



# Anaerobic digestion of animal waste: effect of mixing

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## Abstract

Six laboratory scale biogas mixed anaerobic digesters were operated to study the effect of biogas recycling rates and draft tube position on their performance. All the digesters performed very similarly with methane (CH<sub>4</sub>) production rates of 0.40 to 0.45 L per L of digester volume per day. A higher methane production rate was observed in the unmixed digester and an increased gas circulation rate had a negative impact on the methane production. However, there was no difference in the methane production rate for digesters with different positions of the draft tube. Air infiltration (up to 15% oxygen in the biogas) was observed in the digesters mixed with biogas recirculation. The observed air infiltration could be because of slight air permeability of the tubing, leakage on the vacuum side of the air pump, etc. Similar performance of all the digesters (mixed or unmixed) could be because of the lower solid concentration (5%) in the fed animal slurry, where mixing created by the naturally produced gas was sufficient enough to overcome the hydrodynamic limitations.

## 1 Introduction

Growth and concentration of the livestock industries provide a large source of affordable and renewable energy whilst bringing in the requirement for means of safe disposal of the large quantities of animal waste (manure) generated at dairy, swine, and poultry farms. In the United States itself over 100 million tons of dry matter produced every year [1]. Unsafe and improper disposal of decomposable



animal waste causes major environmental pollution problems including surface and groundwater contamination, odors, dust, and ammonia leaching. There is also a threat from methane emissions, which constitutes to the green house effect. The ever mounting growth in the animal industries has resulted in the formulation of new laws and regulations governing safe handling and disposal of animal waste. A survey of dairy and swine farms in the country reaffirmed that anaerobic digestion is a technology with considerable potential. Ignoring caged layer poultry, the inventory of these economically recoverable emissions suggests that about 0.426 Tg of methane are potentially recoverable from 3,000 dairy and swine farms in 19 states of the USA [2].

Anaerobic digestion is a promising animal waste management option as it leads to the generation of methane which can be used as a renewable energy source. Over the past 25 years, anaerobic digestion processes have been developed and applied to a wide array of industrial and agricultural waste [3, 4]. The performance of anaerobic digesters is affected primarily by the retention time of the substrate in the reactor and the degree of contact between the incoming substrate and a viable bacterial population. These parameters are a function of the hydraulic regime (mixing) in the reactors. Thorough mixing of the substrate in the digester is required to distribute organisms uniformly throughout the mixture and to transfer heat, and is thus regarded to be essential in high-rate anaerobic digesters [5, 6]. Furthermore, agitation aids in particle size reduction as digestion progresses and in removal of gas from the mixture. The importance of mixing in achieving efficient substrate conversion has been noted by many workers [7, 8, 9], although the optimum mixing pattern is a subject of much debate. An intermediate degree of mixing appears to be optimal for substrate conversion [9]. Mixing can be accomplished with a variety of mechanical mixers, recirculation of digesters contents or recirculation the produced biogas using recirculation pumps. Mechanical mixers are reported to be most efficient in terms of power consumed per gallon mixed [10]. However, the internal fittings and equipment (required for mechanical mixing) are not accessible for maintenance purpose during digester operation and the long term reliability of operation is of paramount importance. In general, such reliability can be more readily attained with biogas or liquor recirculation systems, where there are no moving parts within the digester [7]. On the other hand, many works in the literature report mixing achieved by biogas recirculation as most efficient for biogas production from anaerobic digesters [8, 11, 12].

In the case of a digester mixed with biogas there are various important parameters which can affect the mixing pattern inside the digester, such as: biogas recycling rate, bottom clearance of the draft tube, slope of the hopper bottom, draft tube to tank diameter ratio, position of injection point, solids loading rate, etc.

The ongoing research work is involved in finding the optimal mixing conditions for anaerobic digesters dealing with animal waste and in visualizing the change in the mixing pattern and hydrodynamics with the change in mixing conditions using advanced non-invasive techniques like Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT). In the

Chemical Reaction Engineering Laboratory (CREL) at Washington University in Saint Louis, these techniques have been successfully implemented on various types of multiphase reactors, such as stirred tank, fluidized bed, ebullated bed, bubble column, etc. [13, 14, 15] and are now being employed on anaerobic digesters. The data collected from the CARPT experiment provides various important hydrodynamic parameters like 3D flow pattern, velocity components, kinetic energy, shear stresses, turbulent eddy diffusivities, etc. in the 3D domain of the digester. In addition, the CARPT data can be processed to get information about the trajectory length distribution (TLD), mixing indices and stagnancy regions. Computed tomography data gives the information about phase's holdups at different crosssections of the digester. Another important objective of this project is to advance these techniques to multiparticle computer automated radioactive particle tracking (MP-CARPT) and dual source computed tomography (DSCT), which would be more appropriate for a three phase system like digesters having moving solid particles of more than one size and density. However, the current paper is intended to evaluate the effect of different mixing conditions (biogas recycling rate and draft tube position) on the performance of anaerobic digesters mixed with biogas recirculation.

## 2 Materials and methods

Six laboratory scale digesters viz., Digesters 1 - 6, having a working volume of 3.73 L was operated at a controlled temperature of  $35 \pm 2^\circ\text{C}$ . Biogas generated in the digesters was collected in tedlar bags and was recirculated from the top of the digesters to create mixing using an air pump and draft tube arrangement as shown in Figure 1. The digesters were inoculated with 373 mL anaerobic seed sludge collected from a dairy farm operated by the University of Tennessee. The seed sludge had a total suspended solid (TSS) and a volatile suspended solid (VSS) of 66.13 g/L and 35.63 g/L, respectively. The remaining 90% of the working volume was filled with fresh prepared manure slurry having a dry solid concentration of 50 g/L (i.e. 5% solids that is 100 mL of slurry contains 5g of dry solids). The hydraulic retention time (HRT) was kept constant at 16.2 days resulting in a solid loading rate of 3.08 g TS/L-d. About 460 mL of effluents were taken out from the bottom of the digesters on every alternate day and fed with the same amount of freshly prepared animal waste slurry. The digesters were operated with different biogas recirculation rates and draft tube positions as described in Table 1. Digesters were operated under steady-state conditions for about three to four weeks. Steady-state conditions were considered when the coefficient of variation for daily gas production was less than 10% [16].

Feed and effluent samples were analyzed for total solids (TS), volatile solids (VS), TSS, VSS, volatile fatty acids (VFA), total chemical oxygen demand (TCOD), dissolved chemical oxygen demand (DCOD), and total nitrogen (TN). The total volume of the biogas generated was measured and the composition of the biogas was analyzed three times every week. All the analyses were performed as per standard procedures [17] unless otherwise mentioned separately.

Volatile fatty acids (formic, acetic, propionic, butyric, and valeric acids) were determined by centrifuging a small sample at greater than 10,000 rpm for 5 min, filtering the liquid through a 0.2- $\mu\text{m}$ -pore-size filter, and injecting 10  $\mu\text{L}$  sample into a high pressure liquid chromatograph (HPLC). In the HPLC, the mobile phase (filtered 5 mM  $\text{H}_2\text{SO}_4$ ) was pumped at 0.6 ml/min through a 300 mm  $\times$  7.8 mm (8  $\mu\text{m}$  particle size) RHM Monosaccharide column (Phenomenex, Torrance, CA) held at a temperature of 65°C to a refractive index detector (Model 2410, Waters Corporation, Milford, MA) held at a temperature of 40°C.

Total nitrogen was determined by diluting approximately 1 g of slurry to 50 mL with ultra pure water. Five mL of this dilute solution and 5 mL of ultra pure water was then digested for 60 min at 121°C using 1.5 mL potassium persulfate solution (1 g  $\text{K}_2\text{S}_2\text{O}_8$ , 1 g NaOH, 17 mL ultra pure water) in Teflon-capped vials. Digested samples were cooled and pH was adjusted with  $\text{H}_2\text{SO}_4$  (50%) to pH 2.7. This procedure converts all organic and inorganic nitrogen to nitrate, which was measured using a nitrate ion-sensitive electrode (Models 9307, 9300BN, and 900200; Thermo Orion, Beverly, MA) [18, 19].

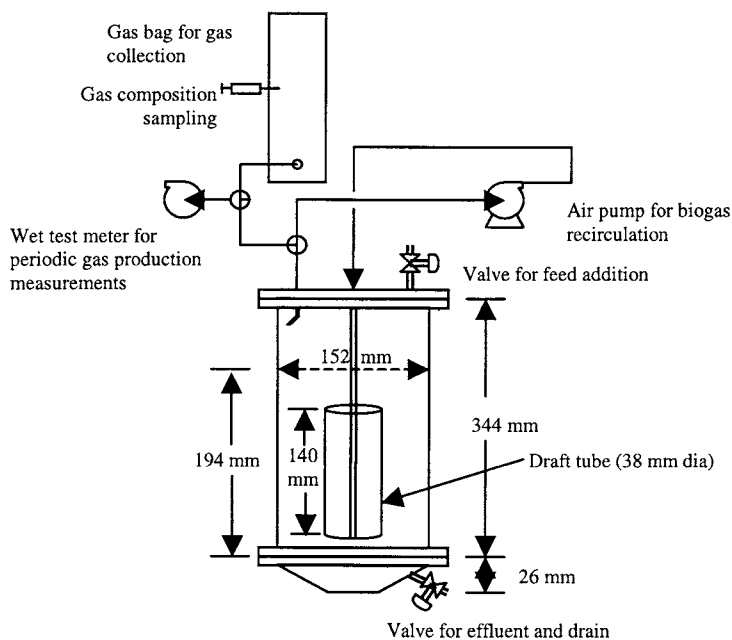


Figure 1: Schematic diagram of the experimental set-up.

Biogas volume was measured using wet gas test meters (GSA/Precision Scientific, Chicago, Ill) and the samples (150  $\mu\text{L}$ ) for biogas composition were collected using a gas-tight syringe. The samples were injected in duplicate into a Hewlett Packard (Model 5890 Series II, Avondale, PA) gas chromatograph (GC) with a 0.53 mm  $\times$  30 m GS-Q phase capillary column (J&W Scientific, Folsom, CA). The injector, oven, and thermal conductivity detector (TCD) temperatures

were kept at 125, 50, and 250°C, respectively. The carrier gas (helium) flow rate through the column was maintained at 4 ml/min. The samples were injected in a split mode with approximately 10% of the sample going through the column. The column, make-up, and reference gas in the GC was helium. Initially GC was calibrated with 99.9% pure methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), and air samples by injecting their different volumes (50–200µL). Later, periodic calibration was performed by injecting different amounts of air and using the relationship between TCD response factors as described by Dietz [20].

Table 1: Operational conditions for the digesters.

Digesters	Biogas recirculation rate (L/min)	Draft tube position from bottom (mm)
Digester 1	None (unmixed)	40
Digester 2	1	40
Digester 3	1	26
Digester 4	2	40
Digester 5	3	40
Digester 6	1	13

### 3 Results and discussion

The performance of the six laboratory scale digesters, over a period of about 60 days, is shown in Figures 2–7. It can be seen from the figures that initially there was a variation in the biogas production rate in all the six digesters. This corresponds to a period when a modified feeding procedure was adopted. The change in feeding procedure resulted in a change of hydraulic retention time, which caused a short term upset as the digester adjusted to the new conditions. However, the methane content of the biogas was always close to 65%.

The average biogas production rate and the composition under steady-state conditions have been presented under Table 2. Each value has been calculated as a mean value over 21 days and the error term corresponds to the 95% confidence interval of the mean, using a Student's t-distribution. The biogas and methane production rate has been calculated as the volume of biogas/methane produced per L of digester volume per day. It can be noted from Table 2 that all the six digesters performed very similar with CH<sub>4</sub> production rates of 0.40 to 0.45 L/kg/day. The performance of the digesters as a function of gas circulation rate and position of the draft tube (Table 1) has been plotted in Figures 8 and 9. Based on the results collected, we draw the conclusion that increased gas circulation rate had a negative impact on the methane production rate. However, statistically there was no difference in the methane production rate for digesters with different positions of the draft tube (Figure 9).

It is important to note that biogas circulation in laboratory digesters increases the chances for 'infiltration' of air into the system (due to slight air permeability of tubing, leakage on the vacuum side of the air pump, etc.) as shown in Table 2. Since the presence of oxygen is known to have a detrimental effect on methane

production, the difference in the performance of the digesters could be attributed to oxygen infiltration. The oxygen infiltration was estimated from the nitrogen content in the biogas, which ranged from 3% in digester 1 to 15% in digester 4, assuming all nitrogen in the biogas was the result of air infiltration. However, no clear relationship between  $O_2$  infiltration and methane productivity could be established. One important thing observed during this study was that slight air infiltration into the digesters resulted in the reduction of hydrogen sulfide ( $H_2S$ ) in the biogas as shown in Table 2. Higher methane production rates in unmixed digesters have also been reported by Ghaly and Ben-Hassan [21]. On the other hand Bello-Mendoza and Sharratt [22] observed that unmixed reactors perform worse, especially when they were large in size.

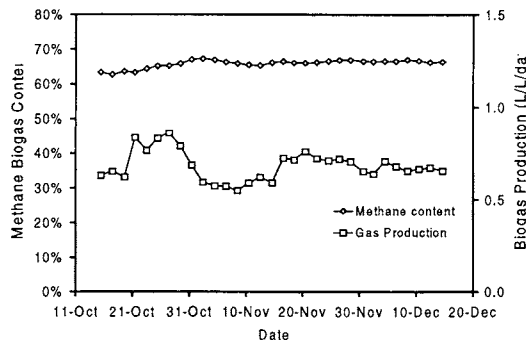


Figure 2: Performance characteristics of Digester 1.

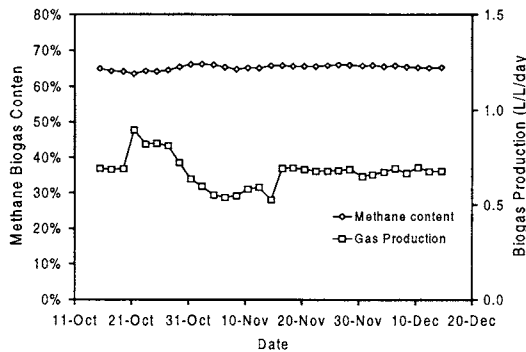


Figure 3: Performance characteristics of Digester 2.

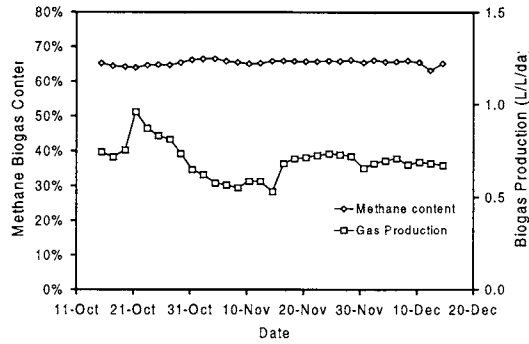


Figure 4: Performance characteristics of Digester 3.

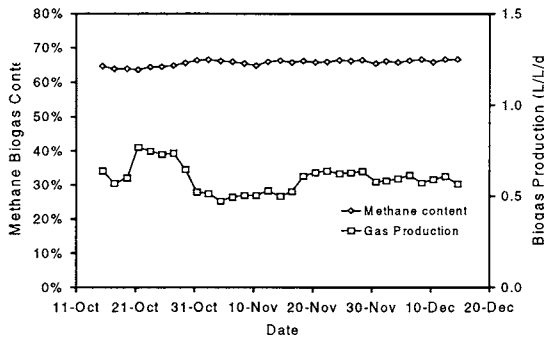


Figure 5: Performance characteristics of Digester 4.

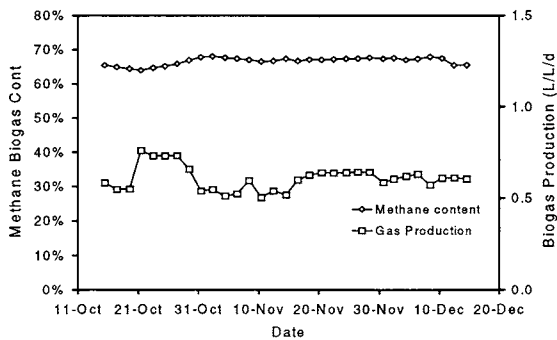


Figure 6: Performance characteristics of Digester 5.

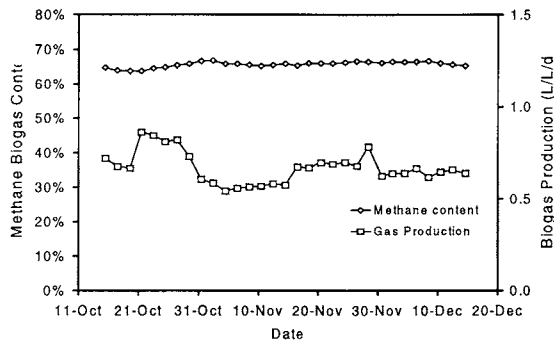


Figure 7: Performance characteristics of Digester 6.

Table 2: Performance data of the digesters.

	Biogas production Rate (L/L/day)	Methane content (% CH <sub>4</sub> )	CH <sub>4</sub> Production Rate (L/L/day)	H <sub>2</sub> S (ppm)	O <sub>2</sub> Infiltration (L/day)
Digester 1	0.68	67±0.1	0.45	350	0.16
Digester 2	0.67	66±0.2	0.44	<2.5	0.79
Digester 3	0.69	65±0.6	0.45	<5	0.61
Digester 4	0.60	66±0.3	0.40	<5	0.82
Digester 5	0.61	67±0.6	0.41	10	0.52
Digester 6	0.65	66±0.3	0.44	<2.5	0.83

Table 3 shows the average steady-state data of TS, VS, TSS, VSS, VFA, TCOD, DCOD and TN in the feed and effluents from all the six reactors. The table shows that total solids and volatile solids reductions were about 30–38% and 40–48%, respectively in all the six digesters. Total COD in the feed was about 52.7 g/l, about 18% of which was present in the form of dissolved COD. The reduction of TCOD was observed as 44% to 50% for all the six digesters. No volatile fatty acids accumulation was observed in any digesters. The only fatty acid detected in the effluents from the digesters was acetate and the concentration of VFA in effluents was very low as shown in Table 3.



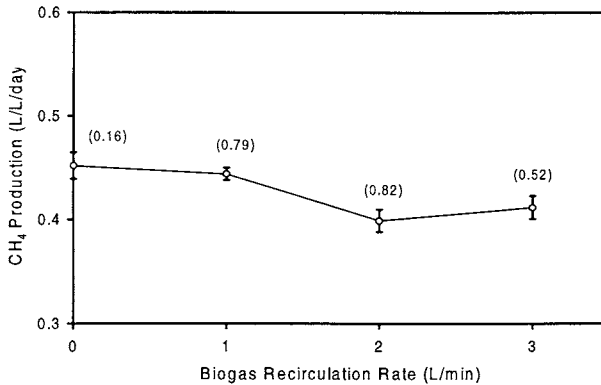


Figure 8: Methane production rate for different biogas recirculation rates. (Values in parentheses correspond to estimated O<sub>2</sub> infiltration rates in L O<sub>2</sub>/day.)

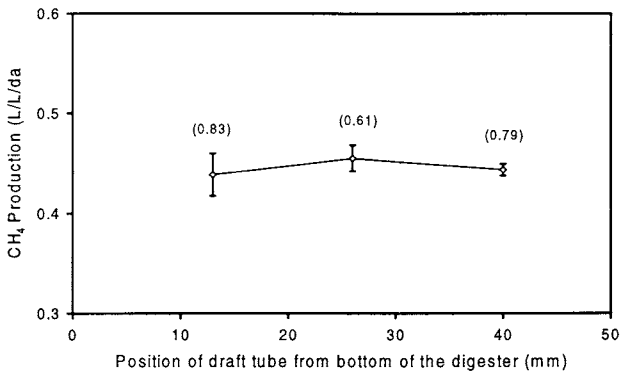


Figure 9: Methane production for digesters having different draft tube positions. (Values in parentheses correspond to estimated O<sub>2</sub> infiltration rates in L O<sub>2</sub>/day.)

Table 3: Average steady-state observation data for feed and effluents.

	TS (%)	TVS (%)	TSS (%)	VSS (%)	VFA (g/L)	TCOD (g/L)	DCOD (g/L)	TN (g/L)
Feed	5.0	2.5	2.9	1.5	3.0	52.7	9.45	1.33
Digester 1	3.1	1.3	2.6	1.2	0.06	26.5	4.22	1.37
Digester 2	3.5	1.5	2.6	1.3	0.01	28.2	3.75	1.65
Digester 3	3.2	1.4	2.0	0.9	0.01	28.6	3.83	1.37
Digester 4	3.5	1.6	3.2	1.5	0.03	29.3	3.96	NA
Digester 5	3.3	1.5	NA	NA	0.03	28.8	4.09	NA
Digester 6	3.5	1.5	NA	NA	0.02	27.2	3.95	NA



## 4 Conclusions and remarks

There was no difference in the performance of all the six digesters with different mixing conditions. This could be because of the lower solids concentration in the fed animal slurry or because of long enough HRT of 16.2 days, where mixing created by the naturally produced gas was sufficient enough to overcome the hydrodynamic limitations. However, it would be interesting to see whether the mixing patterns inside the digesters changed with the applied physical changes in the mixing conditions. Work is in progress to evaluate the mixing patterns of the studied digesters using single particle Computer Automated Radioactive Particle Tracking and single source gamma-ray Computed Tomography.

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## References

- [1] Fontenot, J.P. & Ross, I.J. Animal waste utilization. In: *Livestock waste: A renewable resource. Proc. 4<sup>th</sup> Int. Symp. on Livestock Wastes*, ASAE, St. Joseph, MI, 1980.
- [2] Lusk, P. Methane Recovery from Animal Manures: A Current Opportunities Casebook. 3rd Edition. *NREL/SR-580-25145*. Golden, CO: National Renewable Energy Laboratory. Work performed by Resource Development Associates, Washington, DC, 1998.
- [3] Speece, R.E. *Anaerobic Biotechnology for Industrial Wastewaters*. Vanderbilt University, Arachae Press, 1996.
- [4] Ghosh, S. Anaerobic Digestion For Renewable Energy and Environmental Restoration. *The 8th Intern. Conference on Anaerobic Digestion*, Sendai International Center, Sendai, Japan, Ministry of Education Japan, 1997.
- [5] Sawyer, C.N. & Grumbling, A.M. Fundamental consideration in high-rate digestion. *Inc. Sew. Eng. Div. ASCE*, pp. 86-92, 1960.
- [6] Meynell, P.-J. *Methane: Planning a Digester*. Prism Press, London, pp. 55-57, 1976.
- [7] Casey, T.J. Requirements and methods for mixing in anaerobic digesters. *Anaerobic digestion of sewage sludge and organic agricultural wastes*, Elsevier, App. Sci. Pub., pp. 90-103, 1986.
- [8] Lee, S.R., Cho, N.K. & Maeng, W.J. Using the pressure of biogas created during anaerobic digestion as the source of mixing power. *J. Ferment. Bioengrng.*, **80(4)**, pp. 415-417, 1995.
- [9] Smith, L.C., Elliot, D.J. & James, A. Mixing in upflow anaerobic filters and its influence on performance and scale-up. *Water Research*, **30(12)**, pp. 3061, 1996.



- [10] Brade, C.E. & Noone, G.P. Anaerobic digestion – need it be expensive? *Wat. Pollut. Control*, **80**, pp. 70, 1981.
- [11] Morgan, P.F. & Neuspiel, P.J. Environmental control of anaerobic digestion with gas diffusion. In: McCabe, J. and Eckenfelder, W.W. (ed.), *Biological treatment for sewage and industrial wastes*, vol. 2, Reinhold, New York, 1958.
- [12] Kontandt, H.G. & Roediger, A.G. Engineering operation and economics of methane gas production. In: Schlegel, H.G. and Barnea, J. (ed.), *Microbial energy conversion*. Pergamon Press, pp. 379-392, 1977.
- [13] Roy, S., Kemoun, A., Al-Dahhan, M.H. & Dudukovic, M.P. A method for estimating the solids circulation rate in a closed-loop circulating fluidized bed. *Powder Technology*, **121(2-3)**, pp. 213-222, 2001.
- [14] Chen, J., Rados, N., Al-Dahhan, M.H., Dudukovic, M.P., Nguyen, D. & Krishniah P. Particle Motion in Packed/Ebullated Beds by CT and CARPT. *AIChE Journal*, **47(5)**, pp. 994-1004, 2001.
- [15] Kemoun, A., Ong, B.C., Gupta, P., Al-Dahhan, M.H. & Dudukovic, M.P., Gas holdup in bubble columns at elevated pressure via computed tomography. *Intern. J. of Multiphase Flow*, **27(5)**, pp. 929-946, 2001.
- [16] Vartak, D.R., Engler, C.R., McFarland, M.J. & Ricke, S.C. Attached-film media performance in psychrophilic anaerobic treatment of dairy cattle wastewater. *Bioresource Technology*, **62(3)**, pp. 79-84, 1997.
- [17] *Standard Methods for the Examination of Water and Wastewater*. 16<sup>th</sup> & 17<sup>th</sup> edition, American Public Health Association, Washington D.C., 2000.
- [18] Ferree, M.A. & Shannon, R.D. Evaluation of a Second Derivative UV/Visible Spectroscopy Technique for Nitrate and Total Nitrogen Analysis of Wastewater Samples. *Wat. Res.* **35(1)**, pp. 327–332, 2001.
- [19] Smart, M.M., Rada, R.G. & Donnermeyer, G.N. Determination of Total Nitrogen in Sediments and Plants Using Persulfate Digestion. *Wat. Res.* **17(9)**, pp. 1207–1211, 1983.
- [20] Dietz, W.A. Response Factors for Gas Chromatographic Analyses. *J. of G.C.* **5**, pp. 68–71, 1967.
- [21] Ghaly, A.E. & Ben-Hassan, R.M. Continuous Production of Biogas from Dairy Manure Using an Innovative No-Mix Reactor. *Appl. Biochem. Biotechnol.* **20/21**, pp. 541–559, 1989.
- [22] Bello-Mendoza, R. & Sharratt, P.N. Modeling the Effects of Imperfect Mixing on the Performance of Anaerobic Reactors for Sewage Sludge Treatment. *J. Chem. Technol. Biotechnol.*, **71**, pp. 121–130, 1998.