



## THE POTENTIAL OF ULTRASONIC MEMBRANE ANAEROBIC SYSTEM (UMAS) IN TREATING SLAUGHTERHOUSE WASTEWATER

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### ABSTRACT

In the wake of energy crisis and the drive to reduce CO<sub>2</sub> emissions, the alternative energy sources are much demanded in order to reduce energy consumption, to meet legal requirements on emissions, and for cost reduction and increased quality. The direct discharge of slaughterhouse wastewater causes serious environmental pollution due to its high chemical oxygen demand (COD), Total suspended solids (TSS) and biochemical oxygen demand (BOD). The conventional ways for slaughterhouse wastewater treatment have both economic and environmental disadvantages. In this study, ultrasonic assisted- membrane anaerobic system (UMAS) was used as an alternative, cost effective method for treating slaughterhouse wastewater. Six steady states were conducted as a part of a kinetic study that considered concentration ranges of 7,800 to 13,620 mg/l for mixed liquor suspended solids (MLSS) and 5,359 to 11,424 mg/l for mixed liquor volatile suspended solids (MLVSS). Kinetic equations from Monod, Contois and Chen & Hashimoto were employed to describe the kinetics of slaughterhouse treatment at organic loading rates ranging from 3 to 11 kg COD/m<sup>3</sup>/d. The removal efficiency of COD during the experiment was from 94.8 to 96.5% with hydraulic retention time, HRT from 308.6 to 8.7 days. The growth yield coefficient, Y was found to be 0.52gVSS/g COD the specific microorganism decay rate was 0.21 d<sup>-1</sup> and the methane gas yield production rate was between 0.24 l/g COD/d and 0.56 l/g COD/d. Steady state influent COD concentrations increased from 16,560 mg/l in the first steady state to 40,350 mg/l in the sixth steady state. The minimum solids retention time,  $\theta_c^{\min}$  which was obtained from the three kinetic models ranged from 6 to 14.4 days. The k values were in the range of 0.35–0.519 g COD / g VSS . d and  $\mu_{\max}$  values were between 0.26 and 0.379 d<sup>-1</sup>. The solids retention time (SRT) decreased from 600 days to 14.3 days. The complete treatment reduced the COD content to 2279 mg/l equivalent to a reduction of 94.8% reduction from the original.

**Keywords:** COD reduction, ultrasonic, kinetics, membrane, anaerobic, monod, contoits equation.

### INTRODUCTION

The slaughterhouse wastewaters arises from different steps of the slaughtering process such as washing of animals, bleeding out, skinning, cleaning of animal bodies, cleaning of rooms, etc. the main pollutant in slaughterhouse effluents is organic matter. The contributions of organic load to these effluents are blood, particles of skin and meat, excrements and other pollutants. Slaughterhouse wastewater is very harmful to the environment; therefore, it must be treated before it discharged. In 2011, more than 36 million tons of food waste was generated in the U.S. (U.S. EPA, 2013). Food waste has higher biochemical methane potential. An aerobic digestion of food waste not only produces methane for energy recovery, but also treats waste for environmental and social benefits (Fuchs and Drosch, 2013; Izumi *et al.* 2010; Zhang *et al.* 2013). In the cited literature, several technologies to treat slaughterhouse wastewater have been proposed; including physico-chemical methods (e.g. dilution, evaporation, sedimentation) and biological methods (e.g. aerobic pretreatment, anaerobic digestion [Paraskeva *et al.* 2006]. Effluent discharge from slaughterhouses has caused the deoxygenation of rivers [Zagklis *et al.* 2013] and the contamination of groundwater [Sangodoyin *et al.* 1992]. The pollution potential of meat-processing and slaughterhouse plants has been estimated at over 1 million

population equivalent in the Netherlands [Sayed, 2005], and 3 million in France. Blood, one of the major dissolved pollutants in slaughterhouse wastewater, has a chemical oxygen demand (COD) of 375000 mg/l [Zhang *et al.* 2013]. Slaughterhouse wastewater also contains high concentrations of suspended solids(SS), including pieces of fat, grease, hair, feathers, flesh, manure, grit, and undigested feed. These insoluble and slowly biodegradable SS represented 50% of the pollution charge in screened (1 mm) slaughterhouse wastewater, while another 25% originated from colloidal solids [Izumi *et al.* 2010]. Typical characteristics of wastewater from slaughterhouse are given in Table-1.

**Table-1.** Characteristics of the wastewater from the slaughterhouses [Quinn *et al.* 1989].

Parameter	Concentration (g/l)
pH	6.8-7.8
COD	5.2-11.4
TSS	0.57-1.69
Phosphorus	0.007-0.0283
Ammoniacal nitrogen	0.019-0.074
Protein	3.25-7.86

Table-2 summarizes the performance data of digesters used for the treatment of slaughterhouse wastewater. In recent years, considerable attention has



been paid towards the development of reactors for anaerobic treatment of wastes leading to the conversion of organic molecules into biogas. These reactors, known as second generation reactors or high rate digesters, can handle wastes at a high organic loading rate of 24 kg COD/m<sup>3</sup>/day and high up-flow velocity of 2-3 m/h at a low hydraulic retention time [Ruiz *et al.* 1997]. However, the treatment efficiencies of these reactors are sensitive to parameters like wastewater composition, especially the concentration of various ions [Ruiz *et al.* 1997; Johns, 1995] and presence of toxic compounds such as phenol [Lettinga, 1995]. The temperature and pH are also known to affect the performance of the reactor by affecting the degree of acidification of the effluent and the product formation [Zhang *et al.* 1996]. Table-2 shows some treatment systems for slaughterhouse wastes, while Table-3 shows mathematical expressions for specific substrate utilization rate for three kinetic models.

**Table-2.** Treatment systems for slaughterhouse wastes [Sangodoyin *et al.* 1992].

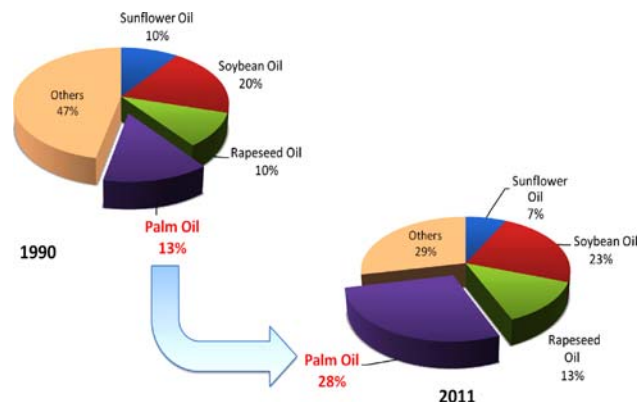
Reactor	Capacity (m <sup>3</sup> )	OLR (kgCOD/m <sup>3</sup> /day)	Reduction (%)
UASB (granular)	33	11	85
UASB (flocculated)	10	5	80 - 89
Anaerobic filter	21	2.3	85
Anaerobic contact	11, 120	3	92.6

**Table-3.** Mathematical expressions of specific substrate utilization rates for known kinetic models.

Kinetic Model	Equation 1	Equation 2
Monod (1949)	$U = \frac{kS}{k_s + S}$	$\frac{1}{U} = \frac{K_s}{K} \left( \frac{1}{S} \right) + \frac{1}{k}$
Contois (1959)	$U = \frac{U_{\max} \times S}{Y(B \times X + S)}$	$\frac{1}{U} = \frac{a \times X}{\mu_{\max} \times S} + \frac{Y(1+a)}{\mu_{\max}}$
Chen & Hashimoto (1980)	$U = \frac{\mu_{\max} \times S}{Y K S_o + (1-K) S Y}$	$\frac{1}{U} = \frac{Y K S_o}{\mu_{\max} S} + \frac{Y(1-K)}{\mu_{\max}}$

An improvement in the efficiency of anaerobic digestion can be brought about by either suitably modifying the existing digester design or by incorporating appropriate advanced techniques. Thus, a plug flow reactor or USSB reactor is found to be superior to the conventional processes due to low concentrations of VFA in the effluent, a high degree of sludge retention and stable reactor performance [Mudrak *et al.* 1986]. Another common problem encountered in the industrial anaerobic plants is biomass washout. This can be addressed, for instance, by the use of membranes coupled with the

anaerobic digester for biomass retention [Fang *et al.* 1997]. This paper introduces a new technique, which Ultrasonic membrane anaerobic system (UMAS) for slaughterhouse wastewater treatment. This system, UMAS avoid and solve the membrane fouling problems. Figure-1 showed the world oil and fat production in 1990 and 2011 [Chin, k. k. 1982].



**Figure-1.** World oil and fat production in 1990 and 2011 [Chin, k, 1982].

## MATERIALS AND METHODS

With the increasing energy prices and the drive to reduce CO<sub>2</sub> emissions, universities and industries are challenged to find new technologies in order to reduce energy consumption, to meet legal requirements on emissions, and for cost reduction and increased quality. Slaughterhouse wastewater causes serious environmental pollution if directly discharged to the land due to its high chemical oxygen demand (COD), Total suspended solids (TSS) and biochemical oxygen demand (BOD). The conventional methods used for slaughterhouse wastewater treatment have both economic and environmental disadvantages. The current study, ultrasonic membrane anaerobic system (UMAS) was used as a high separation, an alternative and cost effective method for treating slaughterhouse wastewater (to avoid membrane fouling).

The raw slaughterhouse wastewater was obtained from Indah Water Treatment Plant, Kuantan, Malaysia. The UMAS was used to treat the raw wastewater in a laboratory digester with an effective 200-litre volume. Figure-2 presents a schematic representation of the ultrasonic-membrane anaerobic system (UMAS) that designed to comprises a cross flow ultra-filtration membrane (CUF) apparatus, a centrifugal pump, and an anaerobic reactor. 25 KHz multi frequency ultrasonic transducers connected into the MAS system. The ultrasonic frequency is 25 KHz, with 6 units of permanent transducers and bonded to the two (2) sided of the tank chamber and connected to one (1) unit of 250 watts 25 KHz Crest's Genesis Generator. The ultrafiltration membrane, UF module had a molecular weight cut-off (MWCO) of 200,000, a tube diameter of 1.25 cm and an average pore size of 0.1 µm. The length of each tube was 30 cm. The total effective area of the four membranes was



0.048 m<sup>2</sup>. The maximum operating pressure on the membrane was 55 bars at 70 °C, and the pH ranged from 2 to 12. The reactor was composed of a heavy duty reactor with an inner diameter of 25 cm and a total height of 250 cm. The operating pressure in this study was maintained between 2 and 4 bars by manipulating the gate valve at the retentate line after the CUF unit.

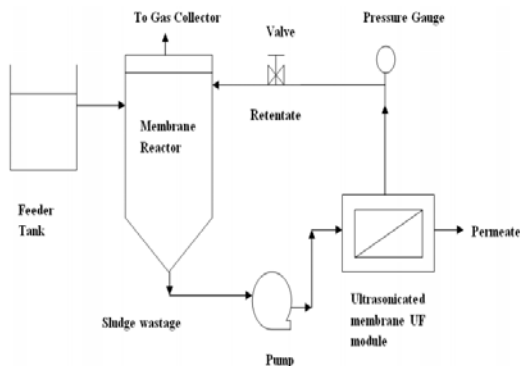


Figure-2. Experimental set-up.

### Raw Slaughterhouse Wastewater

The raw slaughterhouse wastewater samples were obtained from slaughterhouse in Kuantan-Malaysia. The wastewater was stored in a cold room at 4°C prior to use. Samples analysed for chemical oxygen demand (COD), total suspended solids (TSS), pH, volatile suspended solids (VSS), substrate utilisation rate (SUR), and specific substrate utilisation rate (SSUR).

### Analytical Methods

Biogas volume was daily measured with water displacement, and methane content was analysed by J-Tube analyser and a gas chromatograph (GC 2011 Shimadzu) equipped with a thermal conductivity detector and a 2 m x3 mm stainless-steel column packed with Porapak Q (80/100 mesh). For the analysis of TS, VSS, VFA, alkalinity were determined according to the standard Methods (APHA, 2005). The chemical oxygen demand (COD) was measured using a Hach colorimetric digestion method (Method # 8000, Hach Company, Loveland, CO).

### Ultrasonic Membrane Anaerobic System (UMAS) operation

The ultrasonic membrane anaerobic system, UMAS Performance was evaluated under six steady-states, Table-4, with influent COD concentrations ranging from (8,000 to 25,400 mg/l) and organic loading rates (OLR) between (3.0 and 11 kg COD/m<sup>3</sup>/d). In this study, the system was considered to have achieved steady state when the operating and control parameters were within  $\pm 10\%$  of the average value. A 20-litre water displacement bottle was used to measure the daily gas volume. The produced biogas contained only CO<sub>2</sub> and CH<sub>4</sub>, so the addition of sodium hydroxide solution (NaOH) to absorb CO<sub>2</sub> effectively isolated methane gas (CH<sub>4</sub>). Table-5 depicts results of the application of three known substrate

utilization models.

Table-4. Summary of results (SS: steady state).

Steady State (SS)	1	2	3	4	5	6
COD feed, mg/L	8000	10700	15400	18700	20000	25400
COD permeate, mg/L	280	428	662	860	920	1321
Gas production (L/d)	190.5	220	260	320	360	373
Total gas yield, L/g COD/d	0.21	0.32	0.48	0.54	0.62	0.68
% Methane	74	70.5	68.6	67.6	64.2	61.8
CH <sub>4</sub> yield, l/g COD/d	0.29	0.32	0.5	0.54	0.56	0.59
MLSS, mg/L	7800	8740	10080	11280	12546	13620
MLVSS, mg/L	5359	7428	8840	10340	11120	11424
% VSS	68.71	84.99	87.7	91.67	88.63	83.87
HRT, d	308.6	60.3	13.9	10.86	9.64	8.7
SRT, d	580	298	124	26.8	13.44	11.8
OLR, kg COD/m <sup>3</sup> /d	3	5	7	8.2	9	11
SSUR, kg COD/kg VSS/d	0.164	0.195	0.252	0.263	0.294	0.314
SUR, kg COD/m <sup>3</sup> /d	0.023	0.724	2.225	4.576	5.685	7.347
Percent COD removal (UMAS)	96.5	96	95.7	95.4	95.4	94.8

Table-5. Results of the application of three known substrate utilisation models.

Model	Equation	R <sup>2</sup> (%)
Monod	$U^{-1} = 2025 S^{-1} + 3.61$ $K_s = 498$ $K = 0.350$ $\mu_{max} = 0.284$	98.9
Contois	$U^{-1} = 0.306 X S^{-1} + 2.78$ $B = 0.111$ $\mu_{max} = 0.344$ $\alpha = 0.115$ $\mu_{max} = 0.377$ $K = 0.519$	97.8
Chen & Hashimoto	$U^{-1} = 0.0190 S_o^{-1} + 3.77$ $K = 0.006$ $\alpha = 0.006$ $\mu_{max} = 0.291$ $K = 0.374$	98.7

## RESULTS AND DISCUSSION

### The Performance Ultrasonic-Membrane Anaerobic System (UMAS)

The performance of the ultrasonic membrane anaerobic, UMAS was evaluated and summarized in



Table-4. The UMAS performance at six steady-states was established at different HRTs and influent COD concentrations. The kinetic coefficients of the selected models were derived from Equation. (2) in Table-5 by using a linear relationship; the coefficients are summarised in Table-5. At steady-state conditions with influent COD concentrations of 8,000-25,400 mg/l, UMAS performed well and the pH in the reactor remained within the optimal working range for anaerobic digesters (6.7-7.8). At the first steady-state, the MLSS concentration was about 7,800 mg/l whereas the MLVSS concentration was 5,329 mg/l, equivalent to 68.71% of the MLSS. This low result can be attributed to the high suspended solids contents in the slaughterhouse wastewater. At the sixth steady-state, however, the volatile suspended solids (VSS) fraction in the reactor increased to 88% of the MLSS. This indicates that the long SRT of UMAS facilitated the decomposition of the suspended solids and their subsequent conversion to methane ( $\text{CH}_4$ ); this conclusion supported by (Abdurahman *et al.* 2011) and (Nagano *et al.* 1992). The highest influent COD was recorded at the sixth steady-state (91,400 mg/l) and corresponded to an OLR of 9.5 kg COD/m<sup>3</sup>/d. At this OLR the, UMAS achieved 96.7% COD removal and an effluent COD of 3000 mg/l. This value is better than those reported in other studies on anaerobic slaughterhouse wastewater digestion (Borja *et al.* 1993; Ng *et al.* 1985). The three kinetic models demonstrated a good relationship ( $R^2 > 99\%$ ) for the membrane anaerobic system treating slaughterhouse wastewater, as shown in Figures-3, 5. The Contois and Chen & Hashimoto models performed better, implying that digester performance should consider organic loading rates. These two models suggested that the predicted permeate COD concentration (S) is a function of influent COD concentration ( $S_0$ ). In Monod model, however, S is independent of  $S_0$ . The excellent fit of these three models ( $R^2 > 97.8\%$ ) in this study suggests that the UMAS process is capable of handling sustained organic loads between 0.5 and 9.5 kg m<sup>3</sup>/d.

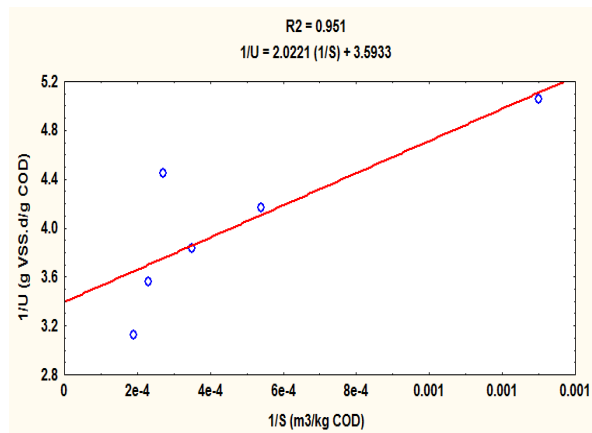


Figure-3. The Monod model.

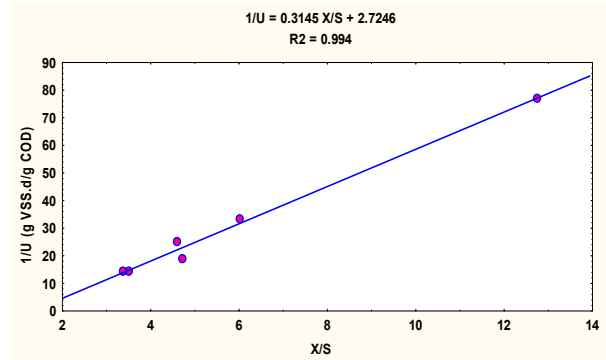


Figure-4. The Contois model.

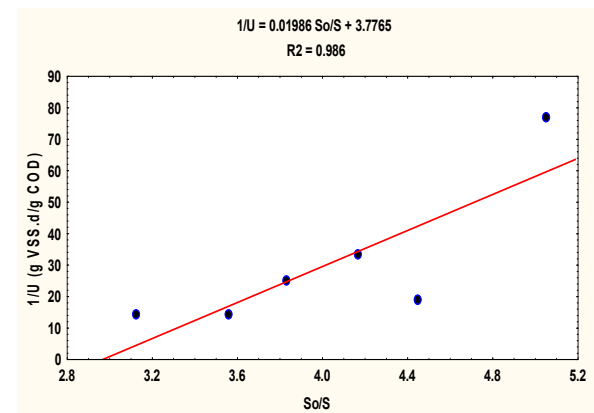
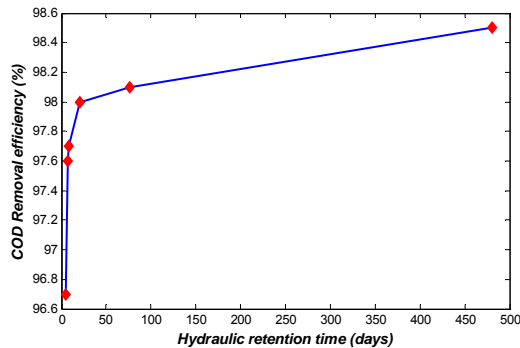


Figure-5. The Chen and Hashimoto model.

Figure-6 shows the percentages of COD removed by UMAS at various HRTs. COD removal efficiency increased as HRT increased from 5.40 to 480.3 days and was in the range of 96.7 % - 98.5 %. This result was higher than the 85 % COD removal observed for slaughterhouse wastewater treatment using anaerobic fluidised bed reactors (Idris *et al.* 1998) and the 91.7-94.2 % removal observed for slaughterhouse wastewater treatment using MAS (Fakhru'l-Razi *et al.* 1999), and the 93.6-97.5% removal observed for POME treatment using MAS (Abdurahman *et al.* 2011). The COD removal efficiency did not differ significantly between HRTs of 480.3 days (98.5%) and 20.3 days (98.0%). On the other hand, the COD removal efficiency was reduced shorter HRTs; at HRT of 5.40 days, COD was reduced to 96.7 %. As shown in Table-2, this was largely a result of the washout phase of the reactor because the biomass concentration increased in the system. This may attributed due to the fact that at low HRT with high OLR, the organic matter was degraded to volatile fatty acids (VFA). The HRTs were mainly influenced by the ultra-filtration, UF membrane influx-rates which directly determined the volume of influent (POME) that can be fed to the reactor.

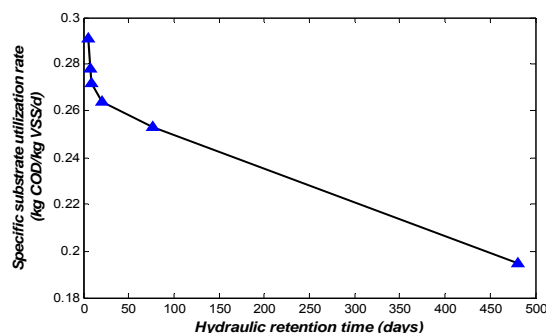




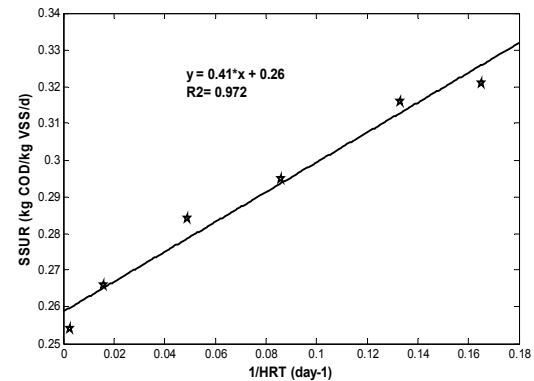
**Figure-6.** COD removal efficiency of UMAS under steady-state conditions with various hydraulic retention times.

#### Determination of Bio-Kinetic Coefficients

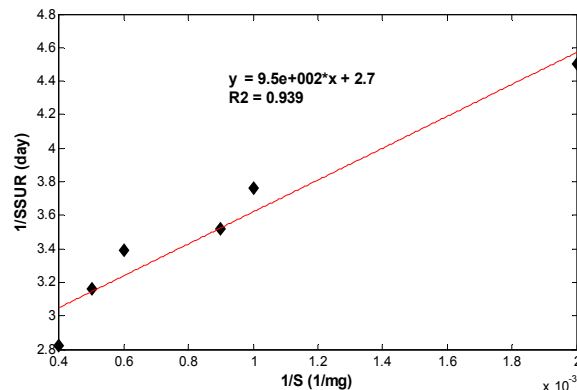
The six steady-state experimental data conditions in Table-4 were analyzed; kinetic coefficients were evaluated and are summarised in Table-5. Substrate utilisation rates (SUR); and specific substrate utilisation rates (SSUR) were plotted against OLRs and HRTs. Figure-7 shows the SSUR values for COD at steady-state conditions HRTs between 5.40 and 480.3 days. SSURs for COD generally increased proportionally HRT declined, which indicated that the bacterial population in the UMAS multiplied (Wu *et al.* 2013). The bio-kinetic coefficients of growth yield (Y) and specific micro-organic decay rate, (b); and the K values were calculated from the slope and intercept as shown in Figures-8 and 9. Maximum specific biomass growth rates ( $\mu_{\max}$ ) were in the range between 0.248 and 0.474  $\text{d}^{-1}$ . All of the kinetic coefficients that were calculated from the three models are summarised in Table-5. The small values of  $\mu_{\max}$  are suggestive of relatively high amounts of biomass in the UMAS (Zinatizadeh *et al.* 2006). According to (Grady *et al.* 1980), the values of parameters  $\mu_{\max}$  and K are highly dependent on both the organism and the substrate employed. If a given species of organism is grown on several substrates under fixed environmental conditions, the observed values of  $\mu_{\max}$  and K will depend on the substrates.



**Figure-7.** Specific substrate utilization rate for COD under steady-state conditions with various hydraulic retention times.



**Figure-8.** Determination of the growth yield, Y and the specific biomass decay rate, b.



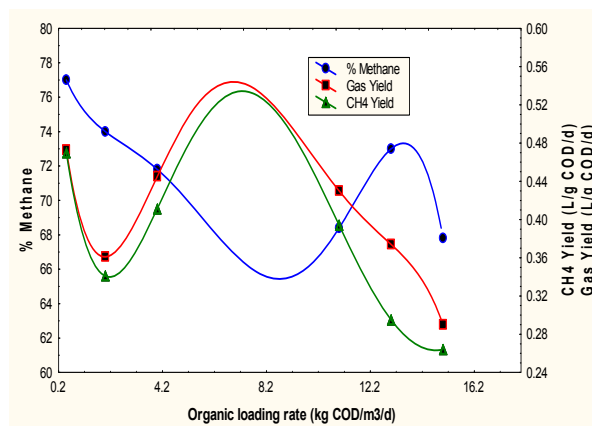
**Figure-9.** Determination of the maximum specific substrate utilization and the saturation constant, K.

#### Production of Methane ( $\text{CH}_4$ ) and Carbon Dioxide ( $\text{CO}_2$ ) Gases

To ensure the performance of anaerobic digesters and prevent failure, there are many parameters must be adequately controlled. For slaughterhouse wastewater treatment, these parameters include pH, mixing, operating temperature, nutrient availability and organic loading rates into the digester. In this study, the microbial community in the anaerobic digester was sensitive to pH changes. Therefore, the pH was maintained in an optimum range (6.8-7) to minimize the effects on methanogens that might biogas production. Because methanogenesis is also strongly affected by pH, methanogenic activity will decrease when the pH in the digester deviates from the optimum value. Mixing provides good contact between microbes and substrates, reduces the resistance to mass transfer, minimizes the build-up of inhibitory intermediates and stabilizes environmental conditions. This study adopted the mechanical mixing and biogas recirculation. Figure-10 shows the gas production rate and the methane content of the biogas. The methane content generally declined with increasing OLRs. Methane gas contents ranged from 68.5% to 79% and the methane yield ranged from 0.29 to 0.59  $\text{CH}_4/\text{g COD/d}$ . Biogas



production increased with increasing OLRs from 0.29 l/g COD/d at 0.5 kg COD/m<sup>3</sup>/d to 0.88 l/g COD/d at 9.5 kg COD/m<sup>3</sup>/d. The decline in methane gas content may be attributed to the higher OLR, which favours the growth of acid forming bacteria over methanogenic bacteria. Thus the methane conversion process was adversely affected with reducing methane content and this has led to the formation of carbon dioxide at a higher rate. The gas production showed an increase from 277.8 to 580 Litres per day during the study. In this scenario, the higher rate of carbon dioxide; (CO<sub>2</sub>) formation reduces the methane content of the biogas.



**Figure-10.** Gas production and methane content.

## CONCLUSIONS

In the current study, the ultrasonic membrane anaerobic system, UMAS was found to be adequate for the biological treatment of undiluted slaughterhouse wastewater, since reactor volumes are needed which are considerably smaller than the volumes required by the conventional digester. UMAS was found to be an improvement and a successful biological treatment system that achieved high COD removal efficiency in a short period of time (no membrane fouling by introduction of ultrasonic device). The overall substrate removal efficiency was very high-about 98.5%. The gas production, as well as the methane concentration in the gas were satisfactory and, therefore, could be considered as an additional energy source for the use in the slaughterhouse. Preliminary data of anaerobic digestion at 30 °C in UMAS showed that the proposed technology has good potential to substantially reduce the pollution load of slaughterhouse wastewater. UMAS was efficient in retaining the biomass. The UMAS process will recover a significant quantity of energy (methane 79%) that could be used to heat or produce hot water at the slaughterhouse wastewater plant.

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