APPLICATION OF GRADUAL CONCENTRIC CHAMBERS REACTOR FOR LOW-COST DOMESTIC WASTEWATER TREATMENT

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Abstract

A reactor named gradual concentric chambers (GCC) was designed and evaluated at lab-scale. The system used a set of simple self-supporting containers assembled to create anaerobic and subsequent aerobic treatment of domestic wastewater. The effluent quality of the GCC reactor was compared with a lab-scale Upflow Anaerobic Sludge Bed (UASB) reactor which also treated the same wastewater. The results showed that both GCC and UASB reactors has good organic matter removal efficiency, i.e ± 90%, measured as Chemical Oxygen Demand (COD). The elimination of Total Kjeldahl Nitrogen (TKN) and Total Ammonia Nitrogen (TAN) in the GCC reactor were 57% and 61%, respectively. The final effluent of the GCC reactor had a low turbidity and is odorless due to the combination of anaerobic and aerobic conditions employed in the system. The recovery of biogas from the anaerobic treatment of the GCC compartment was about 20% of the expected volume, while 53% of biogas of the expected amount could be captured in the UASB.

Keywords: biogas recovery, COD removal, domestic wastewater, GCC reactor.

1. INTRODUCTION

Increasing the availability of domestic sewage treatment is an important issue to preserve the environmental development. Hence, the sewage treated should be discharged safely to the water courses according to governmental standard or even to pave a way to the next treatment level in aiming for water reuse. Built-up expensive and sophisticated systems for wastewater treatment usually fail at short notice, especially in developing countries (Aiyuk *et al.*, 2006). The requirements for the treatment remain simplicity, non-sophisticated equipment, high system output, low capital costs, and low operating and maintenance costs. Seghezzo (2004) pointed that in developing countries, where capital and skills are not readily available, solutions to wastewater treatment should preferably be low-technology oriented. The efforts to get effective designs in terms of simple and non-sophisticated equipment, low capital investment costs, and low operating and maintenance costs have resulted into the so-called *Low Investment Sewage Treatment* (LIST) concept (Sitorus, 2006). This research has been undertaken due to the strong need for further technical development of small-scale sewage treatment units. Specifically the purpose were to start-up and develop a reactor with a simple design, and further to optimize the operation of the reactor leading to better effluent quality.

The present work evaluates a novel *Gradual Concentric Chamber* (GCC) reactor, which combines anaerobic and aerobic technologies by using a simple assemblage of inexpensive vessels. The treatment was started with anaerobic process since anaerobic treatment is considered sustainable and has several advantages over aerobic treatment technologies (Hammes, Kalogo, and Verstraete, 2000). It consumes little energy, as aeration is unnecessary, and produces renewable energy in the form of hydrogen or methane. However, the Chemical Oxygen Demand (COD) removal and especially the nutrient removal in the anaerobic process mostly are inadequate to meet the stringent effluent standards. The effluent also has a bad odor and the pathogenic organisms are only partially removed (Van Haandel and Lettinga, 1994). Therefore, a post-treatment of the anaerobic effluent is required, that was aerobic treatment in this work. Although an extra energy about of 0.025 €/m^3 wastewater treated was needed for the last compartment, the cost should remain relatively low because of the simplicity of the system.

The performance of the GCC reactor has been compared with a well known and efficient technology, the *Upflow Anaerobic Sludge Bed* (UASB) reactor, in terms of organic matter and nutrient removal, together with biogas production. The UASB reactor has been chosen for the comparison since among the anaerobic reactors, the UASB process has gained popularity recently with over 200 installations worldwide. Its feasibility for sewage treatment is particularly well demonstrated in many tropical countries (Mahmoud *et al.*, 2003).

2. MATERIALS AND METHODS

Experimental Set-up

A lab-scale GCC reactor set-up consisted of two polyethylene plastic containers and a ceramic one, arranged up-side right and down to create the different compartments (Figure 1).

The influent was pumped to the bottom of the anaerobic compartment and the concentric distribution of the containers allowed the effluent of the anaerobic compartment entered the outer aerobic compartment. Deflectors

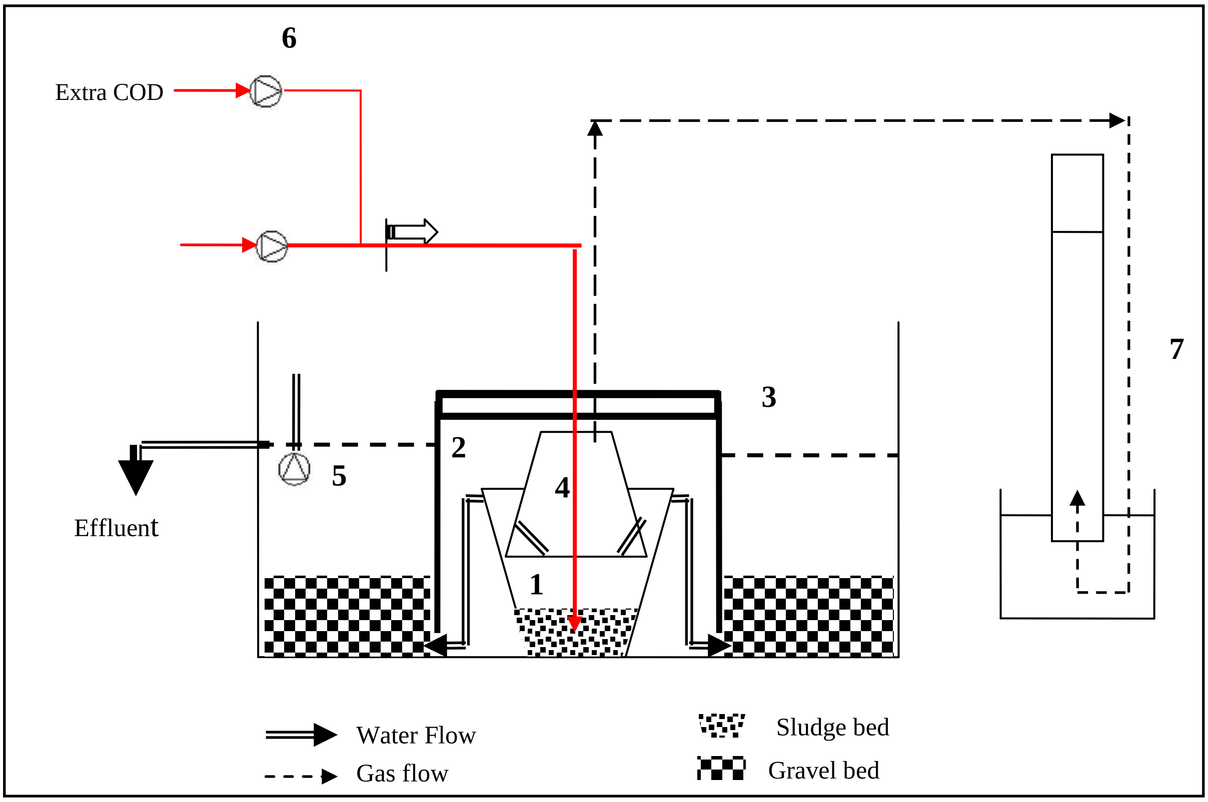

Figure 1. Schematic representation of GCC reactor showing the main components
(1) anaerobic compartment (2) headspace
(3) aerobic compartment (4) gas deflector
(5) water cycling pump (6) influent pumps
(7) biogas collection system

were used to increase the contact between the sludge and the mixed liquor as well as to decrease the sludge wash out. The biogas was collected by volume displacement in a graduated glass column immersed in acidified water (pH = ± 3) to prevent the dissolution of CO_2 in biogas. Table 1 shows the dimensions of the lab-scale GCC reactor.

The anaerobic part of the GCC reactor had a volume of 7.5 L. A 5 L UASB reactor was used as reference. Initially the reactor worked with a low rate condition, the retention time was 9.7-10.4 hours for GCC reactor and 10.5-11 hours for the UASB reactor. Afterwards, both reactors were operated in similar conditions.

Influent

The feeding of the GCC reactor consisted of raw wastewater (Ossemeersen Waste Water Treatment Plant, Ghent, Belgium) containing a total COD concentration of 190 ± 95 mg L^{-1} (Table 2).

To facilitate the application of the reactors for domestic wastewater treatment, the influent COD should be comparable particularly to the common sewage in developing countries. Domestic wastewater has a low organic content with a typical COD concentration in the range of 250-1000 mg L^{-1} (Tchobanoglous and Burton, 1991). Thus the wastewater was strengthened by adding a previously digested commercial starch solution (10 g L^{-1}) and a sodium acetate (99.7%, Merck, Germany) solution (4.3 g L^{-1}), in the start-up and experimental period, respectively. The acetate solution was dosed to increase the influent COD up to 589 ± 50 mg L^{-1} approximately, in the experimental period.

Table 2. Characteristics of raw wastewater used to prepare the influent

Parameter	Unit	Value
pH	-	7.3 ± 0.1 (n = 90) 7.6 ± 0.2* (n = 90)
COD	mg L^{-1}	190 ± 95 (n = 45) 589 ± 50* (n = 45)
NH_4^+	mg L^{-1}	37 ± 6 (n = 45)
TON	mg L^{-1}	0 (n = 45)
TKN	mg L^{-1}	51 ± 4 (n = 45)
TSS	mg L^{-1}	213 ± 35 (n = 20)
VSS	mg L^{-1}	128 ± 26 (n = 20)
$P\text{-}PO_4^{3+}$	mg L^{-1}	4.8 ± 2.0 (n = 20)

* Total influent value
n = number of measurements

GCC and UASB Reactors Start-up and Performance

The anaerobic compartment of the GCC and the UASB reactors were inoculated with anaerobic sludge with VSS of 17 g L^{-1}. The sludge originating from an industrial mesophilic anaerobic digester (potato processing treatment plant, Primeur, Waregem, Belgium), working at a volumetric organic loading rate (B_v) of 7 g COD $L^{-1}d^{-1}$. The reactors were operated at 33 ± 1°C and two periods can be differentiated: the start-up and the experimental phase. The start-up of the reactors lasted two months and the most suitable operational conditions for the experimental phase were investigated. Increasing B_v of 1.8-6 g COD $L^{-1}d^{-1}$ and 1.5-3.4 g COD $L^{-1}d^{-1}$ were applied in the UASB and GCC reactors, respectively, in order to determine the maximum capacity of each system (data not shown).

In order to evaluate the reactor performance in different conditions such as of organic loading rate (B_v) the reactor was operated 90 days at a temperature of 33-34°C. The analysis of physicochemical parameters such as COD, nitrogen, and the biogas was

Table 1. Dimensions of the lab-scale GCC reactor

Dimension	Compartment			
	Anaerobic	Headspace*	Aerobic	Gas Deflector
Diameters (mm)	170-260	300	-	125-200
Height (mm)	205	165	400	185
Length (mm)	-	-	500	-
Width (mm)	-	-	400	-
Volume (L)	7.5	11.6	33.2	5

* Liquid volume of anaerobic effluent under headspace: 6.3 L

conducted every 2 days. The results were evaluated according to the division of experimental periods (4 phases). This division was based on different conditions which were applied in the phases. Phase I started from day 1 to 16, phase II from day 17 to 40, phase III from day 41 to 64, and finally phase IV from day 65 onwards until day 90.

In the GCC reactor, the working conditions were as the following. Phase I: B_v = 1.4 to 1.6 g COD $L^{-1}d^{-1}$ and HRT = 9.7-10.4 hours. Phase II was conducted with B_v = 2 to 2.2 g COD $L^{-1}d^{-1}$ and HRT = 6.2-6.4 hours. During phase III and IV, the reactor was operated at the same B_v and HRT as in phase II. However, in phase III, methanostim was applied whereas in the last phase the addition of methanostim was stopped. Methanostim was a complex additive which expected would optimize methanogenesis. It contains trace elements that promote a better conversion of volatile fatty acids in biogas and also includes all the necessary vitamins for a complete and nutritive balance.

The UASB reactor was operated on the comparable observations with the work conditions of the GCC reactor. In phase I the B_v was 1.4 to 1.5 g COD $L^{-1}d^{-1}$ and the HRT was 16-18 h. Phase II was performed with B_v = 2 to 2.5 g COD $L^{-1}d^{-1}$ and HRT of 7.5-8.5 h. The other phases were carried out in a similar way to the GCC reactor, with application of methanostim simply in phase III.

During the experimental period, the aerobic compartment of the GCC reactor was equipped with a low energy demand internal filter pump (Eheim aquaball, EH-2208020, Germany), whose function was to rotate concentrically the upper water layers, and a gravel bed for settling of both solids and anaerobic biota. The gravel was meant to play a role as a roughing filter and to retain the biomass otherwise washed out from the inner compartment. The recycle pump also produced aeration. It was expected could diminish the disadvantage of the anaerobic digestion concerning effluent odor problem. During the entire period of operation, there was no intentional sludge discharge.

Analytical Methods

COD, Total Suspended Solids (TSS), Volatile Suspended Solids (VSS), Total Kjeldahl Nitrogen (TKN), Total Ammonia Nitrogen (TAN), Total Oxidized Nitrogen (TON), and pH analysis were routinely performed according to the Standard Methods for the Examination of Water and Wastewater (APHA, 1992). The Volatile Fatty Acids (VFA) was analyzed using a gas chromatograph GC 8000 Top Series (CE Instruments, Italy) equipped with an auto-sampler AS 800 (CE Instruments), a capillary column Phase EC^{TM}-1000 (110-165°C), a flame ionization detector (FID, 200°C) and with N_2 as carrier gas. The biogas composition (CH_4 and CO_2) was analyzed using a gas chromatograph GC-14B (Shimadzu, Japan) equipped with a custom packed column Alltech PC-5000 (45-80°C), a thermal conductivity detector (TCD, 200°C), and with helium as carrier gas. Mean values and standard deviations were obtained using standard software (Microsoft Excel).

3. RESULTS AND DISCUSSION

COD Removal

The start-up of the GCC reactor was characterized by a low COD removal efficiency (60%), pH instability of the substrate and reactor souring conditions (data not shown). Therefore, during the experimental period, a more stable feeding solution based on sodium acetate plus wastewater was used as influent. Figure 2 shows the COD concentrations variation of the GCC reactor over time. The average influent COD (sewage plus sodium acetate) was 578 ± 53 mg L^{-1} whereas the effluent COD ranged from 37 to 89 mg L^{-1} (59 ± 13 mg L^{-1}, average concentration).

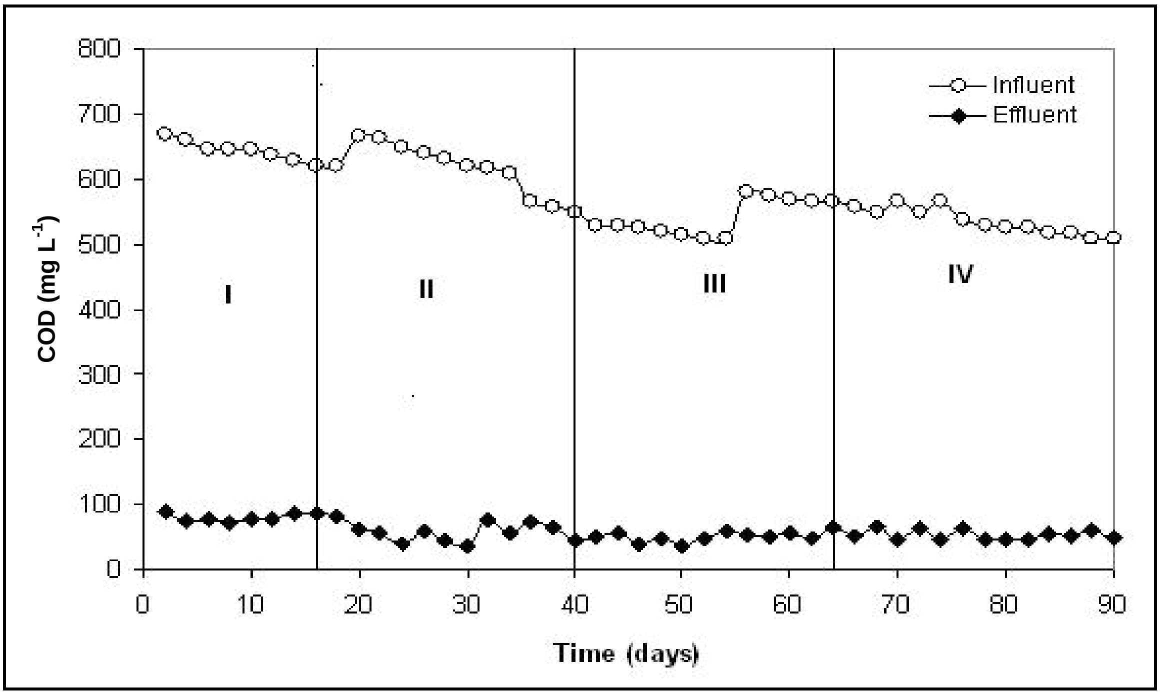

Figure 2. Variation of the COD in the influent and effluent during the experimental period of the GCC (vertical lines show four different phases)

During the four phases, the COD removal efficiencies in the GCC reactor were as follows: 88 ± 1%, phase I; 90 ± 3%, phase II; 91 ± 1%, phase III; and 90 ± 1%, phase IV. It resulted in an average removal efficiency of 90 ± 2% for the whole period (B_v range = 1.4-2.2 g COD $L^{-1}d^{-1}$). The low standard deviation associated with the removal efficiencies along the different phases, indicated that the effluent quality in terms of COD was relatively constant. The effluents pH also showed a narrow variation between 7.4 and 7.8. It was also noticed that the additive used did not affect the reactor performance in terms of COD elimination. The COD removal efficiency percentage of 90 ± 2% was attained by using UASB reactor, which was not different from that obtained in the GCC reactor. The influent COD concentrations of the UASB reactor ranged from 516 to 691 mg L^{-1}, resulting in an average COD of 600 ± 48 mg L^{-1}. The effluent COD concentrations averaged 59 ± 13 mg L^{-1}. The reactor performance in terms of organic matter removal remained high during each experimental period. There were no significant changes related to the COD removal efficiency in each phase. It rose to about 92 ± 1% during phase III (from 88 ± 1% in phase II) when methanostim was added. When methanostim addition was eliminated during phase IV, the COD removal efficiency stayed at 91 ± 1%. After the discontinued methanostim addition, the COD removal was still acceptable, indicating that the vitamins and minerals effect can be long lasting. Methanostim addition, seemed have no effect on COD removal efficiency. The methanostim addition purpose was to optimize the methanogenesis process in order to have a high biogas recovery.

The results generally showed a high performance of the reactor and were comparable with those of previous works. Bodik, Herdova, and Drtil, (2002) reported the treatment of a mixture of synthetic substrate (glucose and sodium acetate) and a real municipal wastewater. The authors presented that the treatment for the mixture which was conducted by means of an Anaerobic Sequencing Batch Reactor (AnSBR) and an Upflow Anaerobic Filter (UAF) had good results as well.

Total Kjeldahl Nitrogen (TKN), Total Ammonia Nitrogen (TAN), and Total Oxidized Nitrogen (TON)

The influent showed an average TKN value of 51 ± 4 mg L^{-1}. The GCC and UASB reactors showed an average TKN removal efficiency of 57 ± 7% and 17 ± 9%, respectively. For the GCC reactor, the TKN removal percentages remained constant along the four phases of study (Table 3).

In contrast, the UASB reactor showed increased values along the phases. TAN influent levels averaged 37 ± 6 mg L^{-1}. Lower TAN concentrations were obtained in the effluents of the GCC reactor (14 ± 4 mg L^{-1}) in comparison with those of the UASB reactor (40 ± 6 mg L^{-1}). Both reactors showed negligible nitrite and nitrate levels in the effluent (< 2 mg L^{-1}). This fact indicates that the elimination of TKN and TAN in the GCC reactor was not reflected in the NO_2^- and NO_3^- levels in the effluents. Although the nitrogen balance in GCC reactor is not yet well established, these results suggest that a partial simultaneous nitrification-denitrification process (SND) could occur in the outer compartment (toxic conditions), where increasing dissolved oxygen (DO) concentrations from the lower still water layers (gravel bed) to the upper horizontally rotated layers are present. Chiu *et al.* (2006) studied the influence of COD/NH_4^+ ratios on SND process treating domestic wastewater, stating that a minimum value of 6 for this parameter and low DO levels (0.3-0.8 mg L^{-1}) are needed for a partial SND process.

Solid Analysis

The GCC reactor promoted higher TSS and VSS removal, 40 ± 9% and 86 ± 2%, respectively, than the UASB reactor, 25 ± 6% and 41 ± 15% (data not shown). One reason for this higher solids removal could be the high rate of solids deposition in the GCC reactor, given the lower dynamic conditions in the sludge-containing compartment, compared to the UASB reactor. Low solids removal is common in UASB operation, but higher elimination could be also obtained depending on various interrelated operational parameters (Mahmoud *et al.*, 2003).

Biogas and Methane Recovery

Figure 3 shows the biogas and methane recovery for the GCC reactor along the experimental period. Biogas production is expressed as volume of biogas per amount of COD removed. Recoveries refer to the total biogas (or methane) produced in relation to the expected theoretical volume, 0.5 and 0.35 L of biogas and methane, respectively, per g of COD removed (Tchobanoglous, Burton, and Stensel, 2003). During the start-up period, the biogas recovery of the GCC reactor was about 38% of the expected value, whereas during the whole experimental period, it varied from 28 ± 2 to 53 ± 11%. The anaerobic treatment of low strength wastewaters usually leads to a loss of more than 50% of biogas in the water phase (Lettinga *et al.*, 1993). The methane recovery ranged from 18 ± 3 to 50 ± 9%, which means a methane production varying between 63 ± 8 and 118 ± 13 mL g^{-1} COD removed. The higher values obtained in phase III were probably due to an improved biogas collection and an increase of methane content (additive effect). This effect is possibly related to the input of the additive, which optimizes the nutritive balance between the different bacterial groups within the microbial consortium, and thus increasing the methanogenesis.

During the start-up, the UASB reactor showed a maximum biogas recovery of 97% at a B_v of 2.6 g COD $L^{-1}d^{-1}$ (HRT = 91 hours). In the experimental period, it decreased to 30-60%. Overall, the biogas recovery in the GCC reactor was lower than that of the UASB reactor. The biogas recovery in the GCC reactor was limited by the inadequate mixing in the anaerobic compartment. It decreased the contact between sludge and wastewater to be treated, as well as the biogas production.

Table 3. Average values of influent and effluent TKN concentrations and removal efficiencies in the GCC reactor

Phase	Influent (mg Kj-N/L)	Effluent (mg Kj-N/L)	Removal Efficiency (%)
I (n = 8)	45 ± 2	21 ± 3	55 ± 6
II (n = 12)	51 ± 3	22 ± 4	57 ± 9
III (n = 12)	55 ± 2	24 ± 2	57 ± 4
IV (n = 13)	50 ± 3	21 ± 4	57 ± 9
Total (n = 45)	51 ± 4	22 ± 3	57 ± 7

n = number of measurements

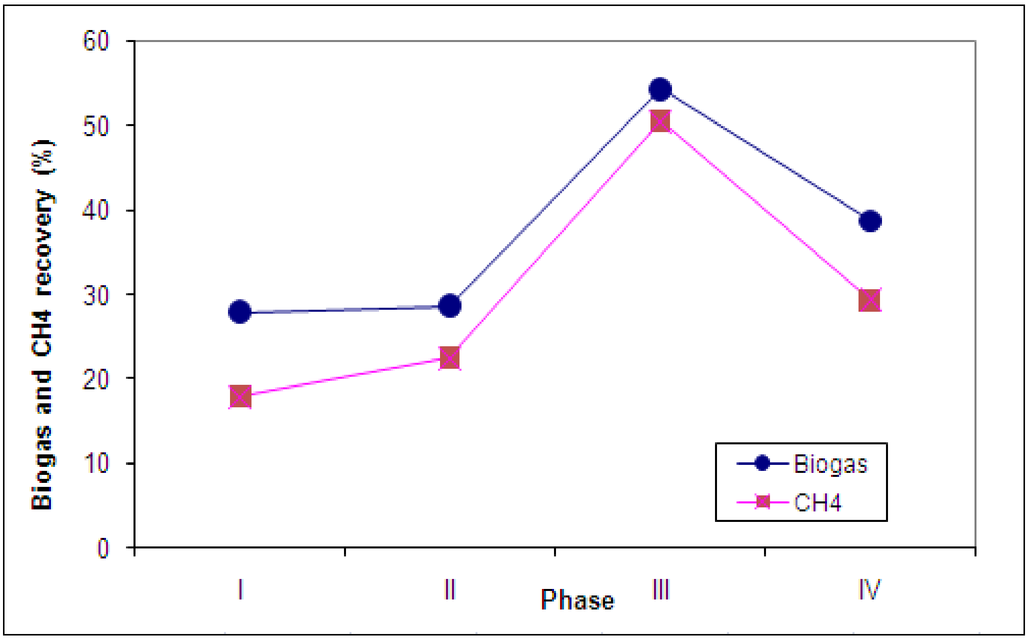

Figure 3. Biogas and methane recovery during the GCC reactor operation

4. CONCLUSIONS

The GCC reactor principle is considered low cost because it is of lower technological complexity than conventional wastewater treatment plants. It is also considered to be less expensive in terms of operation. The application of the GCC reactor seems to be a potential technology for the treatment of domestic sewage, especially in developing countries with tropical or sub tropical climate. The removal efficiency of total COD was generally good (90%). The removal efficiency obtained is similar to the sewage direct treatment by means of UASB as measured in this study. There are two advantages of this system. First, it has a clear effluent which can be reused either in agriculture or in industrial process. Yet, a thorough analysis with regard to the water reuse standard will be needed. Second, the effluent was odorless implying that the system has superiority compared to a treatment which only works anaerobically.

For the UASB reactor tested, the same wastewater had a COD removal of 90% as well. This shows that both the GCC and the UASB reactor performances are appropriate for domestic sewage treatment. The little biogas recoveries in both reactors are related to the low strength of the wastewater treated. However, they do not directly negatively affect the applicability of anaerobic digestion for sewage treatment since the biogas is only a minor aspect relative to the cleaning of the water.

Detailed cost calculations for GCC reactor such as for investment, operation, maintenance, and management, including monitoring for the systems are needed. Improvement of reactor dimension design can be done for the GCC reactor. The preferred sizes of plants in the up-scaling should be chosen to become fixed standard designs based on local conditions and needs.

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