substantially reducing capital costs.

However, in order to enhance the commercial potential of the ABR, more work still remains to be done the following areas: modeling the fate of SMPs solids, intermediate products, and COD removal; nutrient requirements; treatment of toxic wastewaters (e.g. polychlorinated aliphatics , nitrated organics, xenobiotics, haloaromatics, surfactants) which have been treated with success anaerobically; and an improved understanding of the factor controlling bacterial ecology. Finally Table. 3 shows a list of recommendations based on this review of the literature.

S .No.	PARTICULARS	RECOMMENDATIONS
1	Start-up	Low initial loading rates will encourage granule/floc growth pluses of methane precursors (e.g. acetate) have been successfully used to encourage metahnogenic growth and dampen the effects of increases in loading rate. Start – up with long retention times reduces solids loss due to low up-flow velocities and, promotes higher methanogen populations in every compartment.
2	Recycle	Recycle is beneficial with respect to diluting toxicants in feed stream, increasing front pH and reducing production of foam and SMPs, but has several disadavantage.
3	Low strength wastewater	Low retention time enables batter mass transport due to improve hydraulic mixing and reduces biomass starvation in latter compartments. Methane production will originate from scavenging bacteria (Methanosaeta)
4	High strength wastewater	Long retention time will reduce solids washout caused by high gas production; otherwise reactor may be modified (by adding packing) to decrease biomass loss. Methane production will be mainly due to methanosarenia, and hydrogen scavenging methanogens.
5	High solids wastewater	A large front compartment has proved to be effective in treating wastewater with high solids content.
6	Temperature	Reducing temperature to 250C from 35 oC has no effect on easily degradable waste, further decrease in temperature are detrimental on reactor performance, this may be due to potential toxicity, nutrient bioavailability and slower kinetic rates, reactors started-up and kept at lower temperatures perform consistently well.

2.11 BIOLOGICAL TREATMENT PROCES

There are five major groups of biological processes used for wastewater treatment are; Aerobic processes, Anoxic processes, Anaerobic processes, Combined aerobic, Anoxic and Anaerobic processes, and pond processes. The individual processes are further subdivided, depending on whether treatment is accomplished in suspended-growth system or combinations thereof.

By controlling the environment of the microorganisms, the decomposition of wastes is speeded up. Regardless of the type of waste, the biological treatment processes consists of controlling the environment required for optmum growth of the micro-organisms involved.

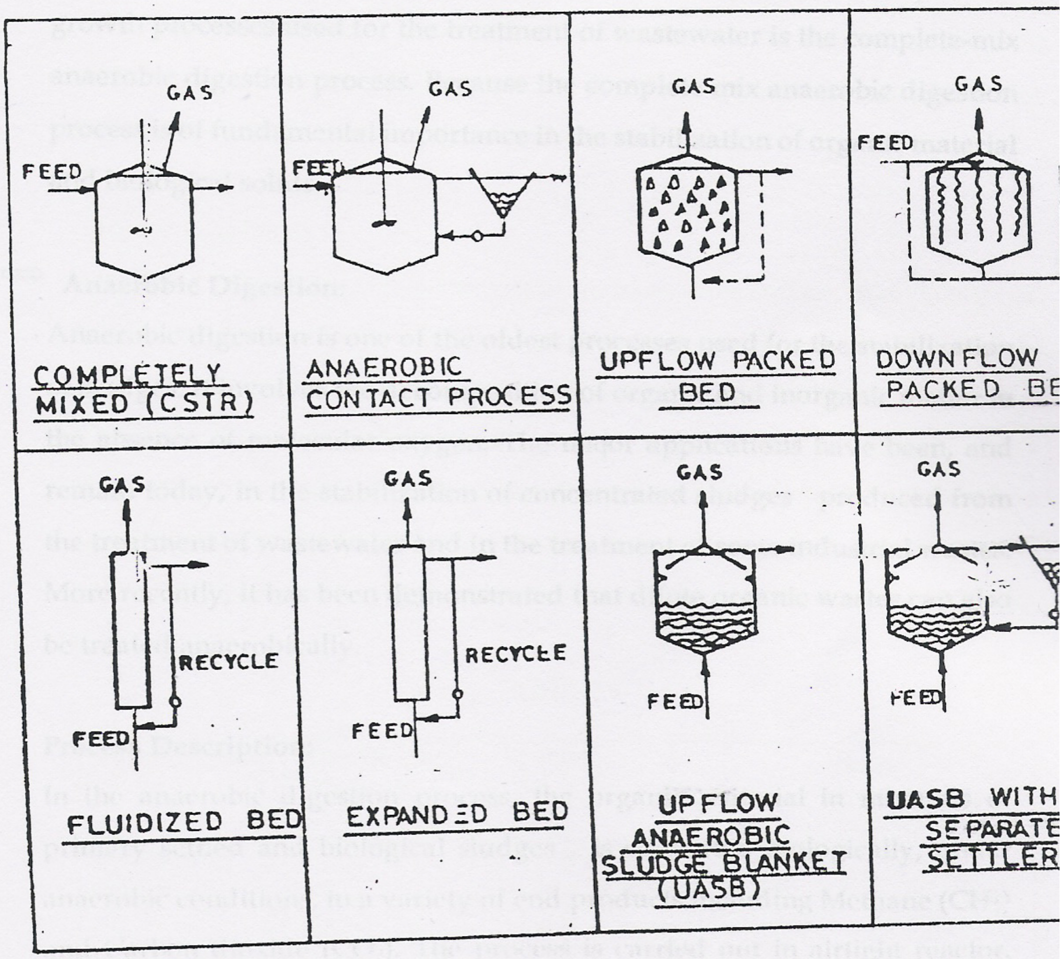
2.11.1 Application of biological treatment process

The principal application of these processes is for:

1. The removal of the carbonaceous organic matter in wastewater, usually measured as BOD, total organic carbon (TOC), or chemical oxygen demand (COD).
2. Nitrification
3. Denitrification
4. Phosphorus removal and
5. Waste stabilization.

2.12 ANAEROBIC SUSPENDED-GROWTH TREATMENT PROCESSES

In the past twenty years a number of different anaerobic processes have been developed for the treatment of sludges and high-strength organic wastes. The more common processes now in use are shown schematically in Fig. 2



Schematic Diagram of Anaerobic Treatment Process

Fig. 2

Of the processes shown in fig 2, the most common anaerobic suspended-growth processes used for the treatment of wastewater is the complete-mix anaerobic digestion process. Because the complete mix anaerobic digestion process is of fundamental importance in the stabilization of organic material and biological solids.

→ Anaerobic Digestion:

Anaerobic digestion is one of the oldest processes used for the stabilization of sludges. It involves the decomposition of organic and inorganic matter in the absence of molecular oxygen. The major applications have been, and remain today, in the stabilization of concentrated sludges produced from the treatment of wastewater and in the treatment of some industrial wastes. More recently, it has been demonstrated that dilute organic wastes can also be treated anaerobically.

Process Description:

In the anaerobic digestion process, the organic material in mixtures of primary settled and biological sludges is converted biologically, under anaerobic conditions, to a verity of end products including Methane ($CH4$) and carbon dioxide ($CO2$). The process is carried out in airtight reactor. Sludge, introduced continuously or intermittently, is retained in the reactor for varying period of time. The stabilized sludge, withdrawn continuously or intermittently from the reactor, is reduced in organic and pathogen content and is nonputrescible.

The two types of commonly used anaerobic digesters are identified as standard-rate digestion process, the contents of the digester are usually unheated and unmixed. Detention time for the standard rate process vary from 30 to 60 days. In a high rate digestion process the contents of the digester are heated and mixed completely. The required detention time for high-rate digestion is typically 15 days or less. A combination of these two basic processes is known as the "Two-stage process". The primary function of the second stage is to separate the digested solids from the supernatant liquor; however, additional digestion and gas production may occur.

Process Analysis:

The disadvantage and advantages of the anaerobic treatment of an organic waste, as compared to aerobic treatment, stem directly from the slow growth rate of the methanogenic bacteria. Slow growth rates requires a relatively long detention time in the digester for adequate waste stabilization to occur. However, the low growth yield signifies that only a small portion of the degradable organic waste is being synthesized into new cells. Typical kinetic co-efficients for anaerobic digestion are reported in Table 4.

Type of waste	Kinetic co-efficients	Basis	Value	
			Range	Typical
Domestic sludge	Y Kd	mgVSS/mgBOD5 d^{-1}	0.040-0.100 0.020-0.040	0.06 0.03
Fatty acids	Y Kd	d^{-1}	0.040-0.070 0.030-0.050	0.050 0.040
Carbohydrate	Y Kd	d^{-1}	0.020-0.040 0.025-0.035	0.024 0.03
Protein	Y Kd	d^{-1}	0.050-0.090 0.010-0.020	0.075 0.014

With the methanogenic bacteria, most of the organic waste is converted to methane gas, which is combustile and therefore a useful end product. If the sufficient quantities are produced, as is customary with municipal wastewater sludge, the methane can be used to operate dual-fuel engines to produce electricity and to provide building heat.

2.13 Anaerobic contact Process:

Some industrial wastes that are high in BOD can be stabilized very efficiently by anaerobic Treatment. In the anaerobic contact process, untreated waste are mixed with recycled sludge solids and then digested in a reactor sealed off from the entry of air. The contents of the digester are mixed completely. After digestion, the mixture is separated in a clarifier or vacuum floatation unit, and the supernatant is discharged as effluent, usually for further treatment. Settled anaerobic sludge is then recycled to seed the incoming wastewater. Because of the low synthesis rate of anaerobic microorganisms, the excess sludge that must be disposed of is minimal.

2.14 Up flow Anaerobic Sludge-Blanket process:

In the up flow anaerobic sludge blanket (UASB) process the waste to be treated is introduced in the bottom of the reactor. The wastewater flows upward through a sludge blanket composed of biologically fromed granules or particles. Treatment occurs as the wastewater comes in contact with the granules. The gases produced under anaerobic conditions (Principally methane and carbon dioxide) cause internal circulation, which helps in the formation and maintenance of the biological granules. The In the up flow anaerobic sludge blanket (UASB) process; the waste to be treated is introduced in the bottom of the reactor. The wastewater flows upward through a sludge blanket composed of biologically formed granules or particles. Treatment occurs as the wastewater come free gas and the particles with the attached gas rise to the top of the reactor. The particles that rise to surface strike the bottom of the degassing baffles, which causes the attached gas bubbles to be released. The degassed granules typically drop back to the surface of the sludge blanket. The free gas and the gas released from the granules are captured in the gas collection domes located in the top of reactor. Liquid containing some residual solids and biological granules passes into a settling chamber, where the residual solids are separated from the liquid. The separated solids fall back through the baffled system to the top of the sludge blanket. To keep the sludge blanket in suspension up flow velocities in the range of 0.6 to 0.9 m/hour have been used.

2.15 Anaerobic Attached-Growth Treatment Processes:

The two most common anaerobic attached –growth treatment processes are the anaerobic filter and the expanded –bed processes used for the treatment of carbonaceous organic wastes. Typical process loading and performance data for the anaerobic filter and expanded-bed processes are reported in table as under.

TABLE 5

Process	Input COD mg/1	Hydraulic detention time, h	Organic loading IbCOD/ft3d	COD remova1%
Anaerobic contact processes	1500-5,000	2-10	0.03-0.15	75-90
Up flow Anaerobie Sludge Blanket	5,000 15,000	4-12	0.25-0.75	75-85
Fixed Bed	10,000-20,000	24-48	0.06-0.30	75-85
Expanded-Bed	5,000-10,000	5-10	0.30-0.60	80-85

2.16 Anaerobic Filter Process:

The anaerobic filter is a column filled with various types of solid media used for the treatment of the carbonaceous organic matter in the waseewater. The waste flows upwards through the column, contacting the media on which anaerobic bacteria grow and are retained. Because the bacteria are retained on the media and wash off in the effluenc, mean cell-residence times on the order of 100 days can be obtained. Large values of he can be used for the treatment of low strength wastes at ambient temperature.

2.17 Expanded-Bed Procss:

In the expanded-bed process, the wastewater to be treated is pumped up ward through a bed of an appropriate medium (e.g. sand, coal, expanded aggregate) on which a biological growth has been developed. Effluent is recycled to dilute the incoming waste and to provide an adequate flow to maiatain the bed in an expanded condition. Biomass concentrations exceeding 15000 to 40000 mg/liters have been reported. Because a large biornass can be maintained, the expanded-bed process can also be used for the treatment of municipal wastewater at very short hydraulic retention times. When treading municipal wastewater, the presence of sulfate can lead to the formation of hydrogen sulfide. A numbers of methods have been proposed for the capture of the hydrogen sulfide in the solution phase. As the quantity of sludge produced in the expanded-bed process is considerably less than that produced in aerobic systems; such as the activated-sludge process, it is anticipated that greater use will be made of this and other attached-growth anaerobic processes for the treatment of municipal wastewater. The recovery of methane, a useable gas, is another important of the anaerobic processes.

Chapter 3

MATERIALS AND METHOD

MATERIALS

A PABR was constructed out of Perspex sheet with a total useful volume of 13 l. In order to determine the microbial growth under mesophilic conditions (35° C), a batch kinetic experiment was carried out in a Periodic Anaerobic Baffled Reactor (PABR). The reactor was inoculated with inoculums brought from the UASB treatment plant of Rail Vihar Rail Vihar, Ghaziabad, U.P. The inoculums kept in the reactor were 28.99 g/l (SS) and 12.16 g/l (VSS). Now the reactor run in the lab under mesophilic condition from feeding 0.5 g - COD / L to 2 g - COD / L. Feeding given to the PABR was consists of combination of glucose and milk powder. During this period of organic loading the PABR was run at constant HRT of 12 hrs, at step rise in organic loading from 0.5 g - COD / L to 2 g - COD / L, at a zero switching frequencies like ABR plug flow mode for the duration of 80 days. The reactor performance under plug flow conditions of zero switching frequencies i.e. ABR situation, the removal efficiencies in terms of COD was observed equal to 85.6%. While running of lab scale PABR under the ABR mode pH of the influent was maintained above 7 by adding sodium bicarbonate to the influent stream and temperature variation was observed between 30 to 35° C. At the end of the experimental run, growth in terms of VSS and SS was 14.72 g/l and 32.24 g/l respectively. The step increase in organic loading rate (OLR) is done when removal efficiency in terms of COD was observed above 80%. For example, 0.5 g - COD / L to 1 g - COD / L as a first step increase in OLR, Second step increase in OLR is from 1 g - COD / L to 1.5 g - COD / L and third step increase in terms of OLR is from 1.5 g - COD / L to 2 g - COD / L at constant HRT of 12 hrs. The net growth in terms of SS during the above mentioned step increase in organic loading rate (OLR) was 3.25 g/l and in terms of VSS was 2.56 g/l. Measurement included during the determination of microbial growth was effluent COD, pH, temperature and suspended solids and volatile suspended solids.

LAB. SCALE
PERIODIC ANAEROBIC BAFFLED REACTOR (PABR)

3.1.2 METHODS

Determination of effluent chemical oxygen demand was carried out as proposed by standard methods (1995). The Biogas production rate was measured by displacement of dilute sulphuric acid solution. Two communicating vessels, filled with a sodium hydroxide solution (40% w/w), were employed for the biogas composition measurement. The first vessel was open and the second was closed to the atmosphere. Gas sample of the specific volume were properly injected into the closed vessel. The Carbon dioxide was converted to sodium carbonate and the remaining methane gas caused to a rise to the liquid level of the open vessel. The biogas composition was proportional to this rise. Residence time distribution study was conducted by potassium permagnate and starch chemical concentration and found that no dead space in the compartment of the Periodic Anaerobic Baffled Reactor (PABR). The Volatile Fatty Acids (VFAs) measurement in done by adopting the following procedures. First sample of each compartment of the reactor is centrifuge for 10 minutes and then the sample is filtered using Watman filter paper. Compositions of VFAs are found from Gas Chromatograph by injecting 1µl sample. The detection of acids is done by running the Gas Chromatograph under FID mode (Flame Ionisation Detector). The sample is injected in Gas Chromatograph operation under Iso mode by setting the temperature of injector and detector port at 200° C and oven temperature at 190° C. Column used is DGES. The pH and temperature measurement is also done by standard instrument.

3.2 Simulation of PABR behaviour

For assessment of the PABR performance and stability characteristics, the mean rate organic matter (COD) removal as a function of the HRT for a given feed concentration. The optimum value for the HRT exists for every value of period. In addition, for small enough HRTs, the mean COD removal rate is greater the smaller the period of switching, whereas for large HRTs it is larger the greater the switching period. Finally the PABR tends to behave as a UASBR as the switching frequency become very high. The equivalent UASBR is then of equal volume to the total volume of the four individual compartments. The same exact behavior is predicted for the mean methane production rate whereas again for every value of the period there is an optimum HRT. Here also, for small value of HRT, the mean methane production rate is greater, the smaller the period of switching and exactly the reverse is true for large valued of HRT. Finally, these conclusion and general trends are valid regardless of the influent COD concentration

In order to access the relative merits of the PABR when it comes to stability, the following simulation were undertaken. When a PABR is operated without switching of the feeding point (namely as an ABR), it fails when a step increase in HRT from 10 to 2 days is imposed, due to methanogen washout (Skiadas and Lyberatos *et al.,* 2000). The PABR, however, when operated with periodic switching of feeding point (T = 1 day), approaches an SPS when exposed to same step change. Thus, it is possible to maintain a continued operation in spite of the large drop of the HRT. When the same PABR is exposed to the reverse step change in the HRT after 100 days operation at two days HRT (before the methanogens have completely washed out), it returns back to the initial steady state. This reversion is more efficient if the PABR is operated with periodic switching of feeding point. In the case of zero switching frequency, the methanogens have almost completely washed out from the first three compartments and they need more time to recover. On the contrary, the response of the PABR at SPS, which is exposed to the same step increase of the HRT, is more efficient if it simultaneously will start, to be operated without switching of the feeding point. There will be enough time for bacteria to remove more organic content from the first three compartments.

The predictions of the performance of the PABR in SPS, as well as for the reactor response in a step change of the HRT, are qualitatively similar to those using Smith's model (Skiadas and Lyberatos, 1998). This proves that the predictions for the behavior of the PABR are not sensitive to the particular model structure, at least qualitatively. Given that a series of several CSTRs provides greater substrate conversion than a CSTR of equal volume for reactions with Monod kinetics (Bailey and Ollis, 1986), the compartmentalised structure of the PABR gives the possibility of optimizing the COD removal rate as a function of the OLR by the manipulation of the switching frequency. When the resulted biomass dilution rate is smaller than the maximum biomass growth rate in each of the four PABR compartments, the COD removal is higher at a PABR operated at zero frequency of switching of the feed point (as a ABR). In contrast, when the biomass dilution rate is relatively high but not higher than the overall biomass production rate, the COD removal is higher at a PABR operated at high frequency of switching the feed point (as an UASBR). For every intermediate value of the Organic Loading Rate (OLR) there is a value of the switching frequency (between zero and infinite) for which the COD removal rate is maximized.

In conclusion, simulation has predicts that for large values of organic loading, the PABR is expected to perform better when operated at a high frequency of switching feed point, namely it behaves as a UASBR, whereas for smaller values of the organic loading PABR should be operated at smaller frequencies approaching that of a simple ABR. In short, one can see that depending on the loading rate, which in principle may be variable, it is possible that the switching frequency should be manipulated accordingly.

In order to access the relative merits of the PABR when its comes to the stability, the following simulation were undertaken. When a PABR is operated without switching of the feeding point (namely as simple ABR), it fails when a step change in the HRT (e.g. a four time decrease) is imposed.

The PABR, however, when operated with e.g. a switching frequency of four days, it approaches a stable periodic state (SPS) when exposed to the same step change. Thus it is possible that a continued operation may be maintained in spite of the small value of the HRT.

In addition to the switching frequency, one must decide the exact manner of switching the feed point and effluent compartments (clockwise, counter clockwise, every second or sequentially etc.). For a four compartment PABR, there are three options (when viewed for the top): "clockwise sequential", " counter clockwise sequential" and "every second". The "counter clockwise sequential" switching manner is not viable because the feeding compartment is switched to the effluent compartment, whenever a switching is taking place. The "every second" option seems to lead to a slightly higher performance and less fluctuation of the effluent concentration when compared with the "clockwise sequential".

Chapter 4

4.1 RESULTS AND DISCUSSIONS

4..2 Experimental Run of Lab-Scale PABR

In the Lab Scale PABR, previously the PABR run from 0.5 g – COD/L to 2 g – COD / L organic loading at HRT of 12 hrs for a period of 18 days under ABR mode and achievement of the removal efficiencies in terms of COD was 85.6 %

The Reactor was again feed up with the previously developed inoculums in the PABR with 16.3 g/1(SS) and 5.868 g/1(VSS). Now the reactor was initially run under ABR mode for a period of 7 days at HART of 12 hrs and organic loading rate of 1g-COD /L to allow the Periodic Anaerobic Baffled Reactor (PABR) to achieve its own stability as Anaerobic Baffled Reactor (ABR). During this experimental run, the PABR achieved the removal efficiency of 65.9% in terms of COD. Now the PABR are run at different switching frequencies of 2 days, 3 days and 4 days to achieve stable periodic state (SPS) under the different switching frequencies, n counter clockwise direction to see the performance of the PABR.

During the Stable Periodic State (SPS) at different switching frequencies the observations taken are, effluent COD, VFAs in each compartment, Biogas production in each compartment and pH are kept above 7 by adding sodium bicarbonate in the influent stream.

4.3 Experimental Verifications

1. Selecting Chamber at switching periods of 2 days.

In the experimental run of the Periodic Anaerobic Baffled reactor (PABR) at organic loading rate of 0.5g –COD/L at HRT of 12 hrs. Where the compartment "a" of the PABR is influent compartment and switching frequency of 2 days. During the two days of switching periods the following observations are made in terms of Effluent COD, Volatile Fatty Acids (VFAs) and Gas production in each compartments of the PABR.

Observation in COD removea1 When the compartment "A" of the PABR as Inffluent compartment

After selecting the compartments "A" of the PABR as a feeding compartment for HRT of 12 hrs, the effluent COD is achieved stable periodic state after running of PABR for 27hrs as seen from fig (3). From the literature of Skiadas and Lyberates et al., 2000, it can concluded that if the switching frequency is set to higher than the removal of COD can achieve earlier because of higher dilution of biomass to form the granules than the slower biomass production.

CALCULATION OF EFFLUENT COD WHEN CHAMBER A OF PABR SELECTED AS INFLUENT CHAMBER @ 0.5g-COD/L FOR HRT=12h

TIME in Hours	EFFLUENT COD in mg/l
0	480
6	368
24	360
27	330
30	352

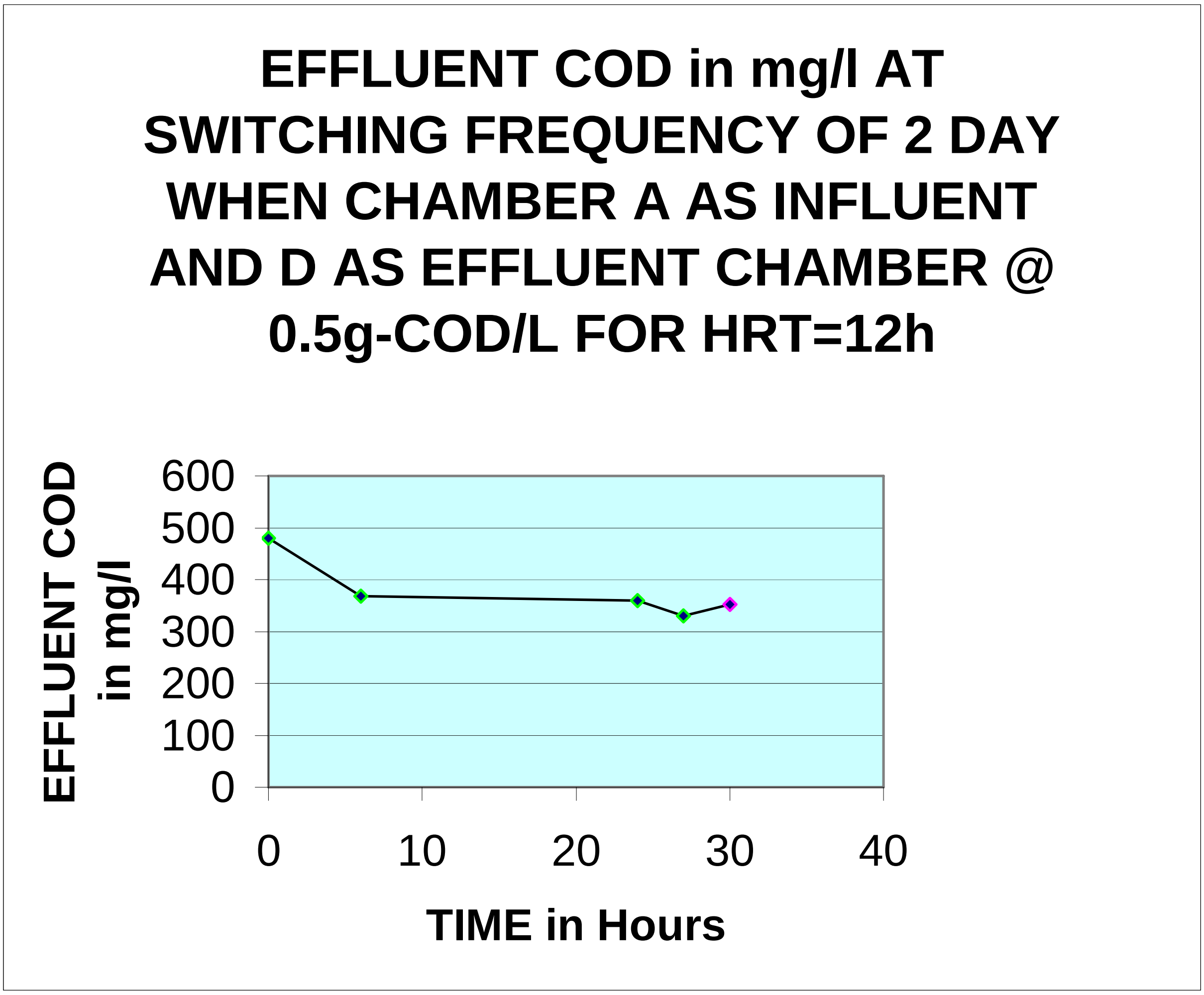


Fig .3

Volatile Fatty Acids Observation

The anaerobic digestion of glucose and milk powder to methane and carbon dioxide passes through the production of lactic, acetic and propionc acid. The concentration of other VFAs such as butyrate and isobutyrate are negligible. The conversion of glucose to biogas is completed according to stoichiometric reactions. It is assumed that the anaerobic biodegradation of glucose is completed in five steps. In the first step, the acidogenic bacteria consume glucose and produce lactic acid, as well as an unknown intermediate (final and/or intracellular) product. Subsequently, different groups of acidogenic bacteria convert lactate and intermediate products (IP) to a mixture of acetate and propionate. The propionate is converted by the acetogenic bacteria to acetate and finally the methanogens, produce CH4 and CO2 using acetate as a substrate.

VFAs Observations in Compartment “A”

In the initial period , there is drastic change in production of Volatile fatty acids (VFAs) as seen from Fig. 4 (a). In the compartment first there is decrease in the production of acetic acids. Simultaneously there is increase in propionic acids and less or insignificant production of isobutyric acids. It can be concluded from Fig 4(a) that compartment is not in stable periodic state (SPS) and achieved its stable periodic state at the end of the switching periods. This conclusion also supported from the plot of Biogas production rate of the compartment “A” that the acetate are converted to methanogens.

VOLATILE FATTY ACIDS CALCULATION IN mg/l

Time in Hours	VOLATILE FATTY ACIDS in mg/l IN CHAMBER A		
	ACETIC ACIDS	PROPIONIC ACIDS	ISOBUTYRIC ACIDS
24	351.6	0	0
27	140.2	249.1	25.3
30	0	267.7	0

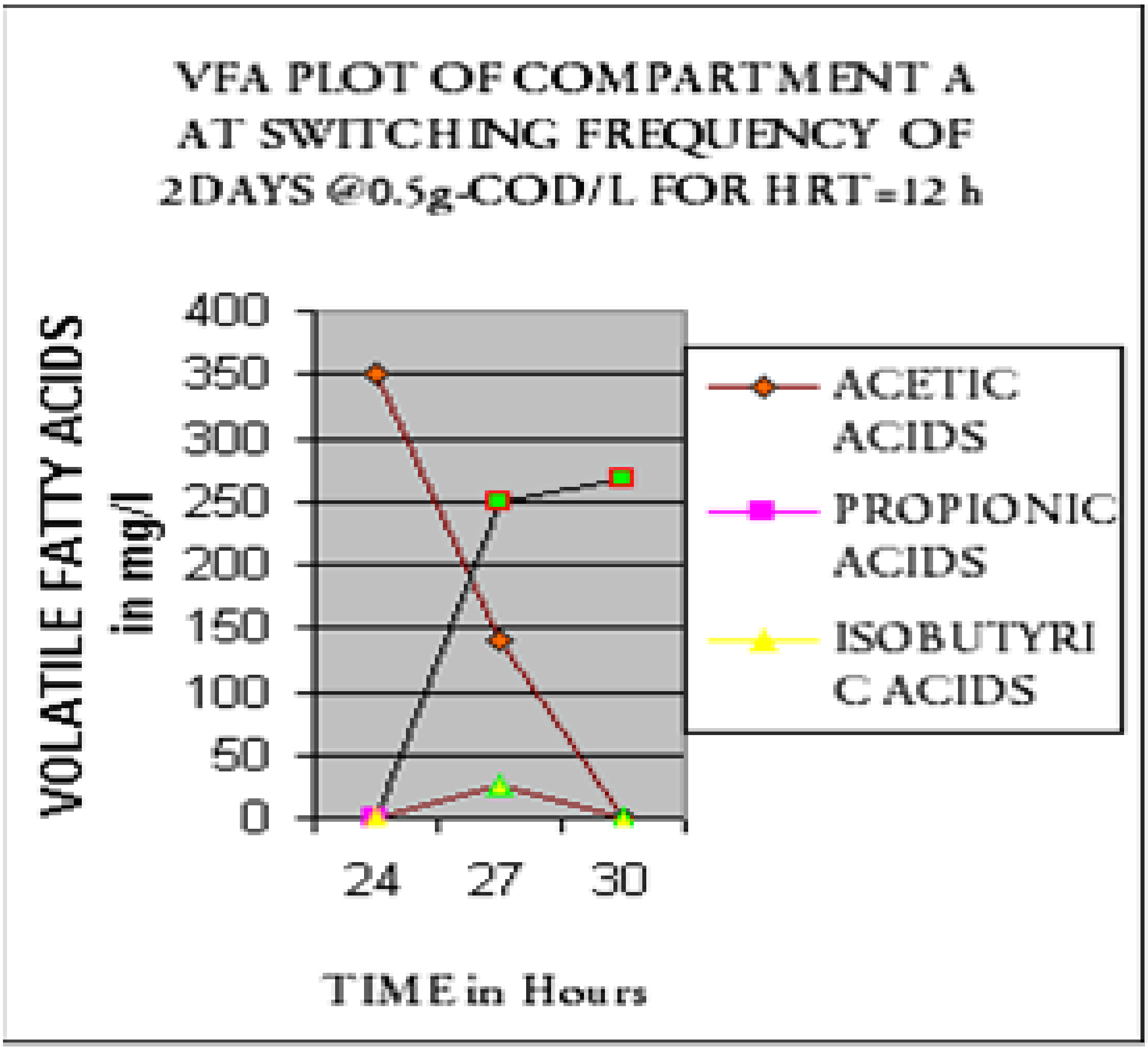


Fig. 4(a)

VFAs observations in compartment “B”

From the Fig. 4(b), it can be seen that the compartment “B” achieves its stable periodic state after 27 hrs. In the initial period, there is gradual decrease in acetic and propionic acids. But butyric and isobutyric acids are very small in amount which is reduced to zero after 27 hrs. The propionic acid is more than the acetic acids due to slow rate of conversion of propionic acids into acetate and subsequent conversion of acetate into methanogens. While comparing the plot of VFAs production in terms of acetic acids compartment “B” shows better growth than compartment “A”. Which is vary between 140 mg/l to 120 mg/l. Where as, propionic acids which is in compartment “A” produce more than 267 mg/l is gone to reduce up to 230mg/l. This observation is also supported from Biogas production plot of the compartment “B” by more improvement in the production of methanogens than the compartment “A”.

VOLATILE FATTY ACIDS CALCULATION IN mg/l

Time in Hours	VOLATILE FATTY ACIDS in mg/l IN CHAMBER A		
	ACETIC ACIDS	PROPIONIC ACIDS	ISOBUTYRIC ACIDS
24	141.3	234.6	17.9
27	127.3	181.3	0
30	123.7	231	0

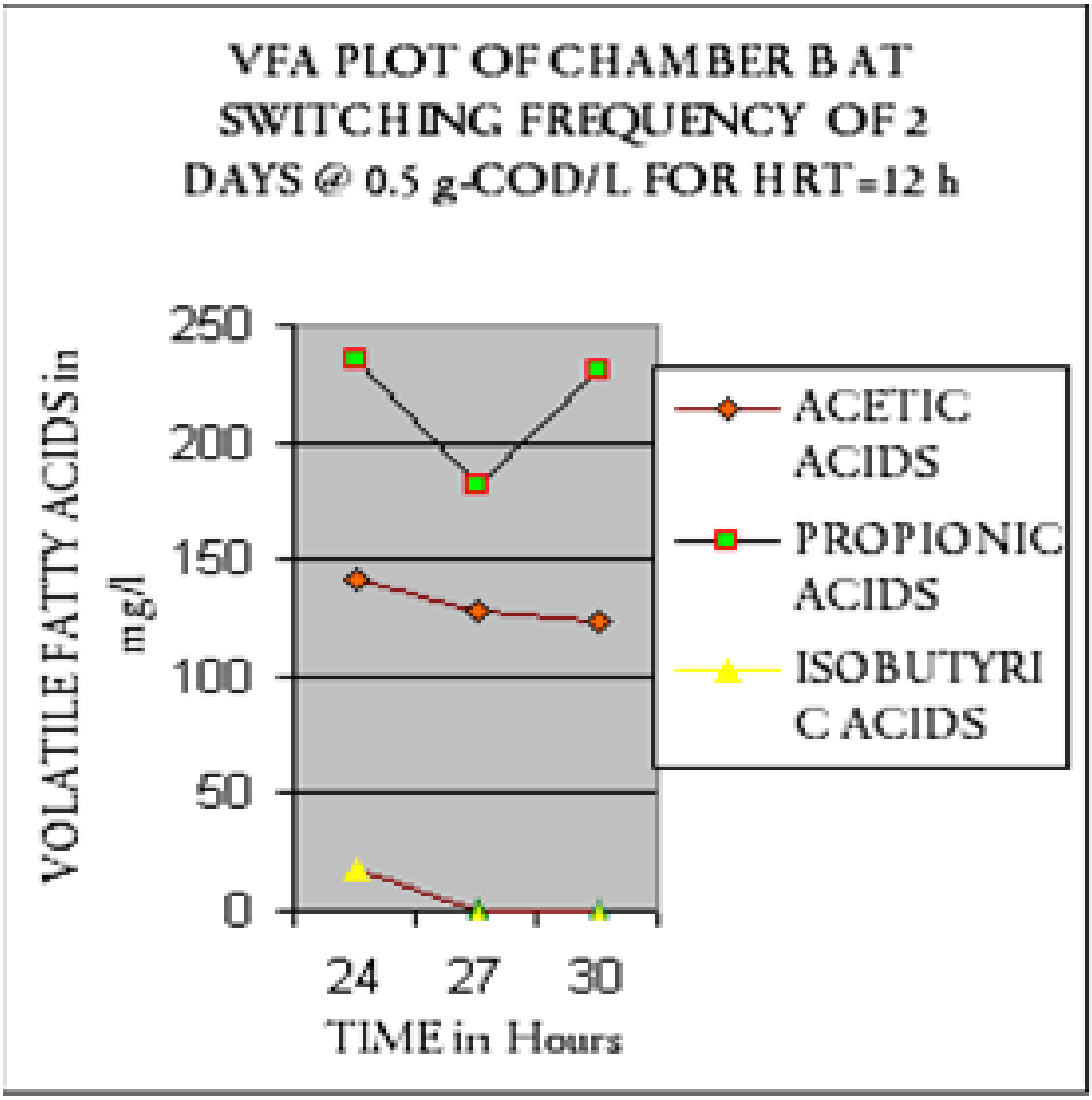


Fig. 4(b)

VFAs observation in compartment “C” (Fig 4 c)

In the initial period, there is slight increase in the propionic acids upto 260 mg/l from 228 mg/l and subsequently decrease from 260mg/l to 200 mg/l. Acetic acids gradually decreases from 190 mg/l to 135 mg/l. That results in percentage methane yield more by conversion of acetate to methanogens. While the isobutyric acids in the initial period is higher which decrease to zero after 27 hrs. Whereas butyric acids are insignificant (5 mg/l) in the initial periods going to decrease to zero after 27 hrs. It can be concluded that compartment “C” achieve its stable periodic state after 27 hrs.

VOLATILE FATTY ACIDS CALCULATION IN mg/l

Time in Hours	VOLATILE FATTY ACIDS in mg/l IN CHAMBER A			
	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
24	191.7	228.3	4.9	78
27	157.3	261.1	0	0
30	136.7	204.4	0	0

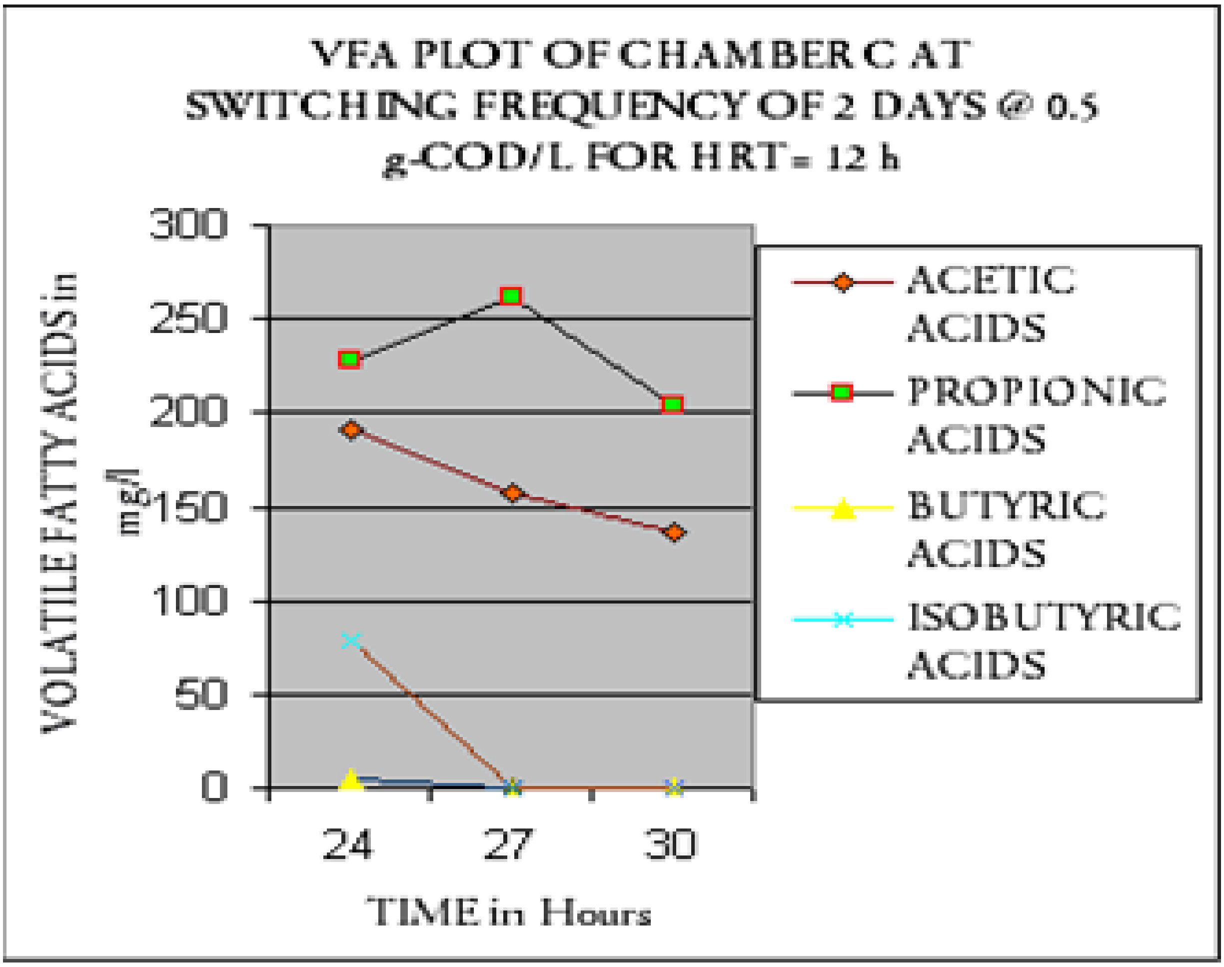


Fig. 4©

VFAs observation in compartment "D"

In compartment "D", there is the major decrease in the volatile fatty acids upto 100 mg/l from the initial periods to 27 hrs of run of reactor at switching frequency of 2 days. Due to the conversion of volatile fatty acids into acetate and from acetate to methanogens, results in 96% of methane yield which is seen from Fig. 4(d) and Fig. 6(d). Suggesting that the compartment "D" achieve its stable periodic state (SPS) after 27 hrs.

VOLATILE FATTY ACIDS CALCULATION IN mg/l

Time in Hours	VOLATILE FATTY ACIDS in mg/l IN CHAMBER A			
	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
24	233.8	312.4	116.9	104.1
27	130.1	228.2	0	0
30	124	204.4	0	0

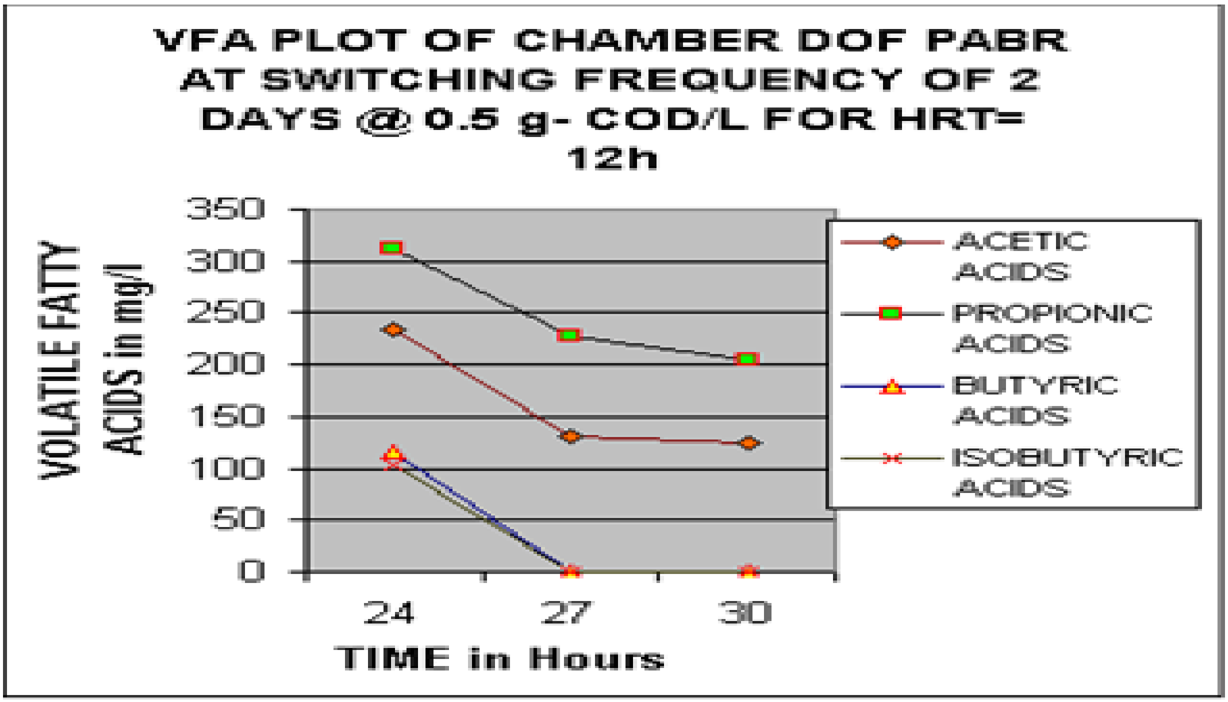


Fig. 4(d)

Biogas generation at switching frequency of 2 days while selecting the chamber "A" of the PABR as Influent, at HRT of 12 hrs

Gas production Observation in compartment "A"

In compartment "A" gas production rate is decrease initially and than increase after 6hrs of the running of experiment at switching frequency of 2 days. Whereas the methane yields is less than 88%. The reason behind this is that due to the drastic behavior of compartment "A" in the production in VFAs and their subsequent conversion into methanogens. Which can be observed from Fig. 5(a) and Fig. 6(a).

GAS MEASUREMENT IN CHAMBER A OF PABR AT SWITCHING FREQUENCY OF 2 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
0	0.011256	0.010104	0.001152
6	0.00869	0.00804	0.000648
24	0.01152	0.01008	0.00144

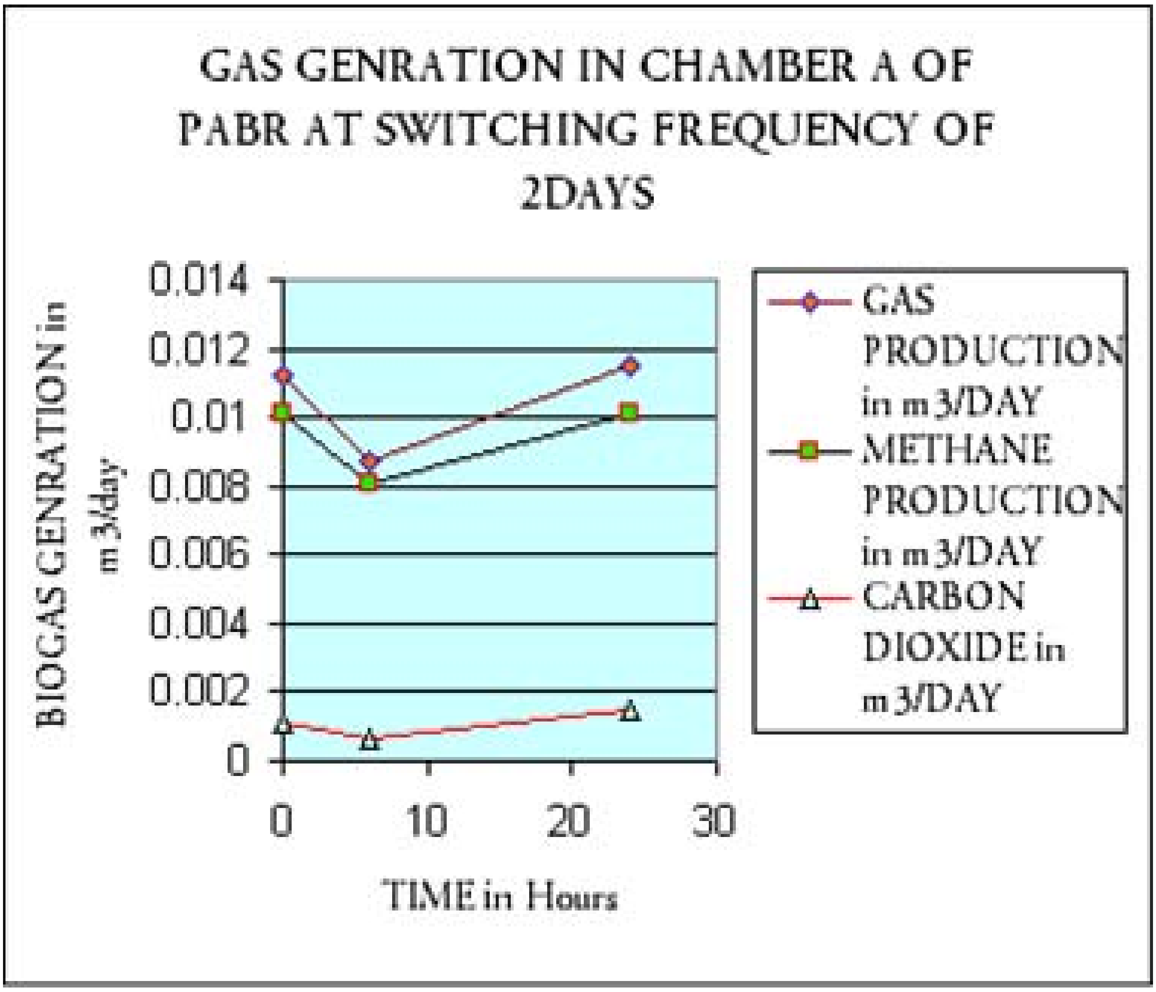


Fig.5 (a)

PLOT FOR PERCNTAGE METHANE YIELD AT SWITCHING FREQUENCY OF 2 DAYS

WHEN A AS INFLUENT CHAMBER @ 0.5g-COD/L METHANE YIELD IN CHAMBER A OF PABR	
TIME in HOURS	% CH4 YIELD
0	89.8
6	92.52
24	87.5

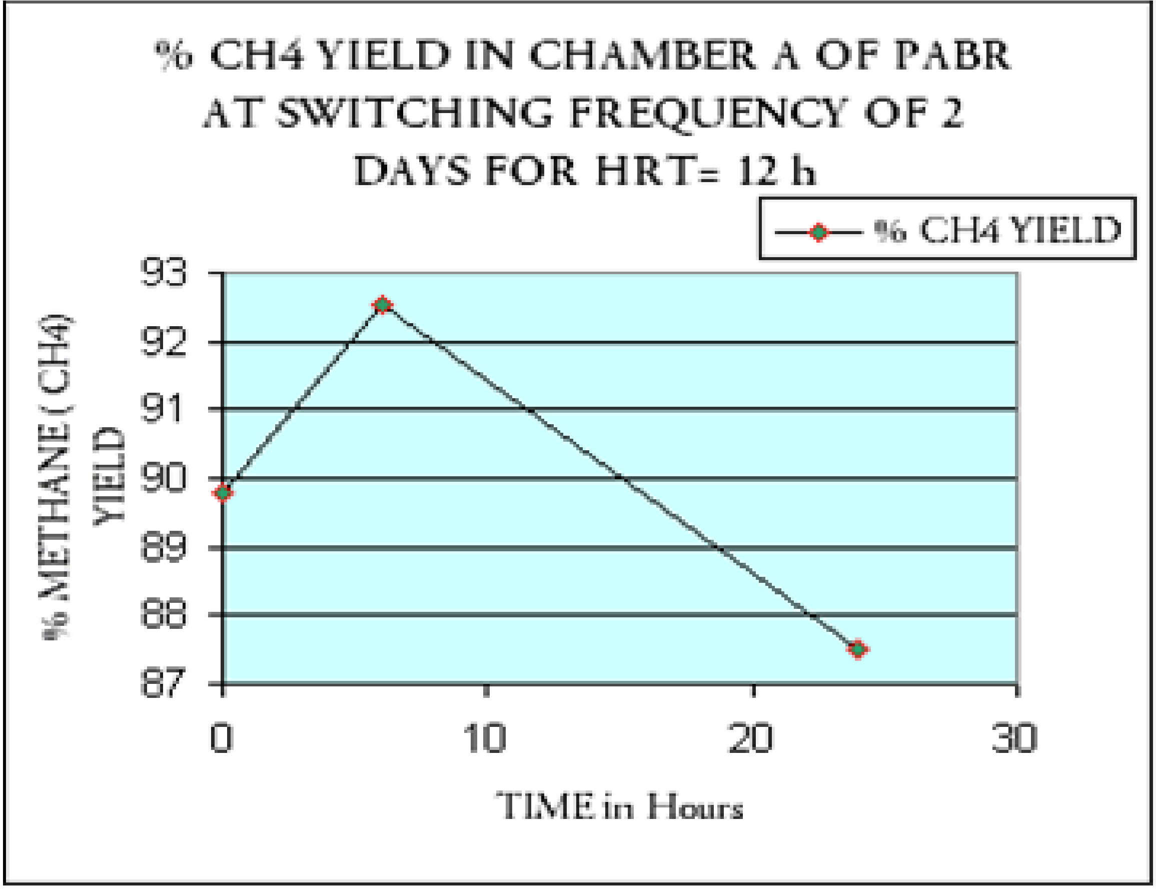


Fig. 6 (a)

Gas production Observation in compartment “B”

In compartment “B”, gas production rate (0.021 m3/day) is higher than compartment “A”. Because of washout of methanogens from the compartment “A” and subsequent accumulation in compartment “B”. It can be seen from Fig 5(a) and Fig 5 (b) i.e. the increase in gas production rate. Also the percentage methane yield is more than 96% from Fig. 6(b).

GAS MEASUREMENT IN CHAMBER B OF PABR AT SWITCHING FREQUENCY OF 2 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
0	0.02083	0.019824	0.001006
6	0.019608	0.01896	0.000648
24	0.01716	0.01656	0.0006

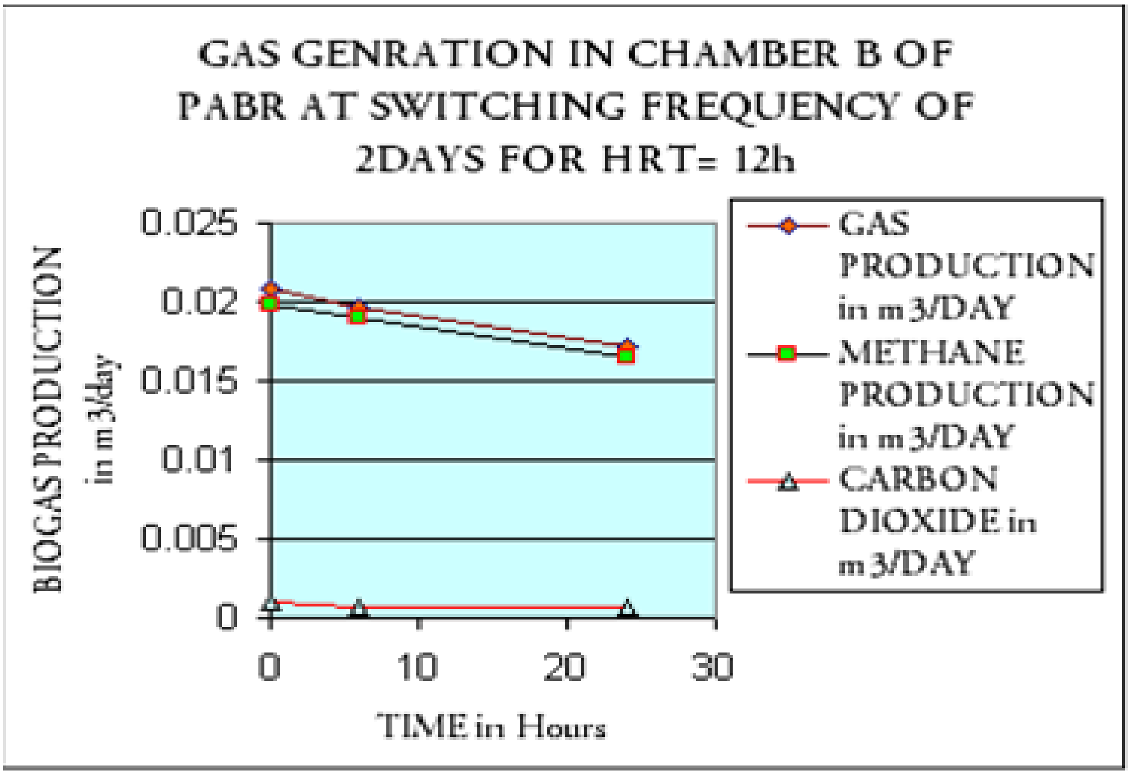


Fig. 5(b)

METANE YIELD IN CHAMBER B OF PABR

TIME in HOURS	% CH4 YIELD
0	95.2
6	96.7
24	96.5

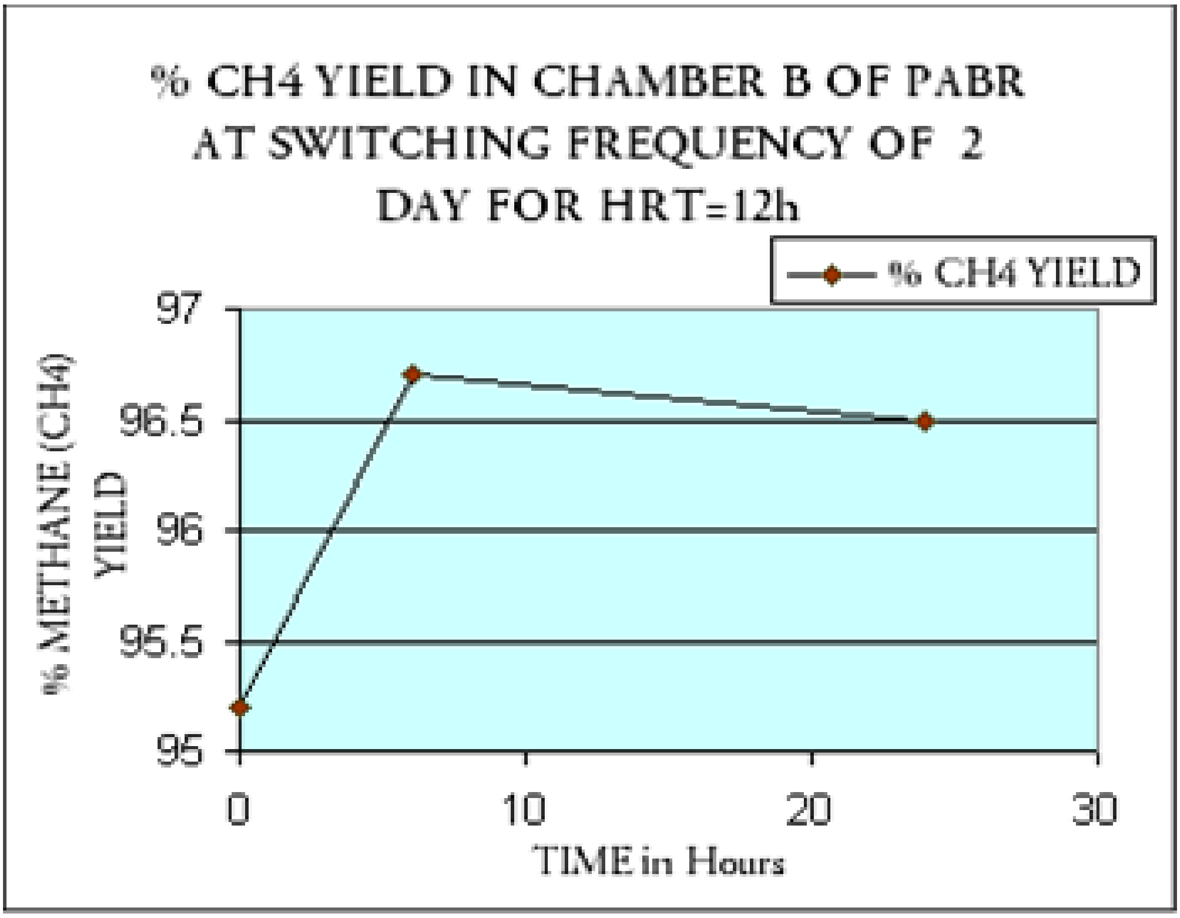


Fig. 6(b)

Gas production observation in compartment "C"

In compartment "C", gas production rate is less than the compartment "B" i.e. 0.015 m3/day which is initially decreases but acquire the same value after 24 hrs of running the PABR as seen from Fig 6©. Due to achievement of stable periodic state and development of methanogens culture in compartment "C".

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 2 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
0	0.014928	0.013248	0.0015
6	0.011232	0.009024	0.002208
24	0.01481	0.01337	0.00144

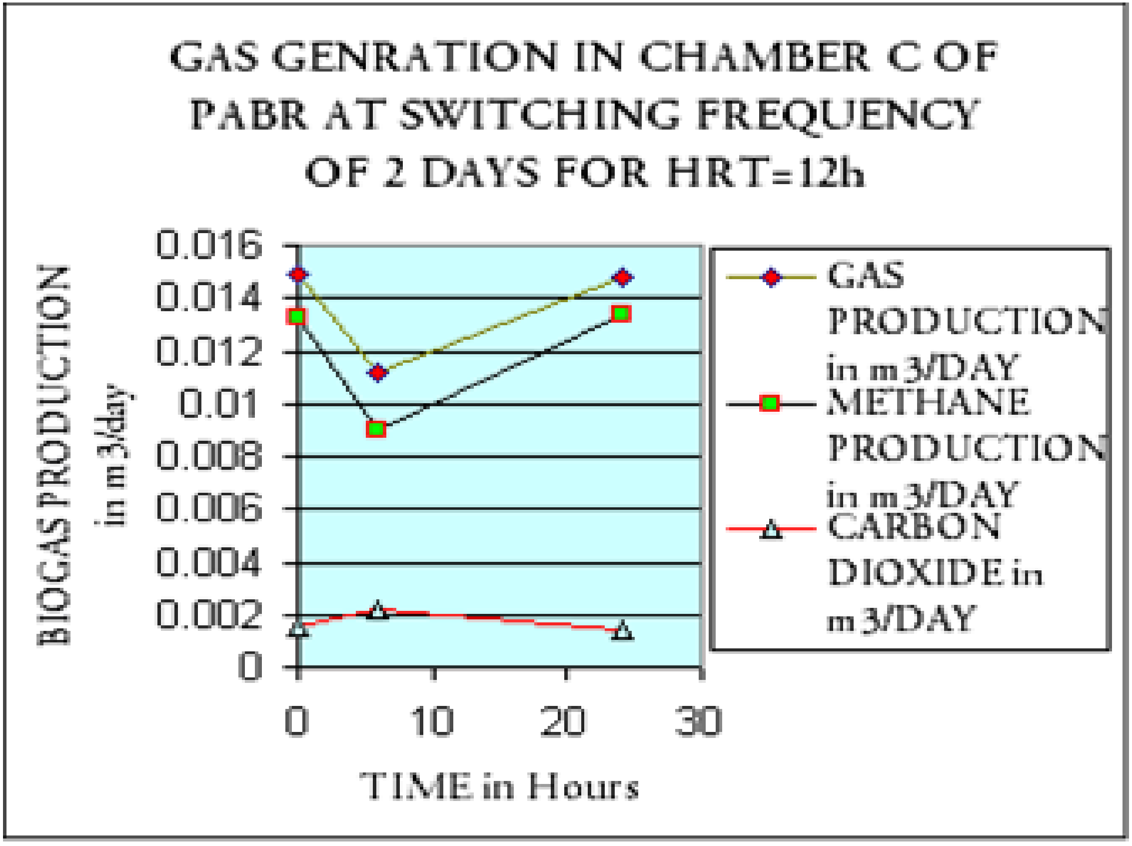


Fig. 5©

METANE YIELD IN CHAMBER C OF PABR

TIME in HOURS	% CH4 YIELD
0	88.74
6	80.34
24	90.3

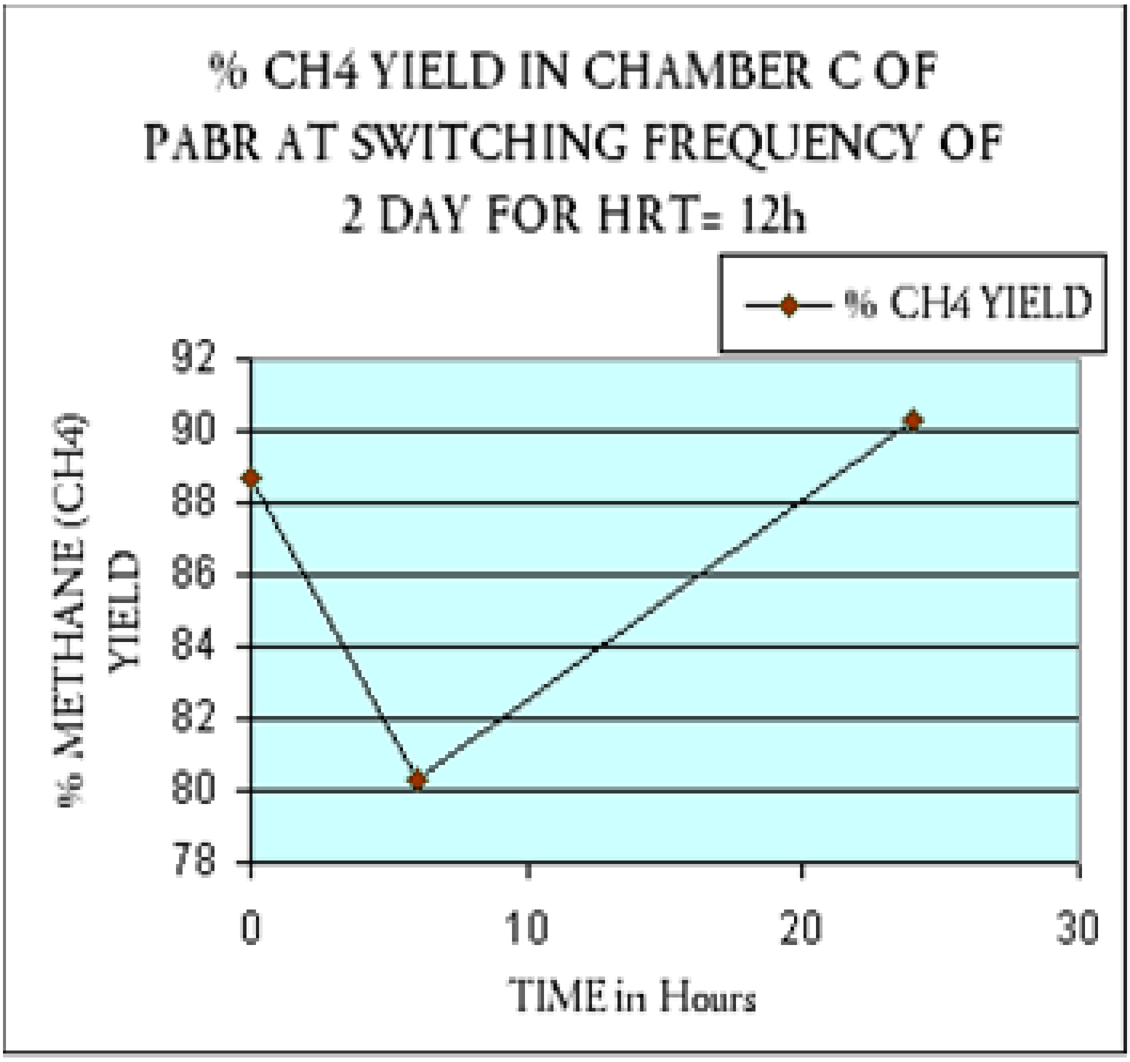


Fig. 6©

Gas production observation in compartment "D"

In compartment "D", there is more or less same gas production rate above 0.01m3/day as seen from Fig. 5(d). Also the percentage methane yields is more than 96% due to the fully developed methanogens culture in the compartment"D" as seen from Fig. 6(d). Whereas there is less gas production rate, the reason behind this is that washout of the gas to the effluent.

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 2 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
0	0.010872	0.010128	0.000744
6	0.01008	0.0096	0.00048
24	0.0108	0.01032	0.00048

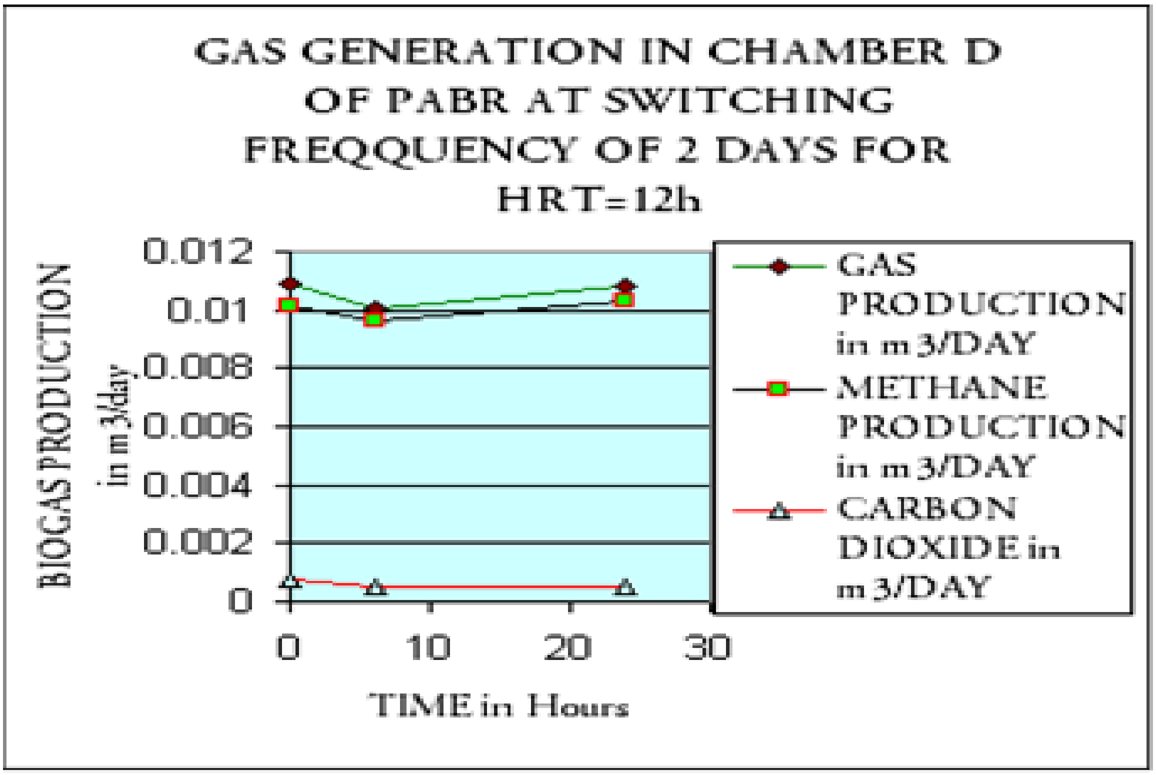


Fig. 5(d)

METANE YIELD IN CHAMBER C OF PABR

TIME in HOURS	% CH4 YIELD
0	88.74
6	80.34
24	90.3

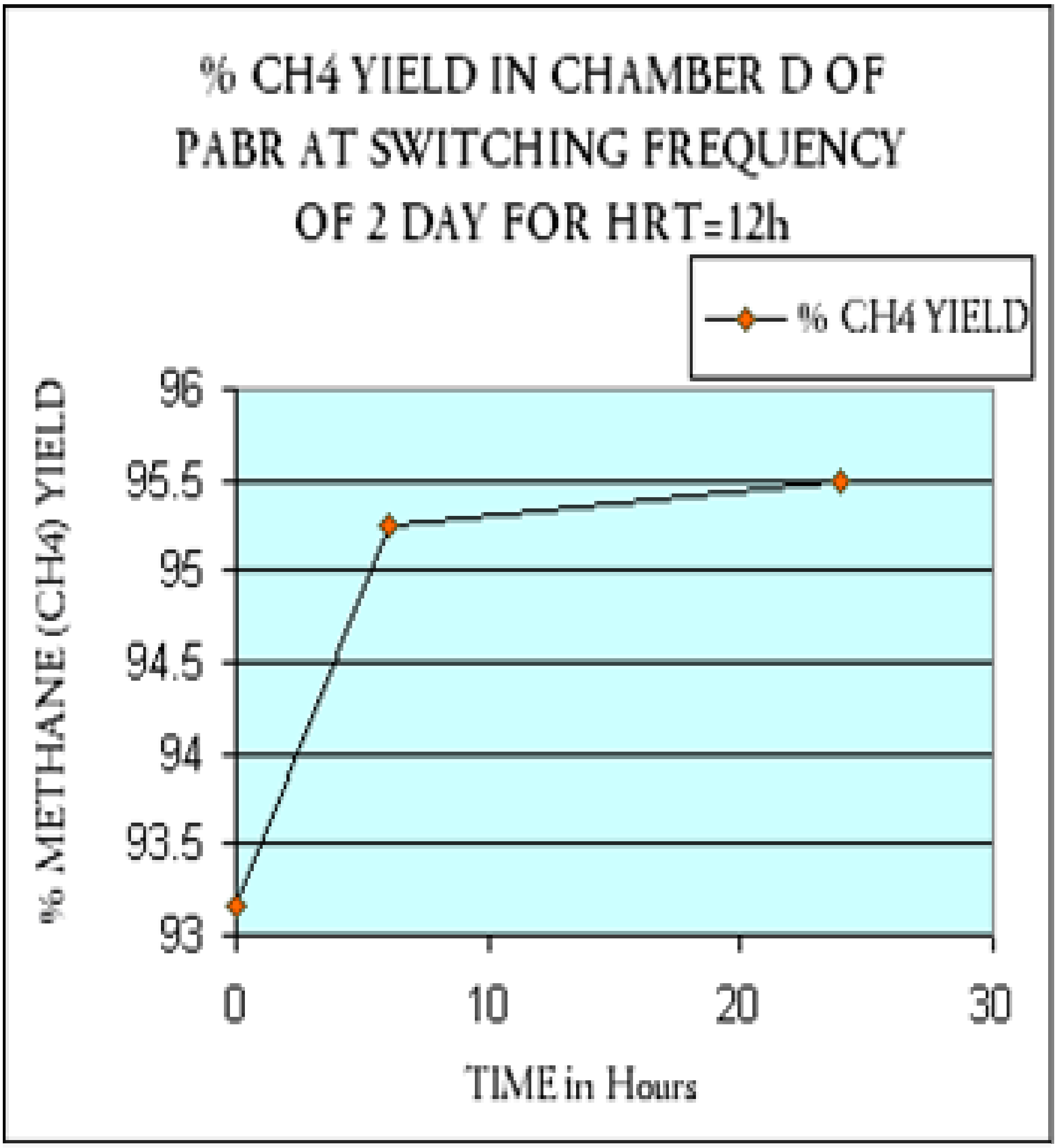


Fig. 6(d)

CONCLUSIONS at the switching frequency of 2 days.

While selecting the switching point in counter clockwise direction, the feeding chamber becomes the effluent chamber. But it stabilizes after 27 hrs of running the PABR at switching frequency of 2 days. Also from Fig 5(b) and 5(d) it can be concluded that there is better methanogenic culture developed in every second compartment. So that if every second compartment of the four compartment PABR selected as feeding compartment than the performance will better than the counter clockwise or clockwise sequentially switching frequency.

2. Selecting chamber "B" of the PABR as influent chamber at switching frequency of 3 days and HRT of 12 hrs:

⟶ Effluent chemical oxygen demand (COD) at switching frequency of 3 days

From the Fig. 7 it can be seen that the PABR is achieved the stable periodic state, after selecting the chamber "B" as feeding chamber for running the PABR after 42 hrs. In the initial periods, there is more effluent COD due to the selection of compartment "A" as effluent chamber which was earlier feeding chamber. While running the PABR at subsequent switching frequency, there is less effluent COD and result in higher stability due to subsequent accumulation of methanogens in compartment "A" from the previous feeding chamber.

OBSERVATION OF EFFLUENT COD AT SWITCHING FREQUENCY OF THREE DAYS SELECTING COMPARTMENT "B" AS INFLUENT COMPARTMENT IN COUNTER CLOCKWISE DIRECTION UNDER STABLE PERIODIC STATE

TIME in Hours	EFFLUENT COD in mg/l
15	368
19	360
38	352
40	336
42	192
62	368
65	272

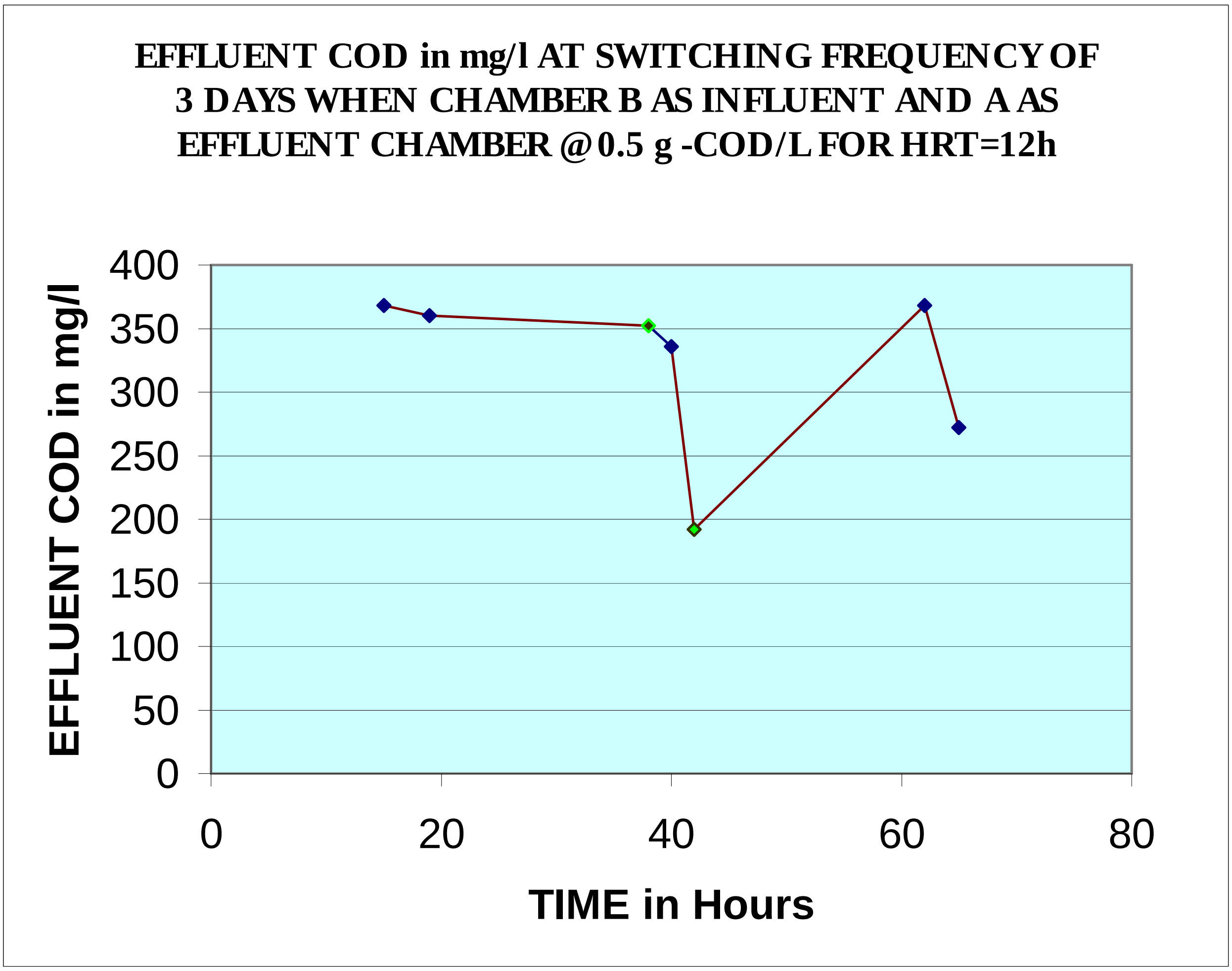


Fig. 7

Volatile fatty acids (VFAs) observation at switching frequency of 3days

VFAs Observations in Compartment “B” (Influent compartment)

From Fig 8(a), it can be seen that waves of the both propionic and acetic acids is going to suppressed after 42 hrs of running the PABR at 0.5 g-COD/l, at the HRT of 12 hrs, at switching frequency of 3 days. There is variation propionic acids about 70 mg/l and acetic acids of about 100 mg/l. In the initial periods there is insignificants amount of isobutyric acids that is reduces to zero after 19 hrs of running the reactor. Here it can be also concluded that the reactor is in better stable periodic state (SPS) at 3 days switching frequency, which is earlier subjected to 2 days switching frequency.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SPS= 3DAYS AND CHAMBER B AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER B OF PABR				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
15	157.3	237.8	0	15
19	133.6	190.2	0	0
38	86.1	209.6	0	0
40	85.4	238.1	0	0
42	58.7	199.4	0	0
62	103.2	213.9	0	0
65	100.9	169.7	0	0

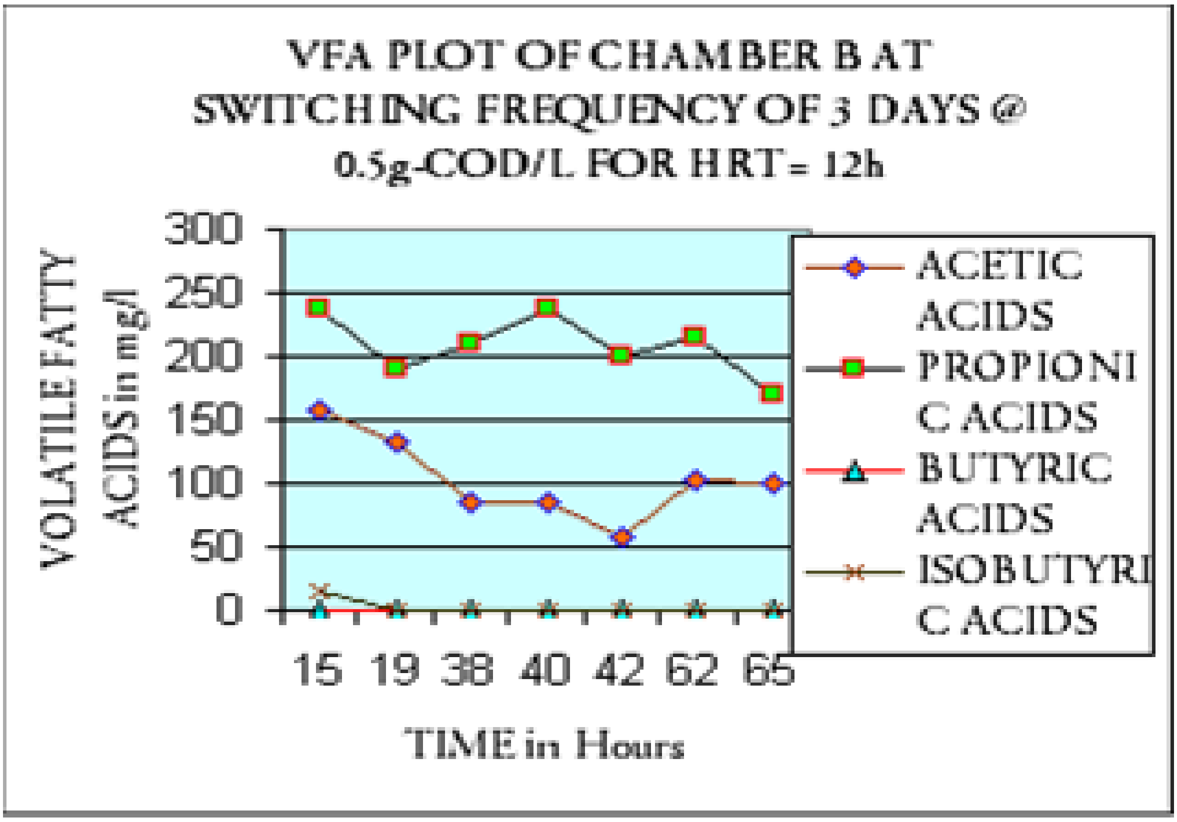


Fig. 8(a)

VFAs Observations in Compartment “C”

From Fig. 8(b), the variation in propionic acids (i.e. from 277 mg/l to 208 mg/l) about 70 mg/l observed. Whereas variations of acetic acids were 50 mg/l, which show that, there is development of acetogens. But the butyric and isobutyric acids throughout the run are zero. After the 42 hrs of run at switching frequency of 3 days the reactor achieve its stable periodic state (SPS). The major change was predicted (no production) interms of butyric and isobutyric acids at switching frequency of 3 days comparative to switching frequency of 2 days.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 3DAYS AND CHAMBER B AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER B OF PABR CHMBER C				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
15	130.3	276.8	0	0
19	123.5	275.3	0	0
38	98	189.6	0	0
40	101.2	264.5	0	0
42	80.1	196.2	0	0
62	90	210.6	0	0
65	96	208.2	0	0

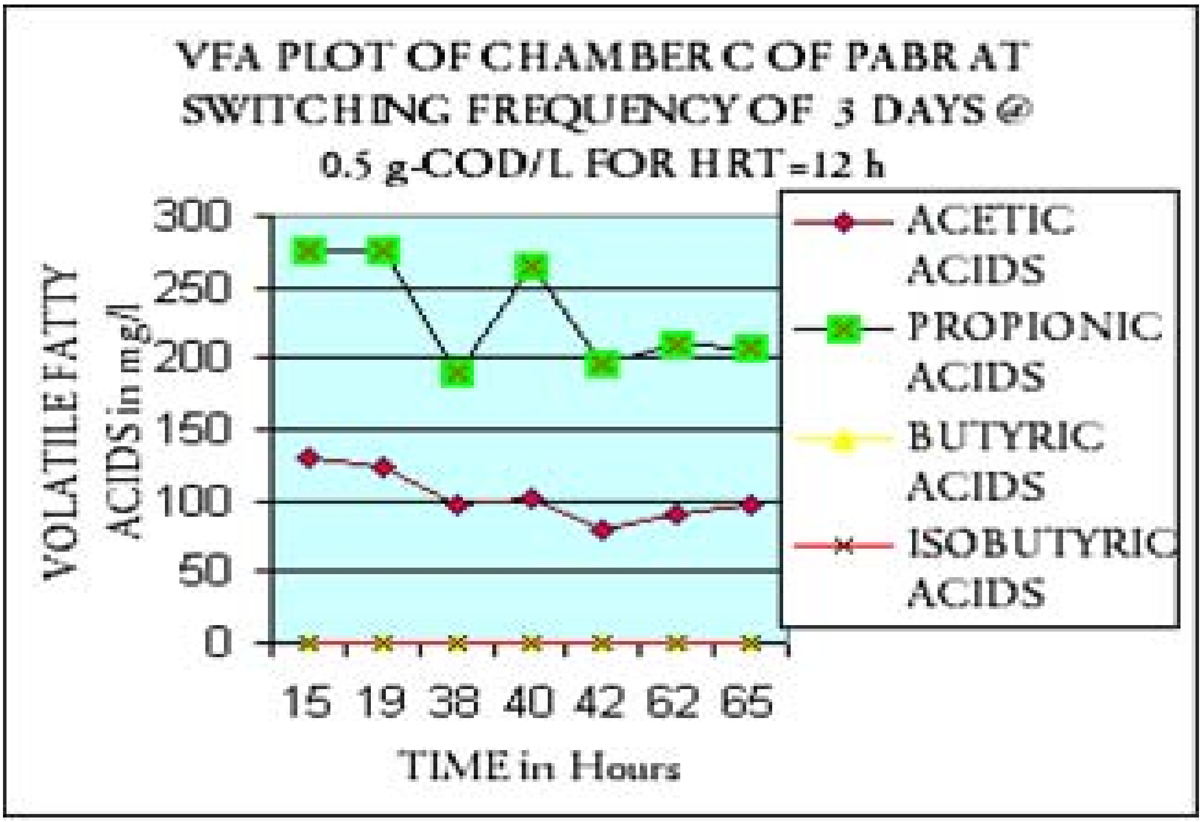


Fig. 8(b)

VFAs Observations in Compartment “D”

From Fig. 8(c), it can be seen that there is more conversion of acetic acids and propionic acids into acetate about 50 mg/l and 150 mg/l in compartment “D”. Whereas variations of acetic acids were 50 mg/l, which show that, there is development of acetogens. But the butyric and isobutyric acids throughout the run are zero. After the 42 hrs of run at switching frequency of 3 days the reactor achieve its stable periodic state (SPS). The major change was predicted (no production) interms of butyric and isobutyric acids at switching frequency of 3 days comparative to switching frequency of 2 days. Which is the effluent compartment at switching frequency of 2 days. It also results in development of good methanogenic culture and better COD removal efficiency.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 3DAYS AND CHAMBER B AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER B OF PABR CHMBER D				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
15	128.9	336	0	14.9
19	128.3	286.7	0	0
38	91.4	279.9	0	0
40	106.3	261.7	0	0
42	81.8	191.8	0	0
62	89.2	172.4	0	0
65	89.3	168.6	0	0

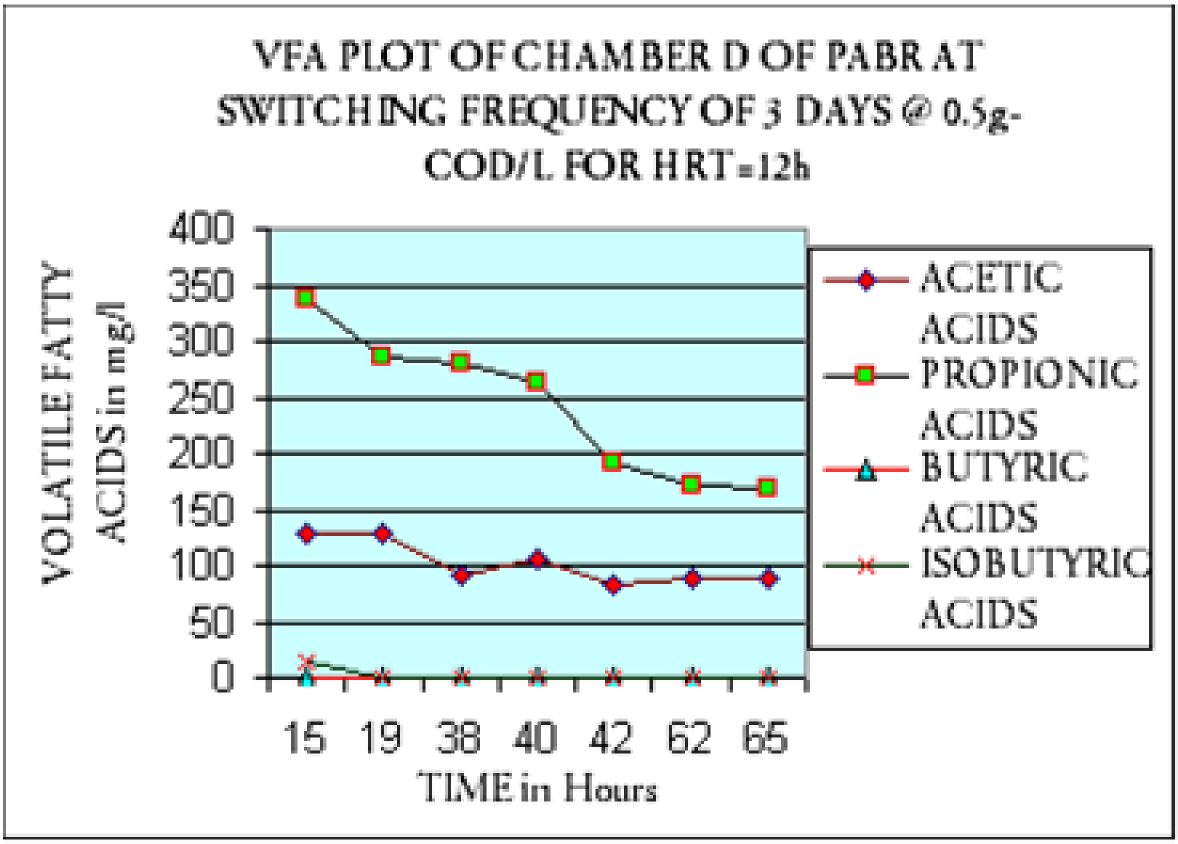


Fig. 8©

VFAs Observations in Compartment “A”

From Fig. 8(d), the chamber “A” achieve its stable periodic state after 40 hrs of running the PABR at switching frequency of 3 days. In this compartment the decrease in propionic acids are about 130 mg/l (i.e. from 310 mg/l to 180 mg/l) and acetic acids are about 70 mg/l (i.e. from 147 mg/l to 80 mg/l). Which results in conversion of propionic and acetic acids into acetate and subsequent conversion of acetate into methanogens. From Fig. 9(d), it can be seen that the variation in gas production rate is very less.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 3DAYS AND CHAMBER B AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER B OF PABR CHMBER D				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
15	122.2	273.6	0	0
19	147.3	311.4	0	0
38	101.7	261.7	0	0
40	78.3	175.1	0	0
42	80	177.4	0	0
62	107.2	280.6	0	0
65	96.8	221.8	0	0

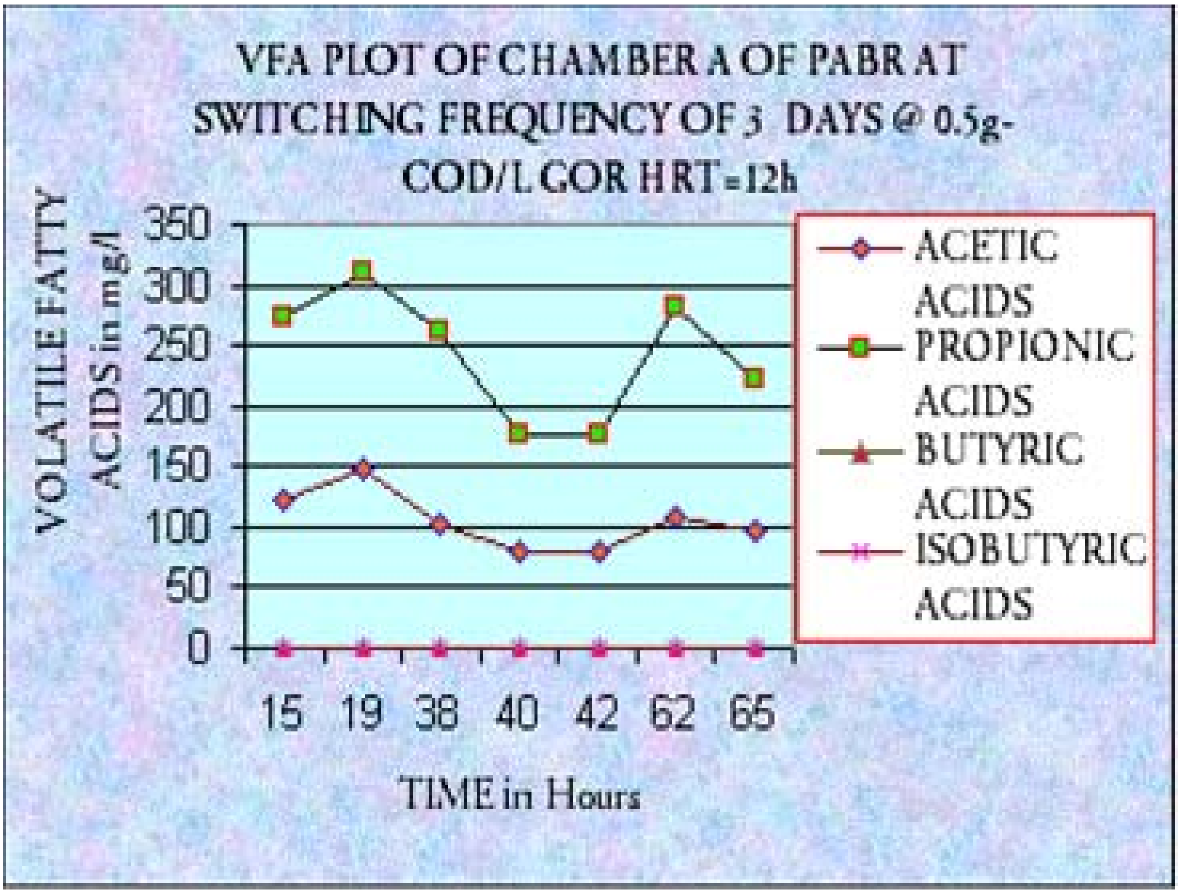


Fig. 8(d)

Biogas production rate observation at switching frequency of 3 days, at HRT of 12 hrs

Gas production observation in compartment “B” (Influent chamber)

From Fig. 9(a), shows that in compartment “B”, there is continuous increase in the gas production and subsequent increase in the production of methane and carbon dioxide gas. But Fig. 10(a), shows that the percentage methane yields decrease from 95% to 90%. This is due to the washout of methanogens from the compartment or no conversion of acetate into methanogens after the 38 hrs of running the PABR. The conclusion can also be made by comparing the compartment “A” (which is influent compartment at switching frequency of 2 days) where the % methane yields is 88% and compartment “B” (influent compartment at switching frequency of 3 days) where the percentage methane yield is higher due to subsequent accumulation of methanogens from the previous feeding compartment. Which further results in achievement of better stable periodic state (SPS), due to sequential switching frequency of feeding point.

GAS MEASUREMENT IN CHAMBER B OF PABR AT SWITCHING FREQUENCY OF 3 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
15	0.00696	0.00643	0.00053
38	0.00984	0.00936	0.00048
63	0.010872	0.00984	0.001032

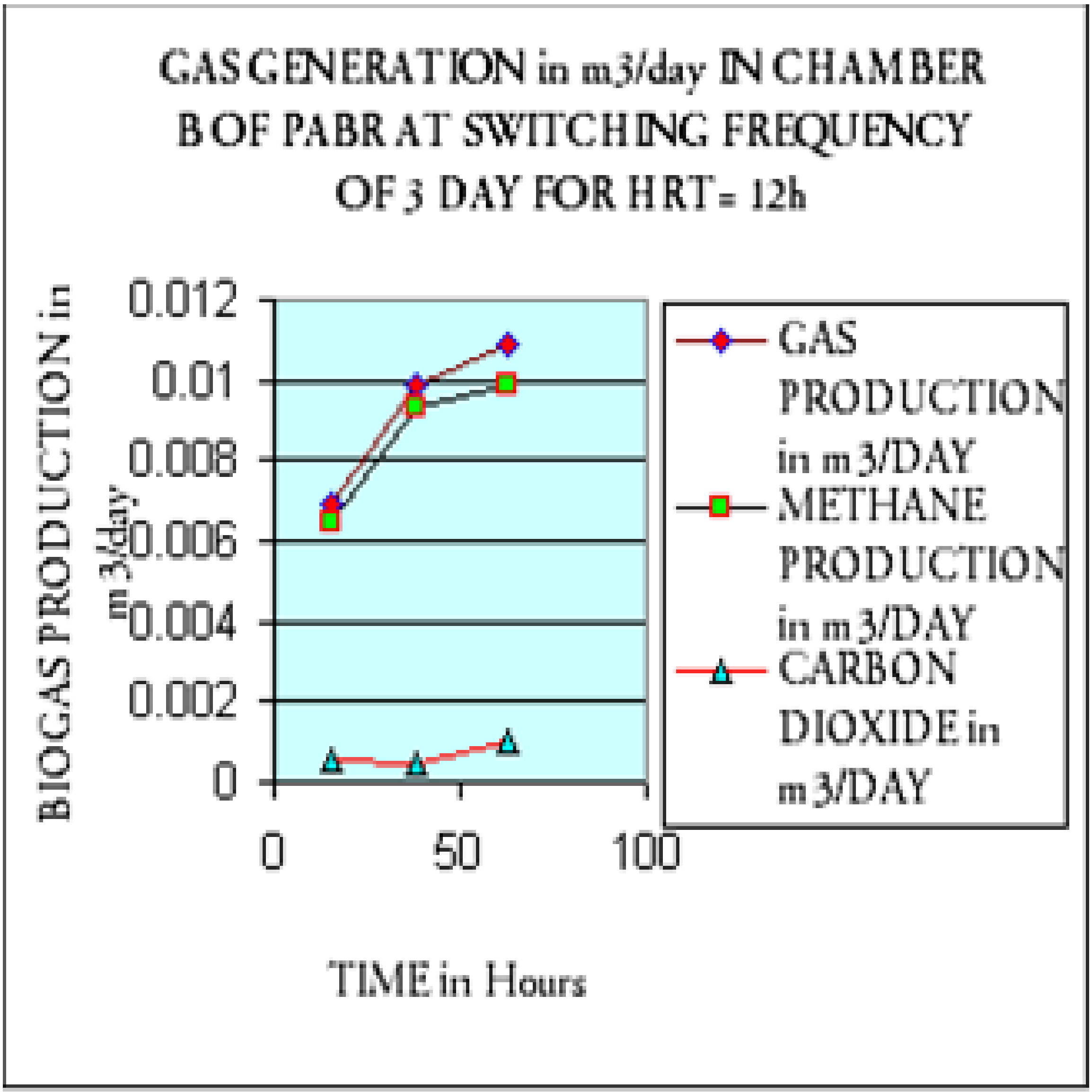


Fig. 9(a)

PLOT FOR PERCENTAGE METHANE YIELD AT SWITCHING FREQUENCY OF 3 DAYS

METHANE YIELD IN CHAMBER B OF PABR	
TIME in Hours	% CH4 YIELD
15	92.4
38	95.12
63	90.5

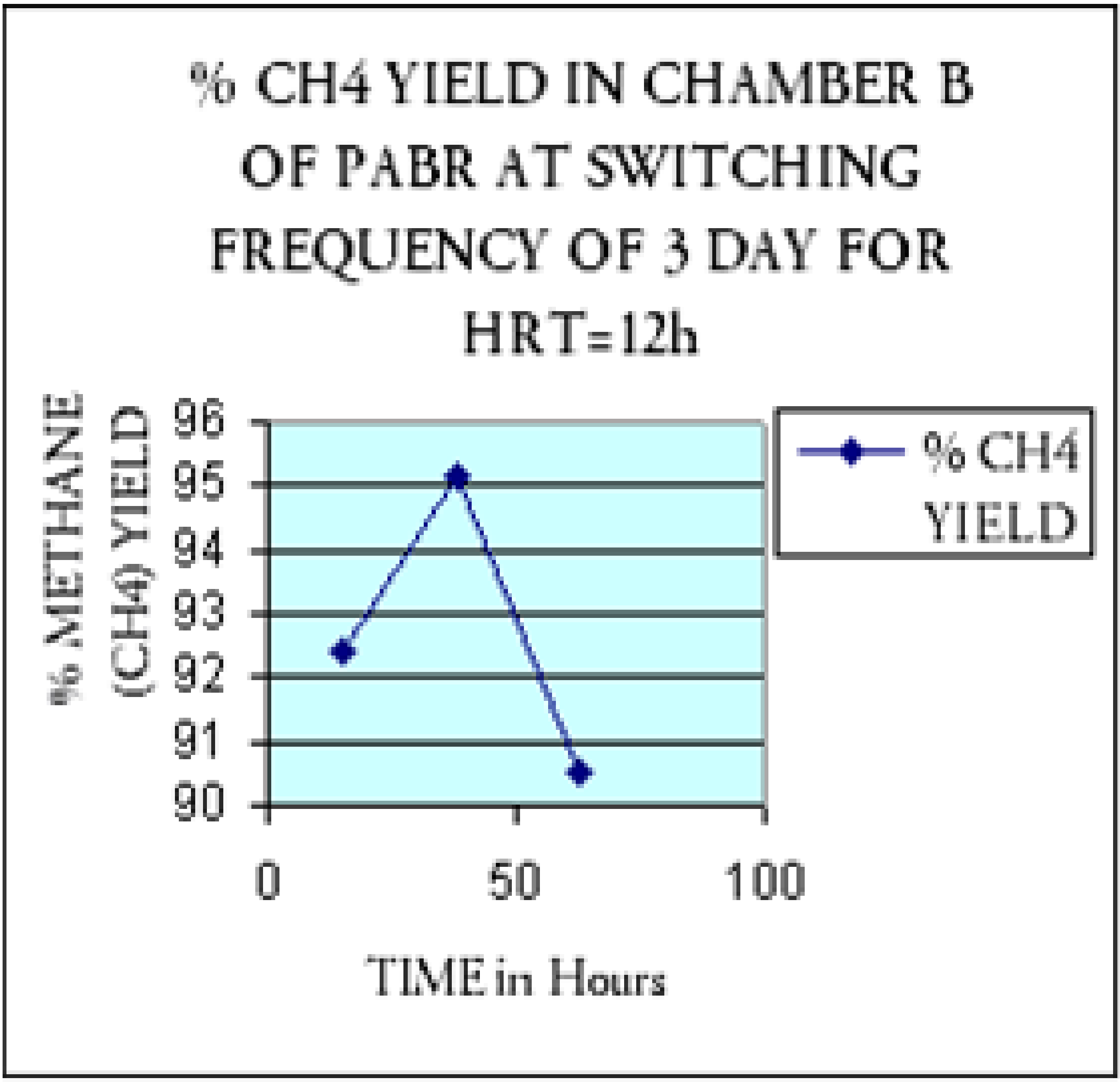


Fig. 10(a)

Gas production observation in compartment “C”

From Fig. 9(b), shows that in compartment “C”, there is continuous increase in the gas production and subsequent increase in the production of methane and carbon dioxide gas. But Fig. 10(c), shows that the percentage methane yields decrease from 95% to 90%. This is due to the washout of methanogens from the compartment or no conversion of acetate into methanogens after the 38 hrs of running the PABR. The conclusion can also be made by comparing the compartment “A” (which is influent compartment at switching frequency of 2 days) where the % methane yields is 88% and compartment “B” (influent compartment at switching frequency of 3 days) where the percentage methane yield is higher due to subsequent accumulation of methanogens from the previous feeding compartment. Which further results in achievement of better stable periodic state (SPS), due to sequential switching frequency of feeding point. Also the quantity of gas production is more than the influent compartment “B” of the PABR at the switching frequency of 3 days.

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 3 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
15	0.01493	0.01428	0.00065
38	0.02028	0.01932	0.00096
63	0.02028	0.01944	0.00084

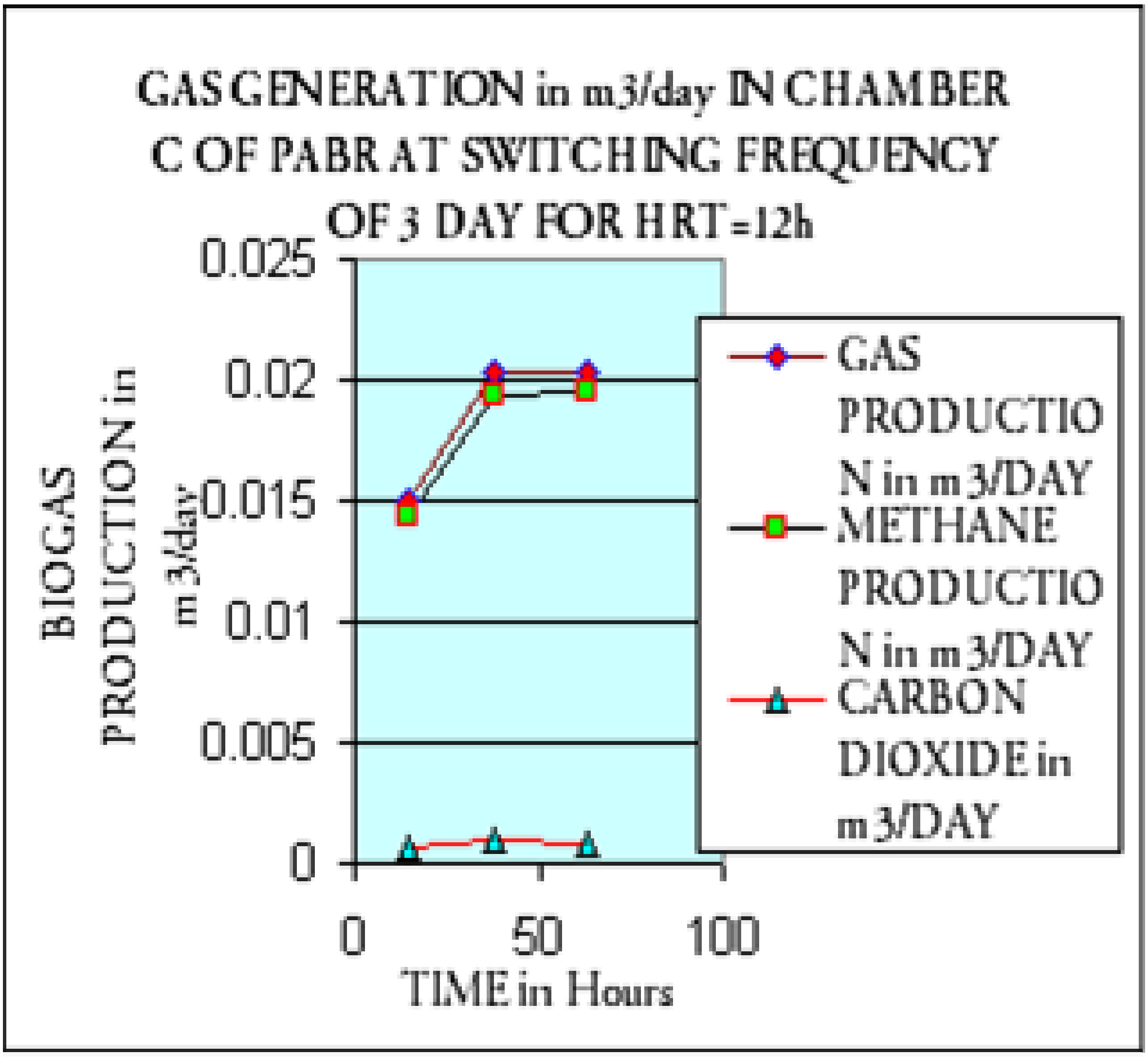


Fig. 9(b)

PLOT FOR PERCENTAGE METHANE YIELD AT SWITCHING FREQUENCY OF 3 DAYS

METHANE YIELD IN CHAMBER C OF PABR	
TIME in Hours	% CH4 YIELD
15	95.65
38	95.27
63	95.86

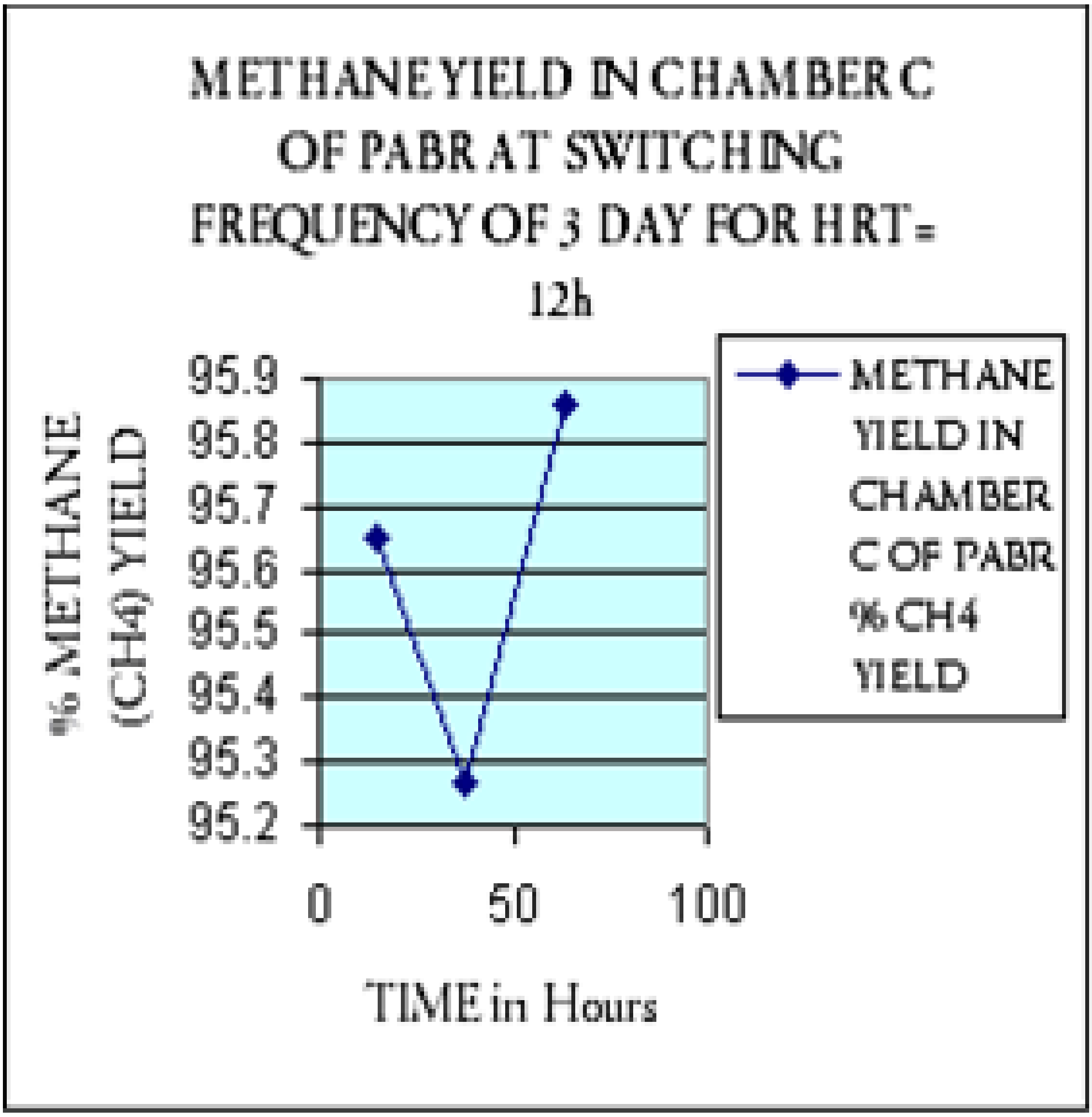


Fig. 10(b)

Gas production in compartment “D”

From fig. 9 ©, it can be seen that the gas production rate is increases from the initial period to 38 hrs and after that it remains more or less constant. While from Fig. 10©, it can be seen that the percentage methane yields is increases continuously due to the conversion of acetate into methanogens. It can be concluded that from Fig. 10 © that there is high rate of growth of methanogenic bacteria at switching frequency of 3 days which one previously subjected to 2 days switching frequency.

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 3 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
15	0.012	0.01116	0.00084
38	0.014832	0.01392	0.000912
63	0.0144	0.01368	0.00072

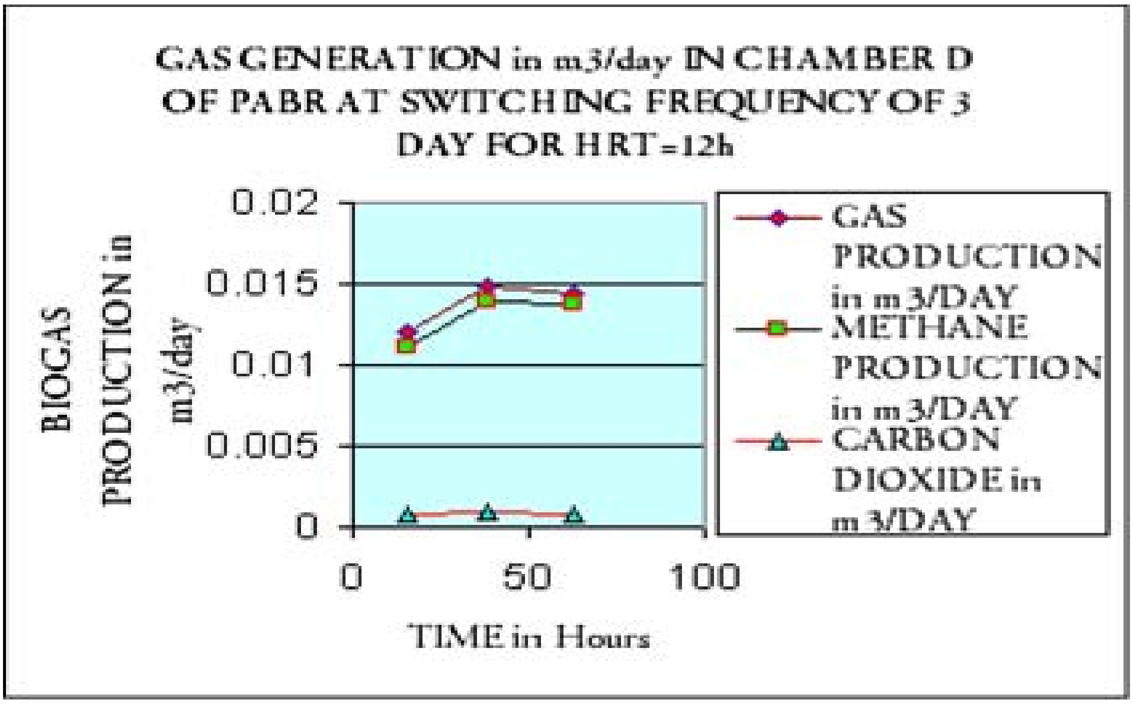


Fig. 9©

PLOT FOR PERCENTAGE METHANE YIELD AT SWITCHING FREQUENCY OF 3 DAYS

METHANE YIELD IN CHAMBER D OF PABR	
TIME in Hours	% CH4 YIELD
15	93
38	93.85
63	95

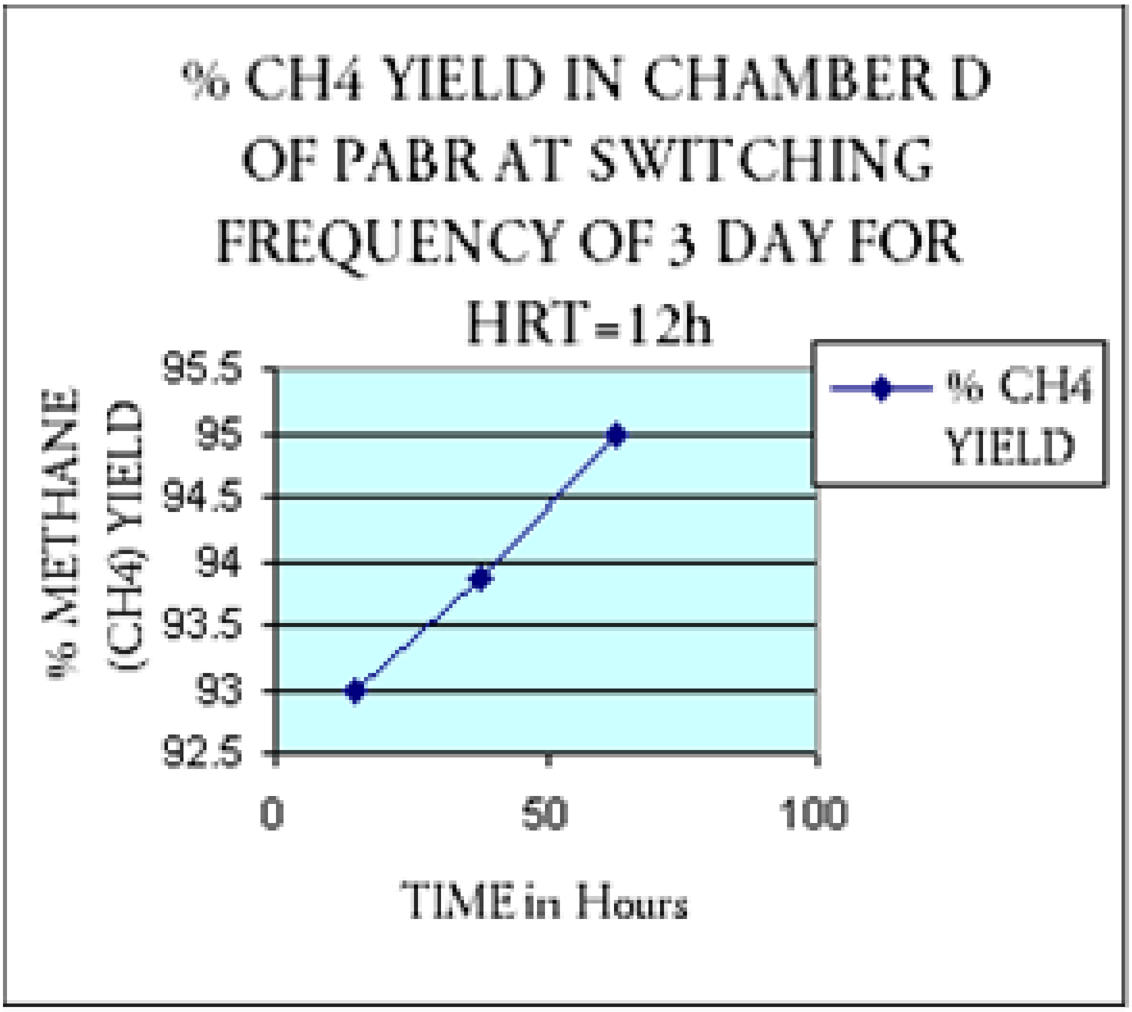


Fig. 10©

Gas production in compartment “A”

From fig. 9 (d), it can be seen that the gas production rate is increases from the initial period to 38 hrs and after that it remains more or less constant. While from Fig. 10©, it can be seen that the percentage methane yields is increases continuously due to the conversion of acetate into methanogens. It can be concluded that from Fig. 10 (d) that there is high rate of growth of methanogenic bacteria at switching frequency of 3 days which one previously subjected to 2 days switching frequency.

From Fig. 10(d), depicts the same cause for the percentage methane yield as described above. While the percentage methane yield is more than 96%, which shows the developed methanogenic culture in the rear compartment of the PABR.

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 3 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
15	0.009888	0.0096	0.000288
38	0.01188	0.011688	0.000192
63	0.010512	0.01008	0.000432

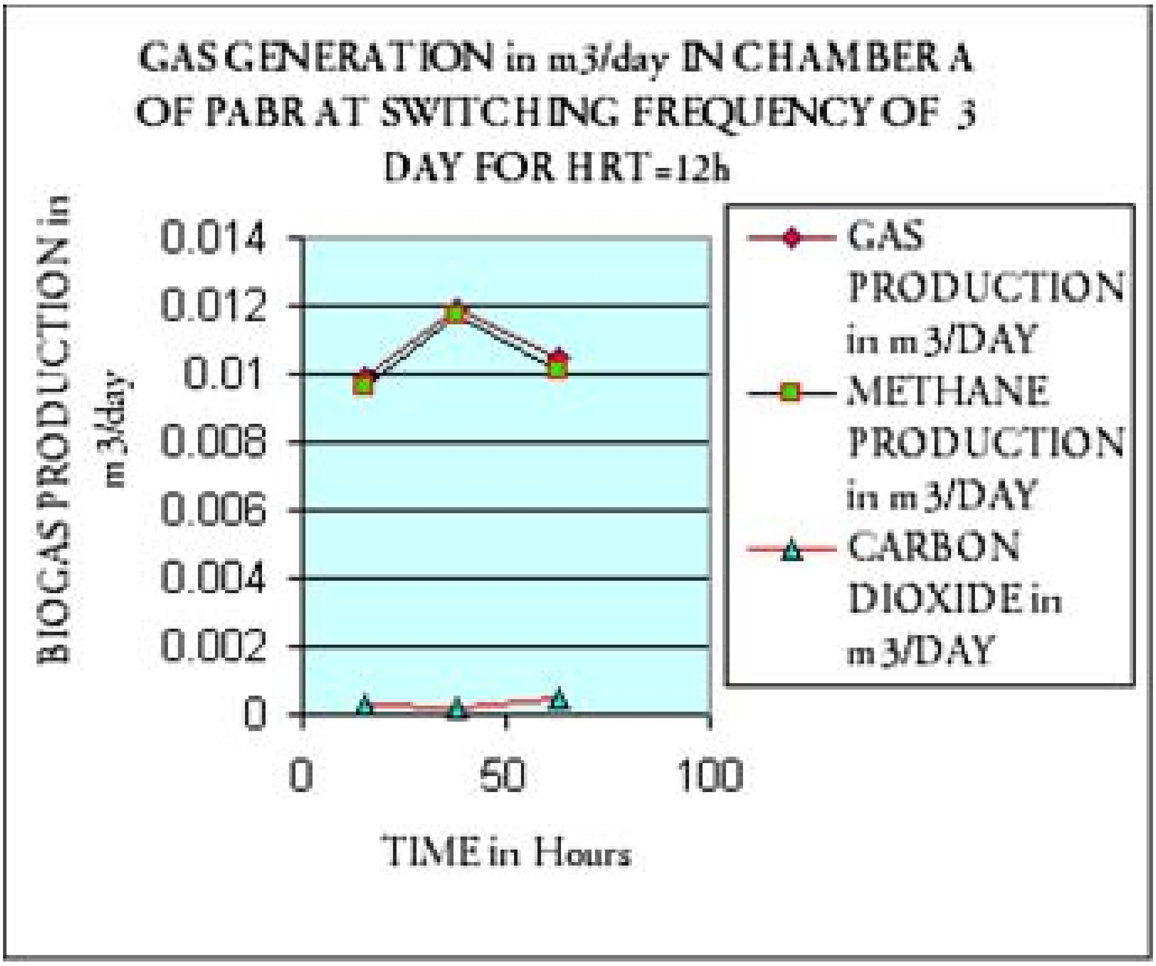


Fig. 9(d)

METHANE YIELD IN CHAMBER A OF PABR	
TIME in Hours	% CH4 YIELD
15	97.1
38	98.4
63	95.9

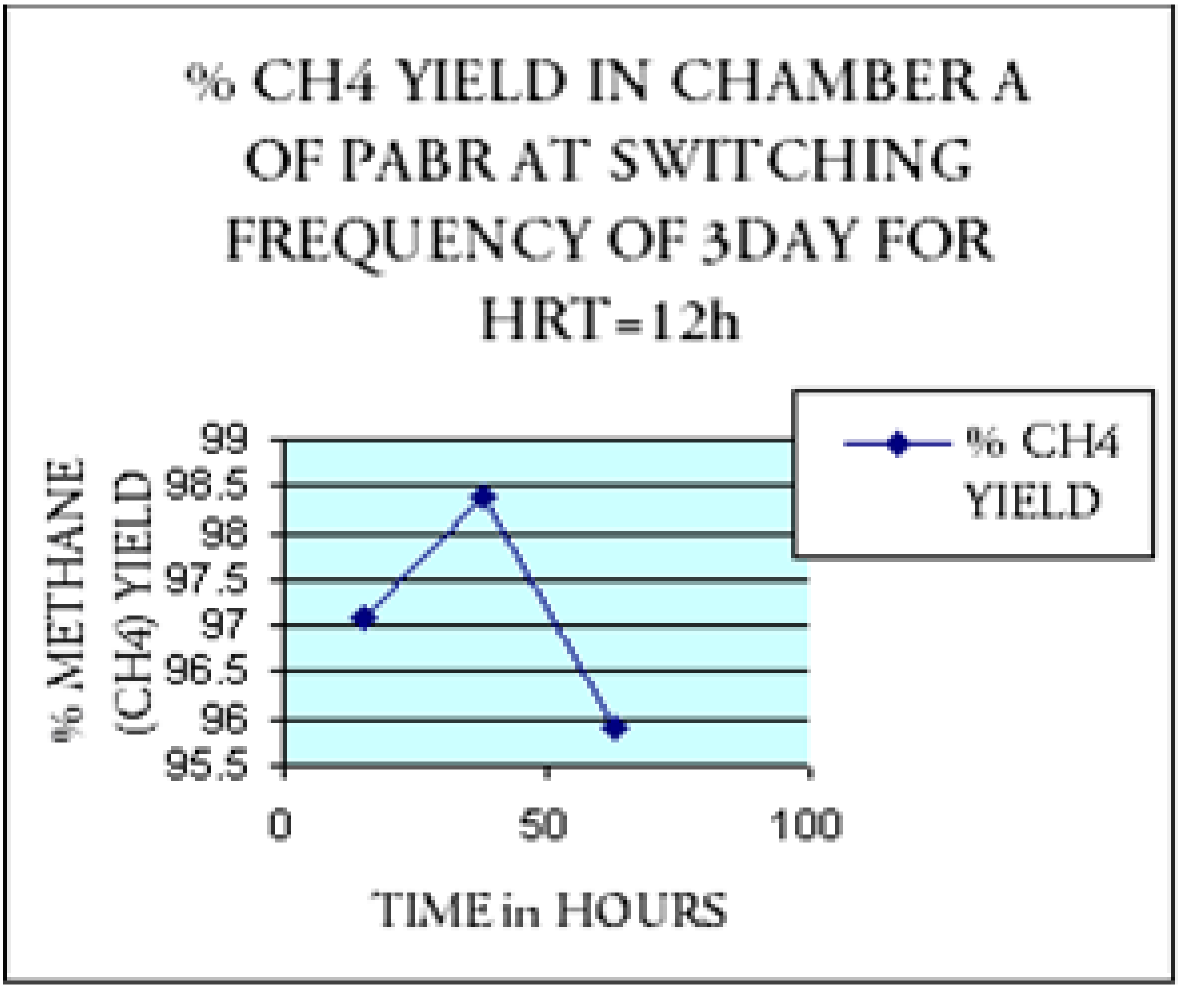


Fig. 10(d)

CONCLUSION at switching frequency of 3 days

While running the reactor at switching frequency of 3 days, the achievement of stable periodic state (SPS) occur after 38 hrs of running the reactor. The stability in terms of effluent COD, VFAs production and conversion, Gas production, Methane production rate and percentage Methane yield is more stable than the reactor running at switching frequency of 2 days.

3. Selecting compartment "C" of the PABR as influent compartment at switching frequency of 4 days, at HRT of 12hrs and at feeding of 0.5 g-COD/l

Effluent COD removal at switching frequency of 4 days

From Fig. 11, depicts that the PABR achieve its stable periodic state (SPS) after 45 hrs of running the reactor at switching frequency of 4days. From the COD removal at the switching frequency of 2 days and 3 days, it can be concluded that the when PABR set to the sequential switching frequency the stable periodic state will achieve in shorter interval of switching frequency. These conclusions satisfy the Skiadas and Lyberatos et al., 1998 experimental verifications. For example from the switching frequency of 2 days to 3 days and from 3 days to 4 days the stability of the reactor achieve in 27 hrs, 38 hrs and 45 hrs respectively (i.e. from switching frequency of 2 days to 3 days the interval is 11 hrs and from 3 days to 4 days the interval is 7 hrs).

CALCULATION OF EFFLUENT COD WHEN CHAMBER C OF PABR SELECTED AS INFLUENT CHAMBER @ 0.5g-COD/L FOR HRT=12h

TIME in Hours	EFFLUENT COD in mg/l
17	336
20	320
42	352
45	224
48	224
65	352
68	272
71	224

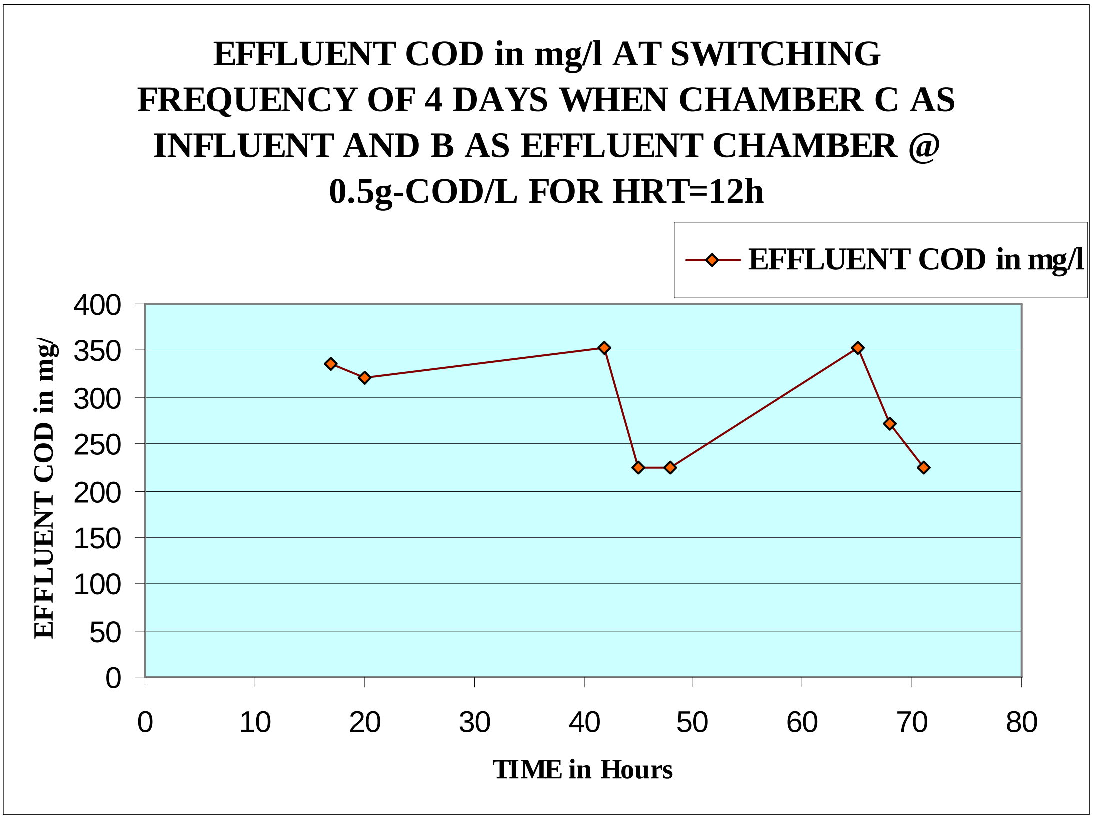


Fig. 11

Volatile fatty acids (VFAs) observation at switching frequency of 4days

VFAs Observations in Compartment "C" (Influent compartment)

From Fig 12(a), it can be seen that waves of the volatile fatty acids is not suppressed, but the lowest values of both propionic and acetic acids is observed after 45 hrs of running the PABR at 0.5 g-COD/l, at the HRT of 12 hrs, at switching frequency of 4 days. Which shows the achievement of stable periodic state, at which the feeding point can be changed. While in the influent compartment "C", there is production of insignificant amount of butyric and isobutyric acids. The increase in volatile fatty acids is due to the hydrolysis of carbohydrates into acetic and propionic acids. The production of acids causes the suppression of the growth of methanogenic bacteria.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 4DAYS AND CHAMBER C AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER C OF PABR				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
17	149.3	192.2	0	8.3
20	151.8	210.7	31.5	0
42	81.7	233.6	0	0
45	74.4	137.6	0	0
48	52.1	184.5	0	0
65	137.5	234.2	0	0
68	134	208.7	0	0

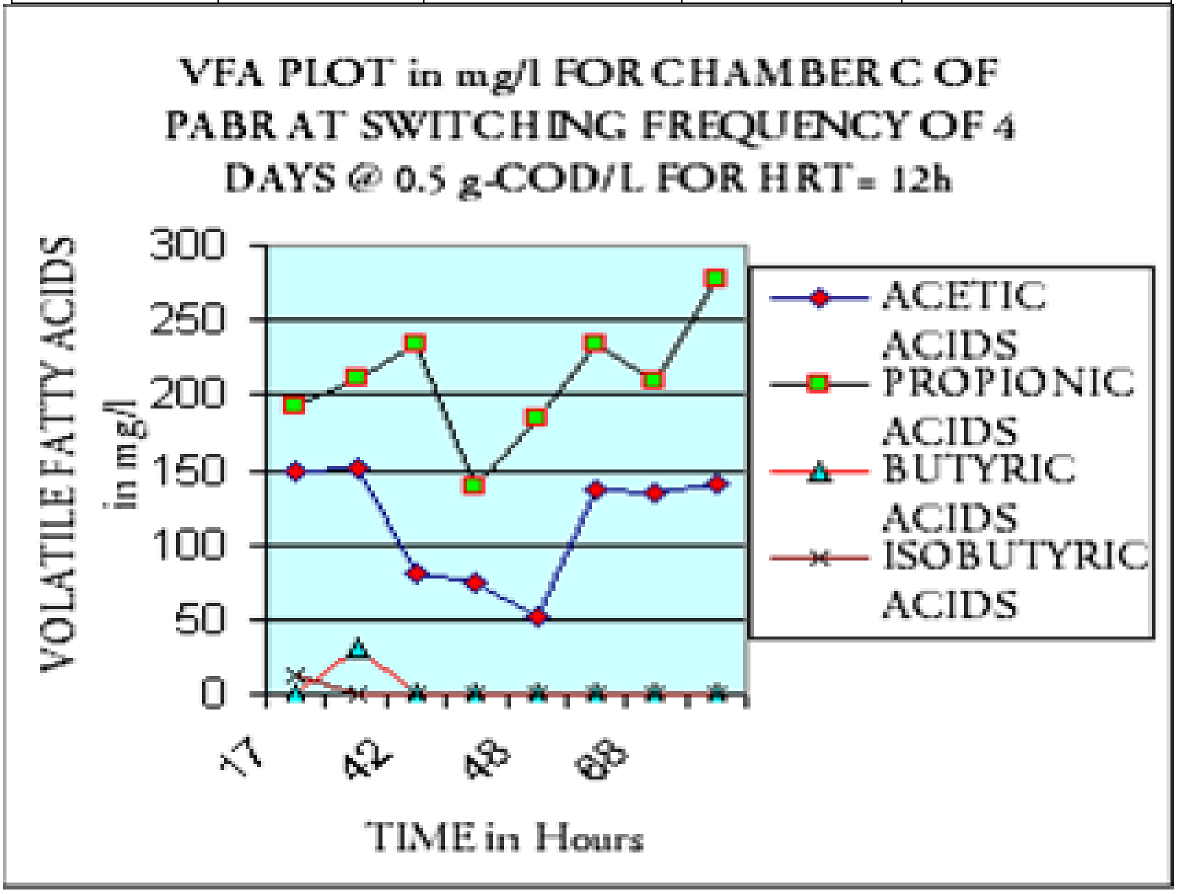


Fig. 12(a)

VFAs Observations in Compartment "D"

From Fig 12(b), it can be seen that the peaks of the acetic and propionic acids are suppressed, after 42 hrs of running the PABR at 0.5 g-COD/l, at the HRT of 12 hrs, at switching frequency of 4 days. But there is slight increase in the amount of the production of acetic and propionic acids at latter period of the run of the reactor. It can also observed that the amount of propionic acids remains below the initial state. While there is increase in the production of acetic acids at latter periods of running the reactor and regains its initial state. Whereas the production of butyric and isobutyric acids are zero in the compartment "D" of the PABR. Therefore the gaining of the stable periodic state after 45 hrs of running the reactor at switching frequency less than that at the switching frequencies of 2 days and 3 days. After gaining of stable periodic state and its subsequent operation at the same frequency results in the deterioration in the performance or the shifting of the PABR as the ABR mode.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 4DAYS AND CHAMBER C AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER C OF PABR				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
17	161.2	257.7	0	0
20	162.5	301.4	0	0
42	102	231.9	0	0
45	111.5	157.3	0	0
48	86.3	195.1	0	0
65	162.6	210.2	0	0
68	152.5	256.5	0	0
71	141.8	230.1	0	0

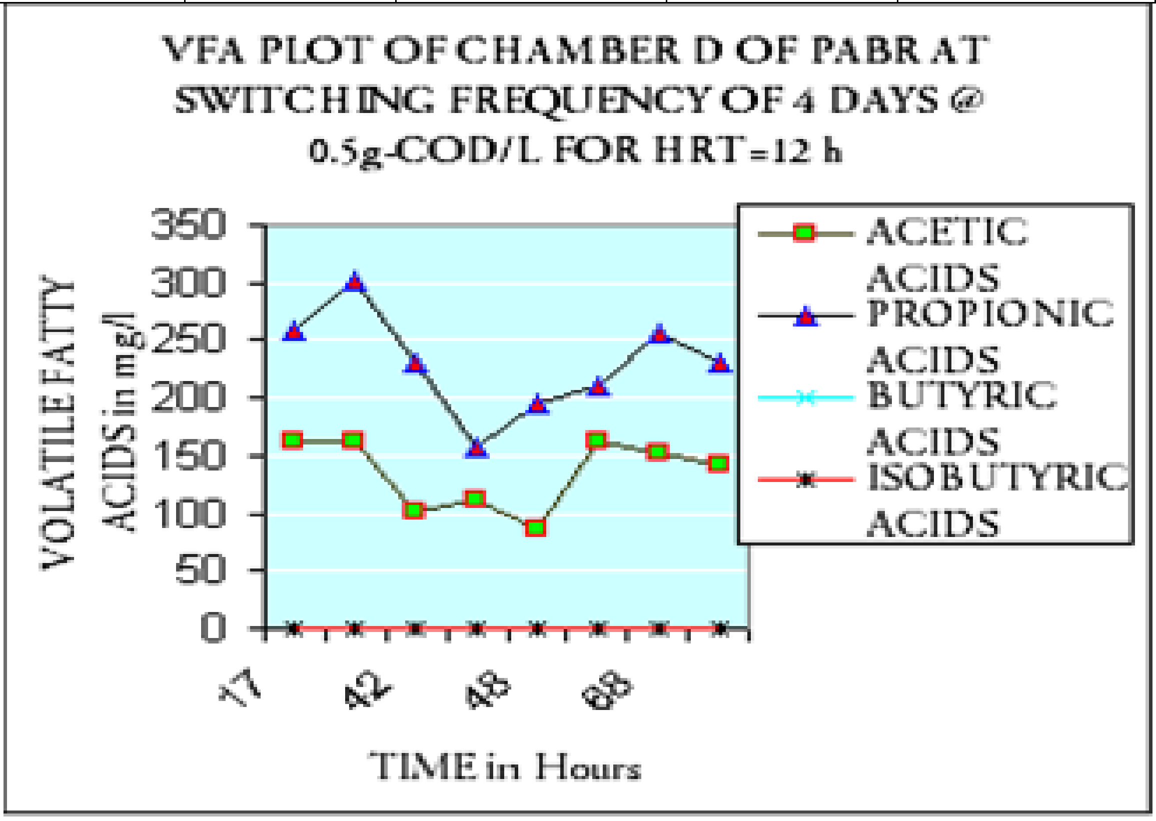

VFA PLOT OF CHAMBER D OF PABR AT SWITCHING FREQUENCY OF 4 DAYS @ 0.5g-COD/L FOR HRT=12 h

Fig. 12(b)

VFAs Observations in Compartment "A and B"

From Fig 12(c) & (d), depicts that the production of volatile fatty acids is minimum at 45 hrs which shows that the attainment of stable periodic state. In compartment "A" the decrease in the propionic acids is about 70 mg/l. While decrease in acetic acids is about 50 mg/l. Whereas in compartment "B" (effluent compartment) the decrease in propionic acids is about 90 mg/l. While variations in acetic acids is about 50 mg/l. The decrease in volatile fatty acids results in conversion of acetate into methanogens. It can also be concluded that the switching frequency at lower organic loading rate cannot be prolong to 2 days which results in shifting of the PABR as the ABR mode.

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 4DAYS AND CHAMBER C AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER A OF PABR				
Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
17	145.9	205.2	0	0
20	167.6	239.1	0	0
42	99	202.7	0	0
45	89.9	163.3	0	0
48	87.9	131.6	0	0
65	142.1	233.7	0	0
68	117.3	176.6	0	0
71	133.5	185.2	0	0

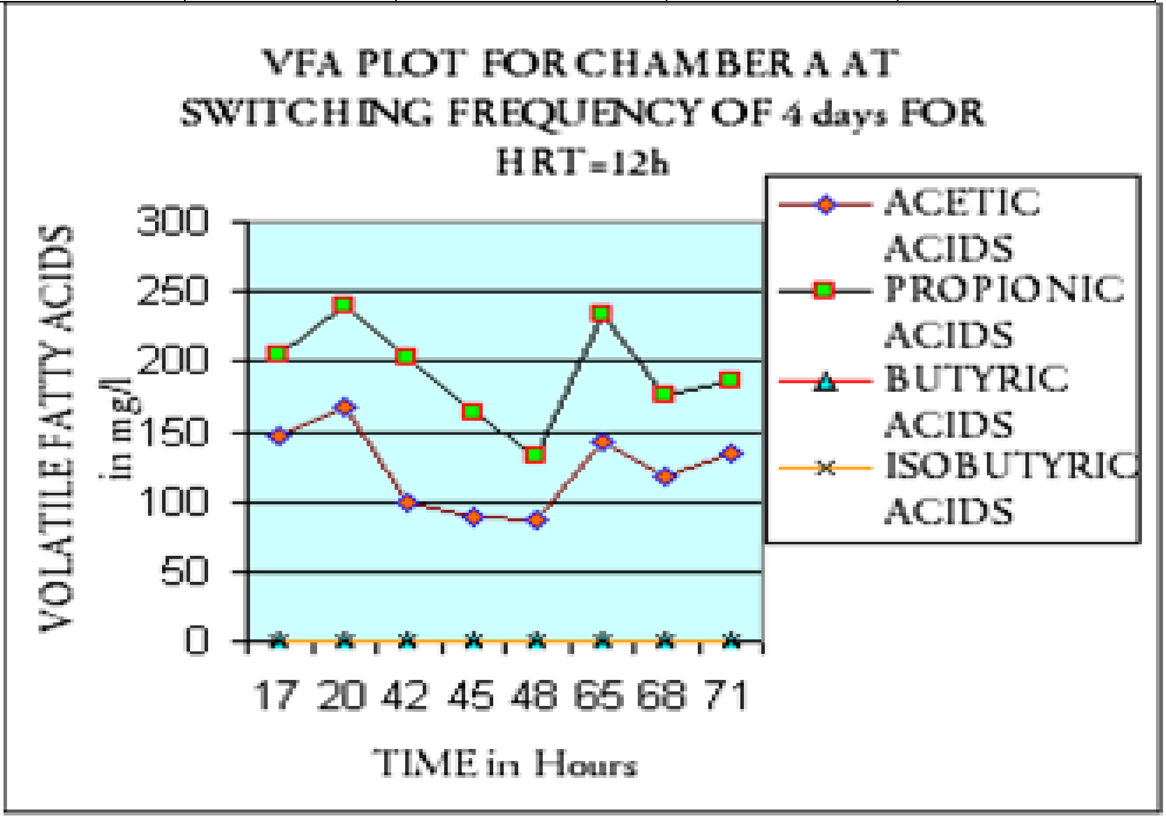


Fig. 12 ©

VOLATILE FATTY ACIDS CALCULATION in mg/l AT SWITCHING FREQUENCY OF 4DAYS AND CHAMBER C AS INFLUENT CHAMBER @ 0.5 g-COD/L FOR HRT=12h

VOLATILE FATTY ACIDS in mg/l FOR CHAMBER B OF PABR

Time in Hours	ACETIC ACIDS	PROPIONIC ACIDS	BUTYRIC ACIDS	ISOBUTYRIC ACIDS
17	127.4	167.3	0	0
20	134.2	203.6	0	0
42	85.5	159	0	0
45	103.4	179.5	0	0
48	93.4	115	0	0
65	83.9	183.3	0	0
68	117.3	203	0	0
71	126.4	187.4	0	0

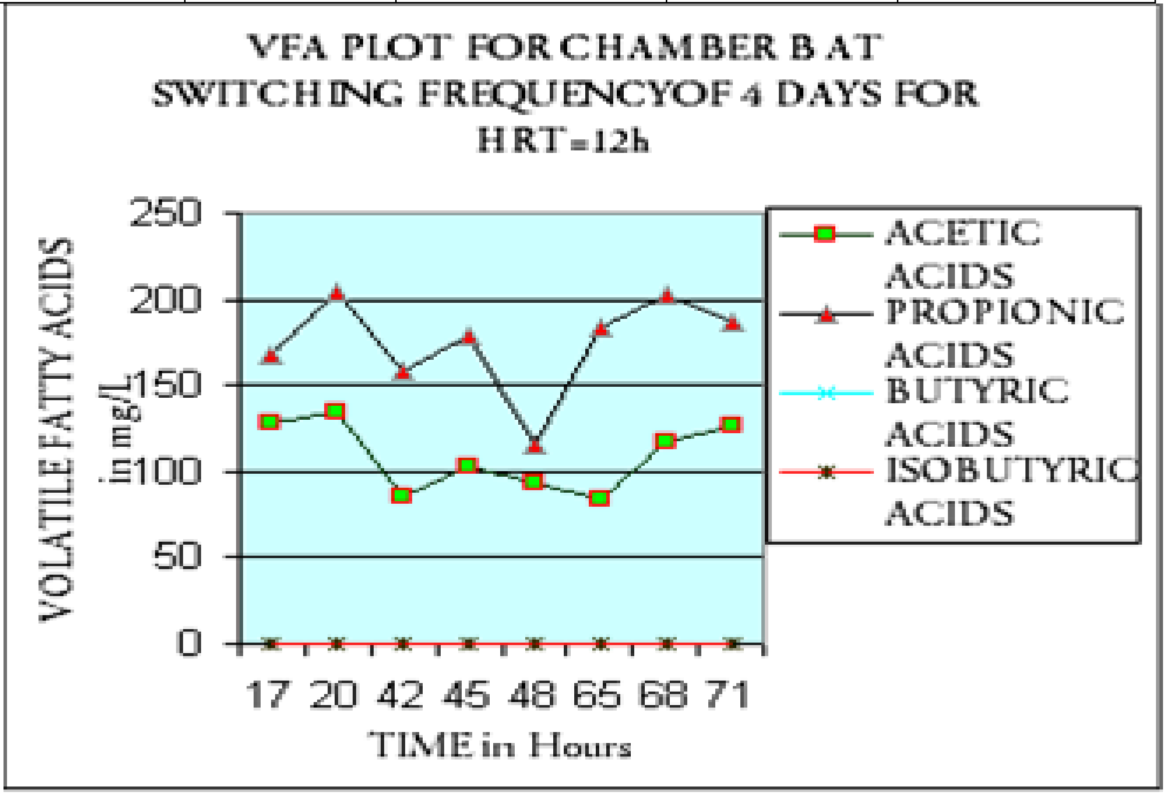


Fig. 12 (d)

Biogas production rate observation at switching frequency of 4 days, at HRT of 12 hrs

Gas production observation in compartment “C” (Influent chamber)

In compartment “C” gas production rate is constant up to 48 hrs and afterwards there is decrease in gas production rate. While the carbon dioxide production is decrease continuously as seen from the Fig. 13(a). Which results in increase in percentage methane yield as seen from Fig 14 (a).

The decrease in gas production rate is due to the production of more volatile fatty acids after the 45 hrs of running the reactor. Which causes decrease in production of acetate in compartment “C”. Whereas the percentage methane yield in influent compartment at the switching frequency of 2 days and 3 days. This proves the Experimental verification of uniform growth of methanogenic bacteria at switching frequency of 4 days as a UASBRs mode of operation of PABRs.

GAS MEASUREMENT IN CHAMBER C OF PABR AT SWITCHING FREQUENCY OF 4 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
18	0.010464	0.009504	0.00096
43	0.01104	0.001068	0.00036
66	0.008352	0.008112	0.00024

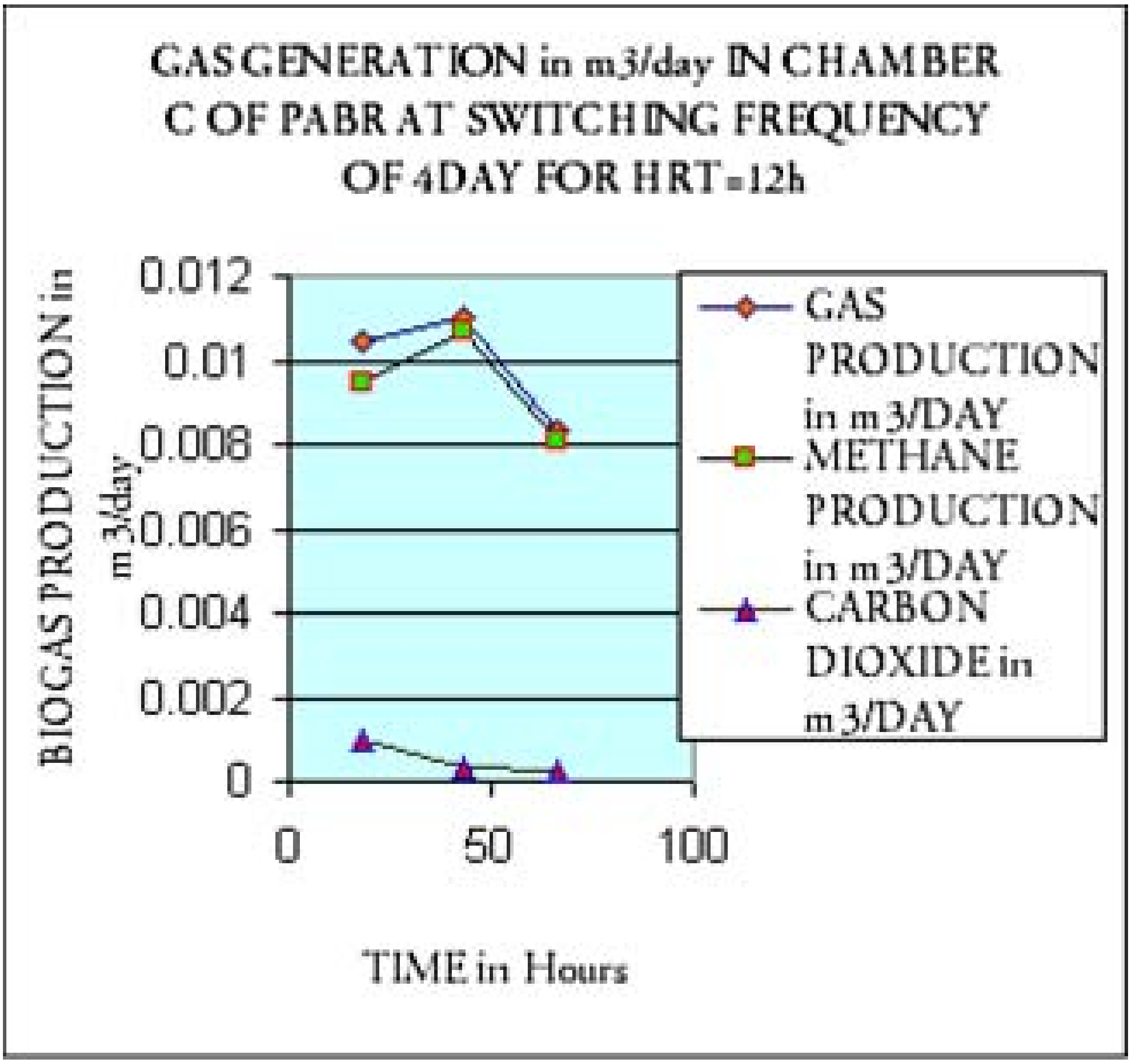


Fig. 13(a)

PLOT FOR PERCENTAGE METHANE YIELD AT SPS=4 DAYS

WHEN C AS INFLUENT CHAMBER @ 0.5 g-COD/L

METHANE YIELD IN CHAMBER C OF PABR	
TIME in Hours	% CH_4 YIELD
18	90.83
43	96.74
66	97.13

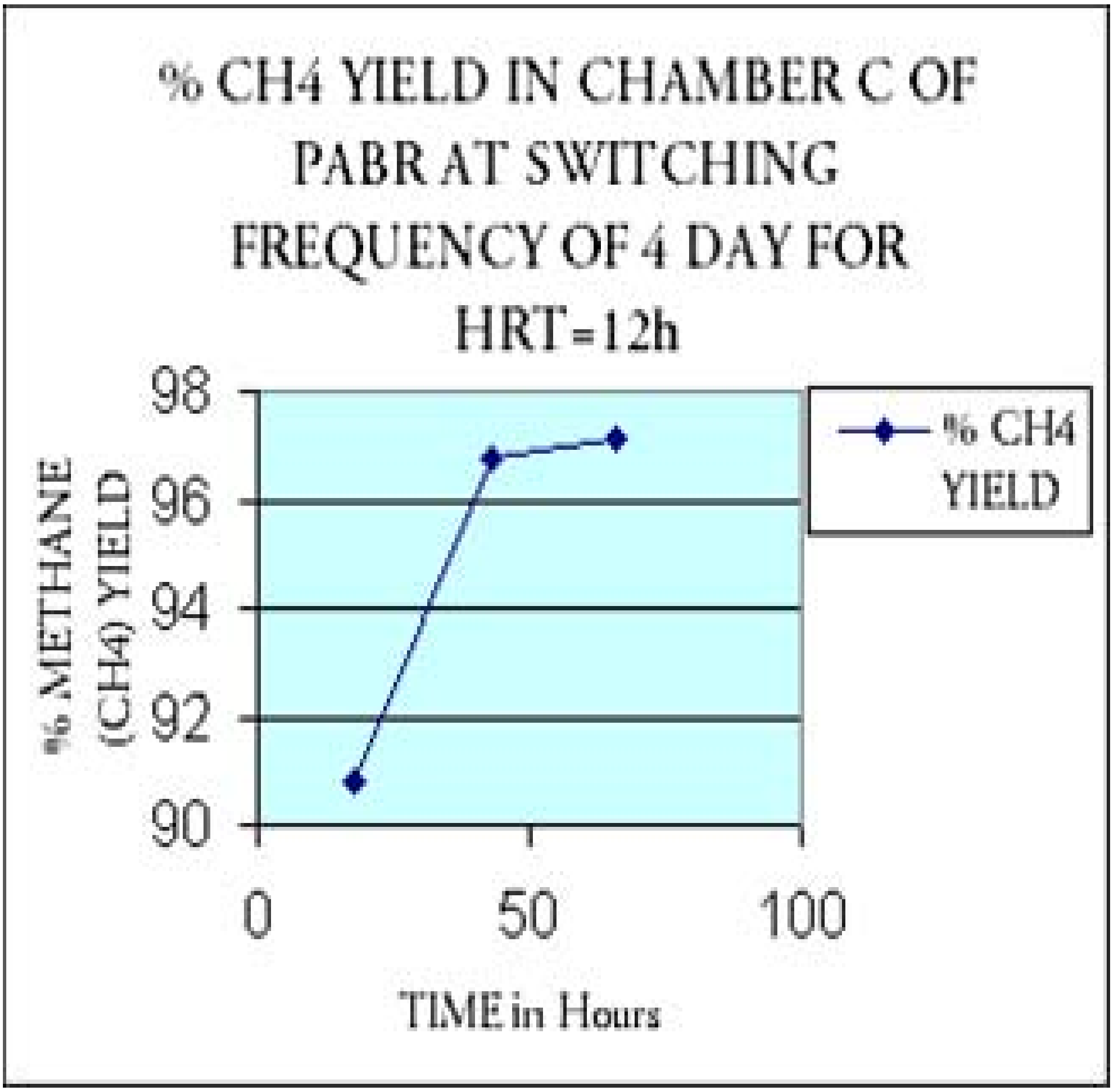


Fig. 14 (a)

Gas production observation in compartment "D"

From fig. 13 (b), it depicts that there is gradual decrease in gas production rate i.e. methane and carbon dioxide. While from Fig. 14 (b), there is continuous increase in percentage methane yields and it is up to 95%. It shows that conversion of propionic and acetic acids into acetate in compartment "C" (influent) is converted to methanogens in compartment "D".

GAS MEASUREMENT IN CHAMBER D OF PABR AT SPS = 4 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
18	0.019104	0.017688	0.001416
43	0.017952	0.016896	0.001056
66	0.01716	0.01632	0.00084

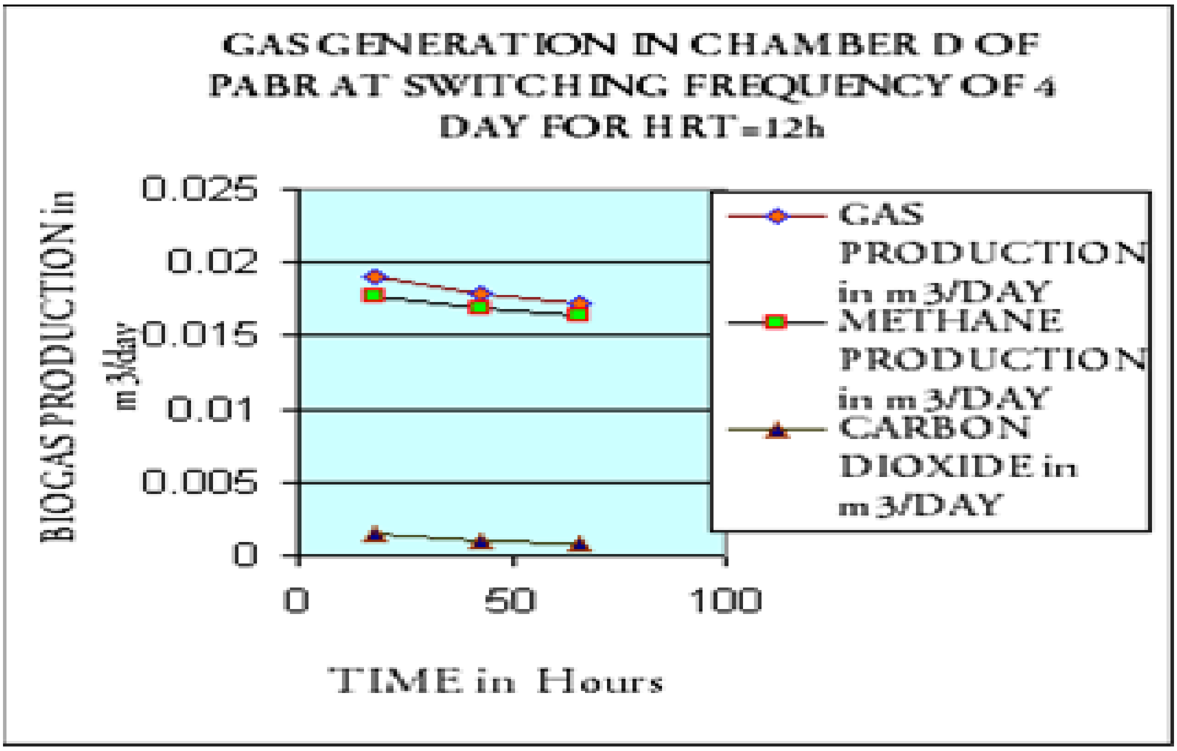


Fig. 13 (b)

METHANE YIELD IN CHAMBER D OF PABR	
TIME in Hours	% CH4 YIELD
18	92.6
43	94.12
66	95.1

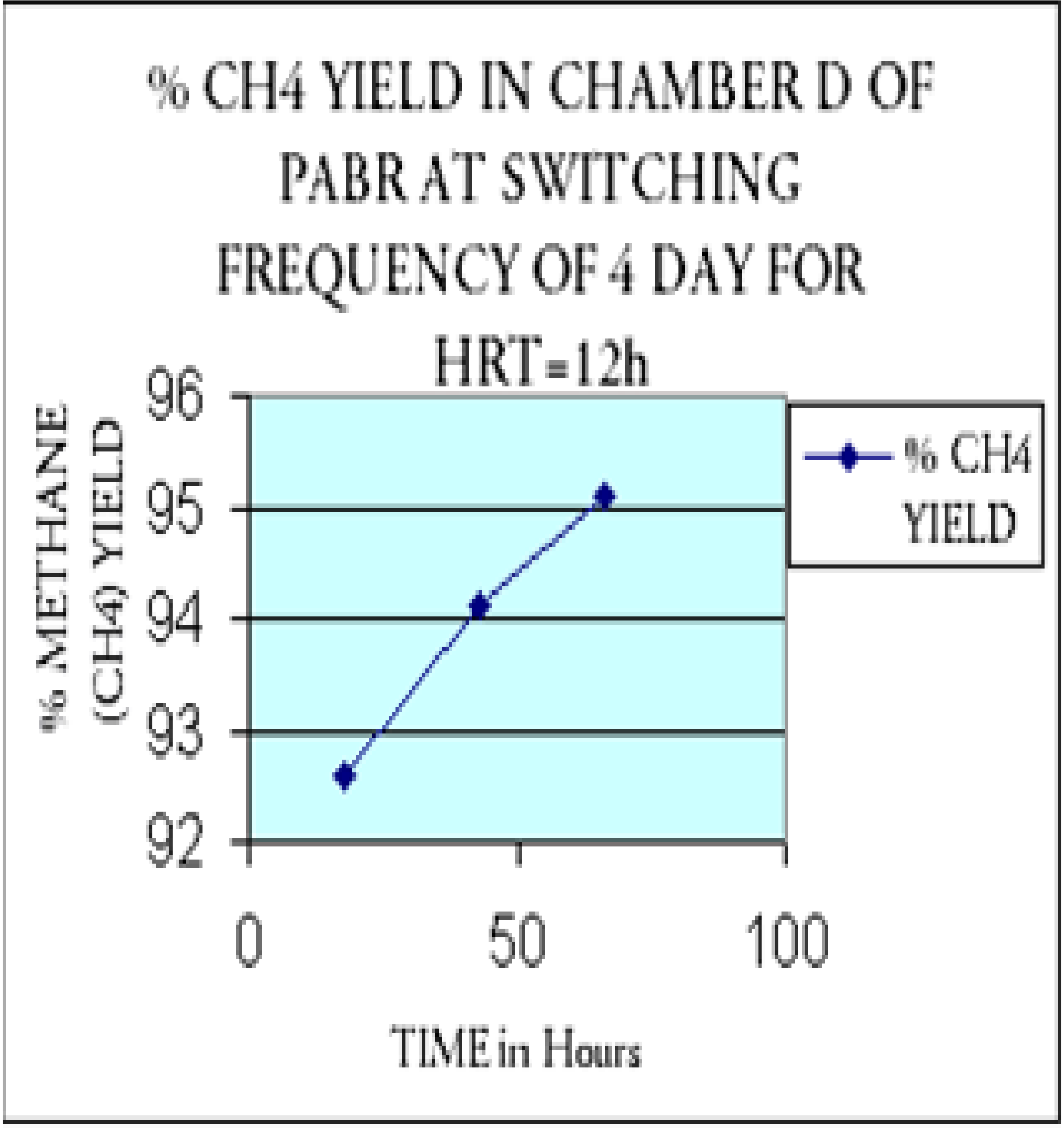


Fig. 14 (b)

Gas production observation in compartment “A”

From fig. 13 (c), it can be seen that there is continuous decrease in gas production rate up to 43 hrs and after 43 hrs the gas production remains constants. The decrease in gas production rate shows that there is a decrease in production of volatile fatty acids and its subsequent conversion to acetate.

While from Fig. 14 (c), the percentage methane yields and it is up to 92% which remains more or less constant. This attributed to the production of carbon dioxide remains more or less constants throughout the running of PABR at switching frequency of 4 days.

GAS MEASUREMENT IN CHAMBER A OF PABR AT SPS = 4 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
18	0.015888	0.014592	0.001296
43	0.012312	0.011328	0.000984
66	0.01296	0.01188	0.001084

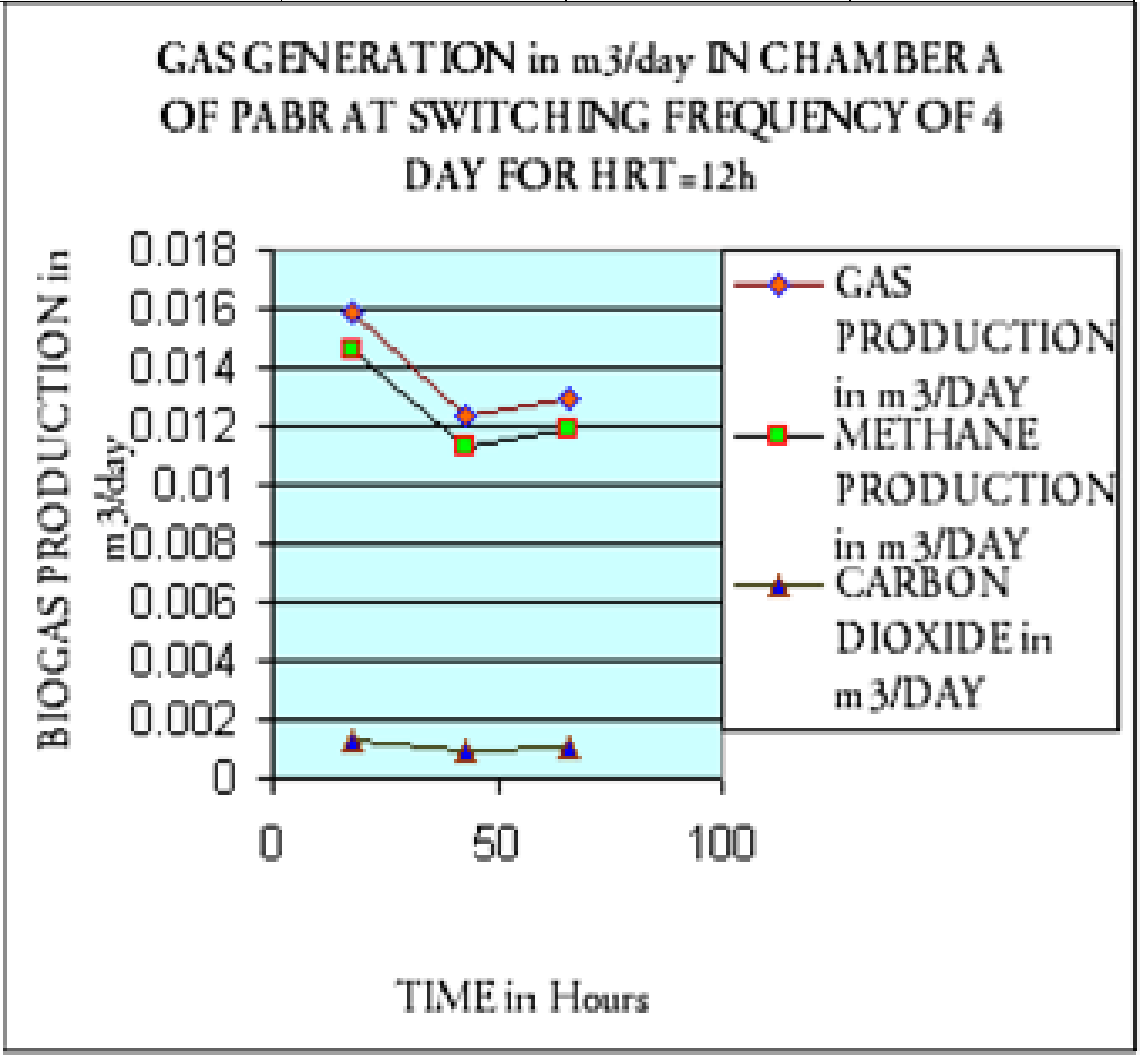


Fig. 13 ©

METHANE YIELD IN CHAMBER A OF PABR	
TIME in Hours	% CH4 YIELD
18	91.84
43	92
66	91.67

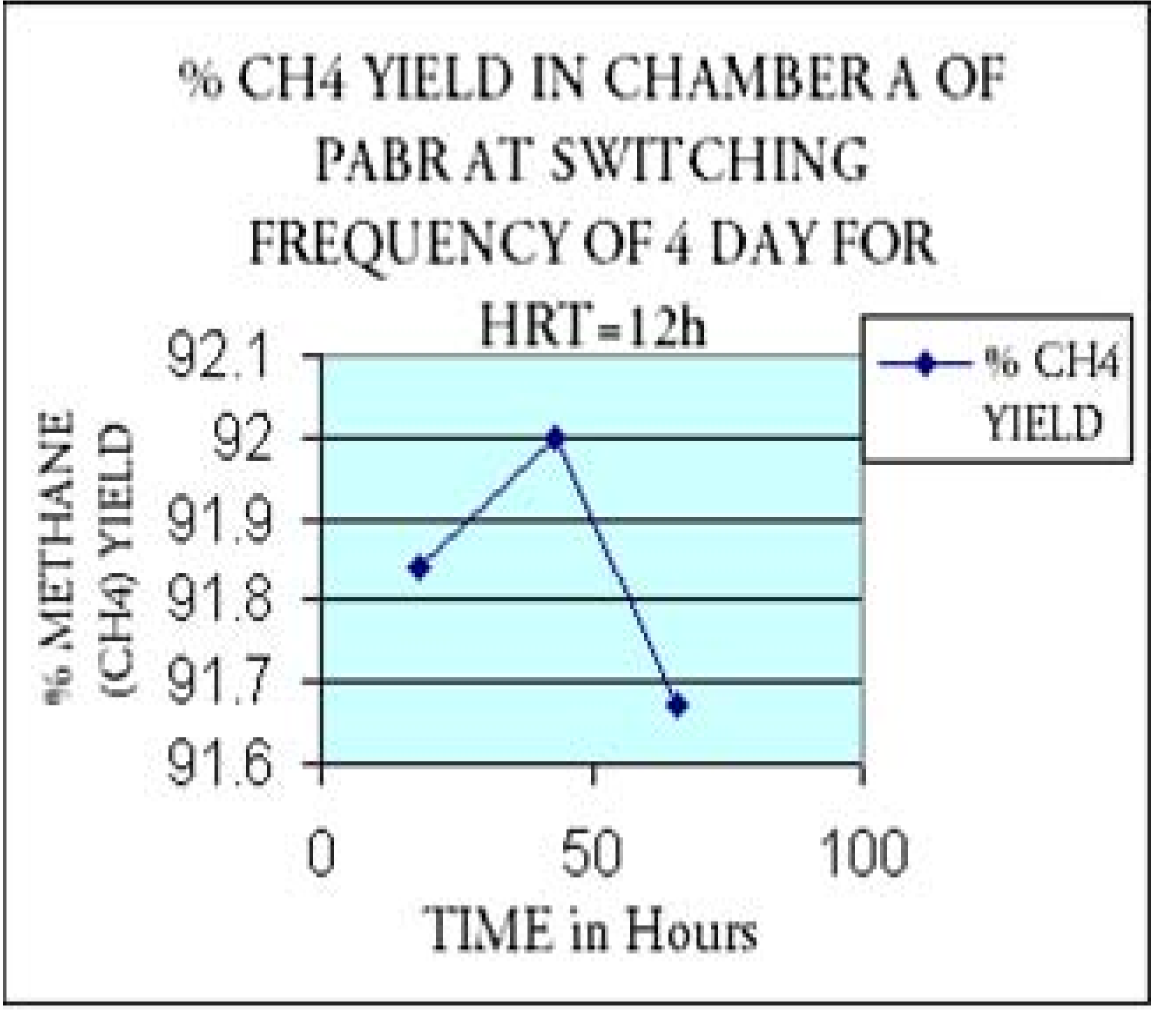


Fig. 14 (c)

Gas production observation in compartment "B"

From fig. 13 (d), it can be seen that the gas generation is increased, this is due to the production of volatile fatty acids at latter stage and its subsequent conversion to acetate and to methanogens. While there is also subsequent increase in the carbon dioxide production. From Fig. 14 (d), it can be seen that there is continuous decrease in percentage methane yields from 98.75% to 90%. The reason behind this due to the: first increase in carbon dioxide production, While second is due to the washout of methanogens to the effluent stream or deterioration of PABR to ABR mode.

GAS MEASUREMENT IN CHAMBER B OF PABR AT SPS = 4 DAYS

TIME in Hours	GAS PRODUCTION in m3/DAY	METHANE PRODUCTION in m3/DAY	CARBON DIOXIDE in m3/DAY
18	0.0096	0.00948	0.00012
43	0.00996	0.009552	0.000408
66	0.01164	0.01044	0.0012

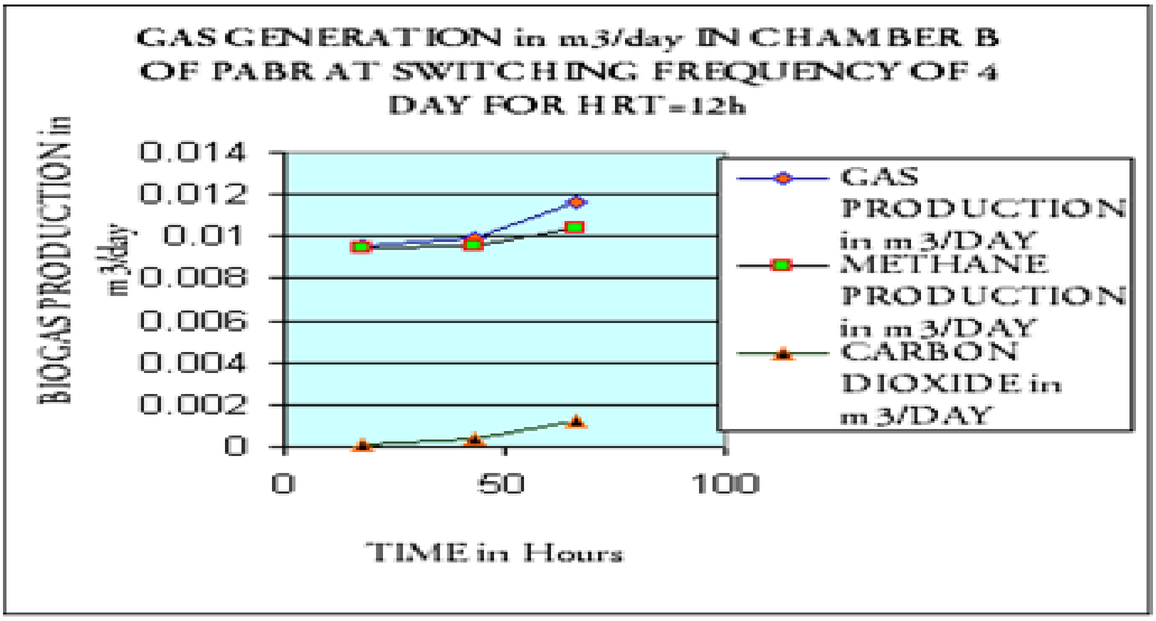


Fig. 13(d)

METHANE YIELD IN CHAMBER B OF PABR	
TIME in Hours	% CH4 YIELD
18	98.75
43	95.9
66	89.7

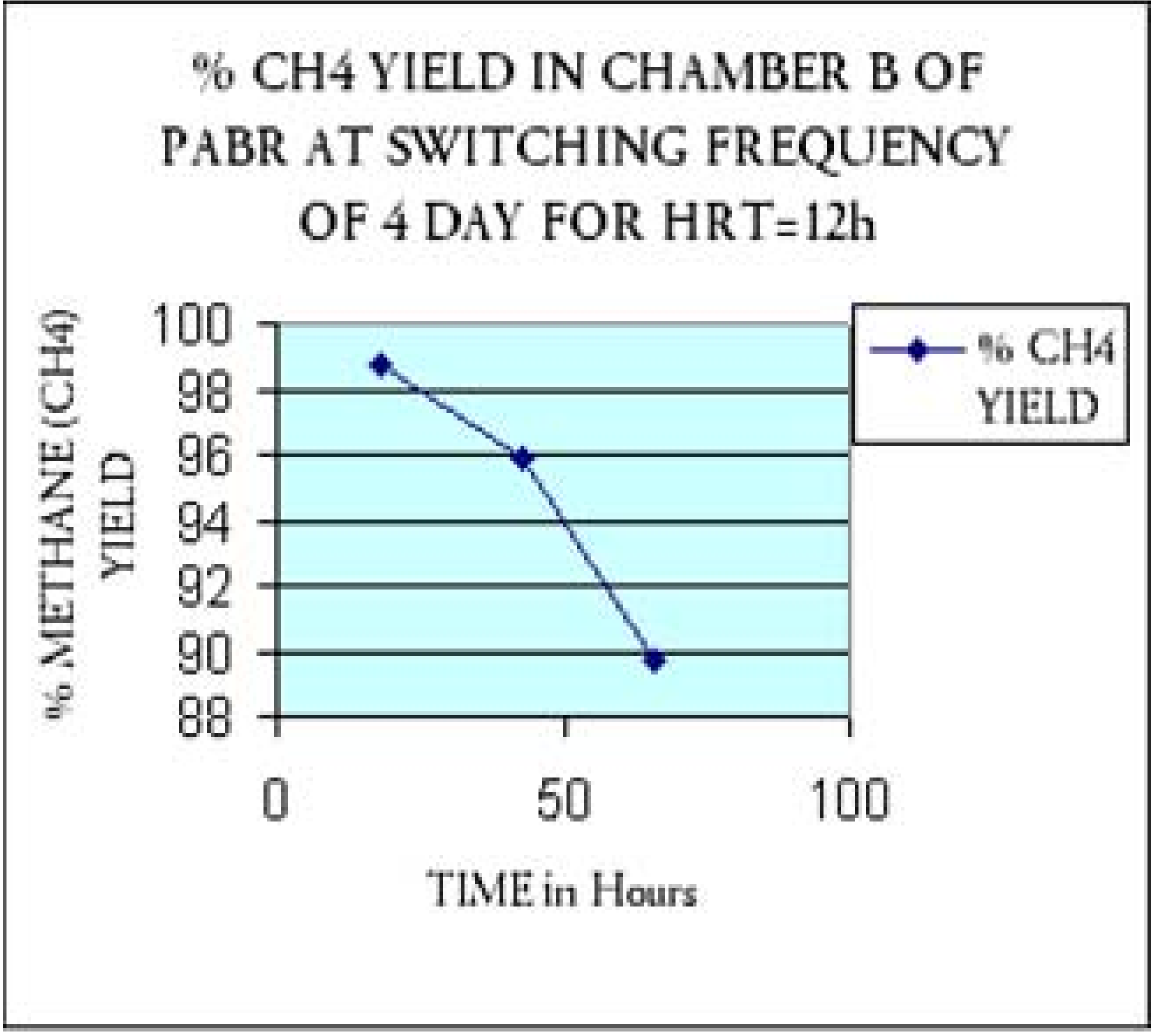


Fig. 14 (d)

Chapter. 5

CONCLUSIONS at the switching frequency of 2 days.

While selecting the switching point in counter clockwise direction, the feeding chamber becomes the effluent chamber. But it stabilizes after 27 hrs of running the PABR at switching frequency of 2 days. Also from Fig 5(b) and 5(d) it can be concluded that there is better methanogenic culture developed in every second compartment. So that if every second compartment of the four compartment PABR selected as feeding compartment than the performance will be better than the counter clockwise or clockwise sequentially switching frequency.

CONCLUSION at switching frequency of 3 days

While running the reactor at switching frequency of 3 days, the achievement of stable periodic state (SPS) occur after 38 hrs of running of reactor. The stability in terms of Effluent COD, VFAs production and conversion, Gas production, Methane production rate and percentage Methane Yield is more stable than the reactor running at switching frequency of 2 days.

CONCLUSIONS

A novel bioreactor, the Periodic Anaerobic Baffled Reactor (PABR) is introduced the fact that the hydraulic behavior of four component PABR is equivalent with behavior of four CSTRs in series, as far as dissolved components are concerned, where as biomass is allowed to be retained in the components of the PABR by precipitation. The accumulation of biomass is simulated assuming that the biomass concentration of the effluent stream from each one of the four component will be equal to (1- □)X if the biomass concentration in the same component is X.

The simulation of the PABR behavior employing the model of Smith *et al.,* (1988) for Anaerobic digestion of glucose and milk powder in the PABR showed that for large values of organic loadings (OLR), the PABR is expected to perform when operated at a high frequency switching feed point, namely it behaves as a UASBR, whereas a for smaller values of the organic loading the PABR should be operated at a smaller frequencies approaching that of an ABR mode. Also the simulation showed that depending on loading rate which is in principle may be variable, it is possible that switching frequency should be manipulated accordingly, allowing for the PABR to be operated as an ABR mode, a UASBR or at an Intermediate mode. Consequently the PABR is best suited for handling time varying loading rate since it allows for maximum conversion rates of all times.

The PABR should prove a useful high rate anaerobic system of high flexibility and it deserves further study and characterization. On the other hand the above-developed model should be useful tool for the future designing of pilot scale PABR; despite that, its validity and prediction capacity are limited to the conditions under which the experiments were conducted.

Finally, the PABR configurtation minimizes the heat losses compare to that ABR, since it is characterized by smaller outer surface area per unit volume (an advantage of the cylindrical shape) and allows for the inner cylinder to be used as a heat exchanger for maintaining the reactor at an elevated temperature.

Chapter. 6

Chapter. 6

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