# KINETIC ANALYSIS OF THERMOPHILIC ANAEROBIC DIGESTION OF WASTEWATER SLUDGE

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**Abstract.** Conventional mesophilic anaerobic digesters are sometimes subject to process upset and have earned the reputation of being difficult to cope with sludge overloading. This study was conducted to examine the thermophilic process as a viable alternative.

An analysis of field data from an operating mesophilic sludge digester was conducted in parallel with experimental runs on a laboratory thermophilic reactor using similar sludge. The results showed that thermophilic anaerobic digestion was a viable alternative to the mesophilic process especially for overloaded digesters in warm climates. The optimum hydraulic retention time for the thermophilic process was 10 days which can lead to substantial savings in digester capacity. A simplified kinetic model was developed and applied in the analysis of steady-state operation of thermophilic anaerobic sludge digesters.

**Keywords:** anaerobic digestion, kinetic models, thermophilic digestion, wastewater sludge

## 1. Introduction

Anaerobic digestion is by far the most common process for treating wastewater sludges. However, the process is sometimes subject to upsets and has earned the reputation of being difficult to operate. Operational problems arise from the complexity of the process and the inability to control inputs. Recent interest in the operation of the anaerobic treatment processes has led to research on development of methods for improving process operation (Parkin and Owen, 1986; Barnett and Andrews, 1992). New developments include advanced digester design and reactor configurations such as employing fixed-film systems, upflow anaerobic sludge blanket (UASB) reactors and fluidized bed reactors (Metcalf and Eddy, 1991). It has also been reported that thermophilic anaerobic digestion is superior to mesophilic in terms of process efficiency and required reactor capacity since shorter hydraulic retention times (HRT's) can be used in thermophilic digesters (Hashimoto *et al.*, 1981; Hill, 1990).

In Kuwait, the anaerobic sludge digesters at the main wastewater treatment plant (Ardiya plant) are operated at mesophilic temperatures and have a record of troublesome operation, accompanied with offensive odors which caused several

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TABLE I

Average characteristics of raw wastewater sludge at Ardiya plant

| Parameter | | Value |
|---|---|---|
| Temperature | °C | 30 |
| pH | | 6 |
| Total suspended solids | mg $L^{-1}$ | 52000 |
| Volatile suspended solids | mg $L^{-1}$ | 38000 |
| COD (total) | mg $L^{-1}$ | 54000 |

community complaints. This is often caused by the periodic excessive hydraulic and organic loadings applied to the digesters. In an attempt to improve digester operation at Ardiya, this study was conducted to examine the feasibility of anaerobic digestion under thermophilic conditions. This approach was motivated by the favorable warm climate in Kuwait, and the potential of existing digesters to handle increased loadings at lower HRT's.

This paper presents the results of an experimental study conducted to characterize the wastewater sludge, examine the performance of a thermophilic anaerobic digester, and determine optimum operating conditions. A kinetic model for design of the thermophilic anaerobic digester is also proposed.

## 2. Materials and Methods

### 2.1. SLUDGE CHARACTERISTICS

Wastewater sludge was collected from the Ardiya Municipal Wastewater Treatment Plant in Kuwait. The sludge was mainly composed of suspended organic solids (settled solids from primary treatment) and excess biomass (from secondary 'biological' treatment), therefore it was highly concentrated organic material. The water content of the sludge averaged 98%. Some characteristics of the raw 'undigested' sludge from the Ardiya plant reported during four months of the study are shown in Table I. These include temperature, pH, total suspended solids (TSS), volatile suspended solids (VSS), and chemical oxygen demand (COD). Sludge temperature was high and its volatile suspended solids content was also high (VSS/TSS is 73%).

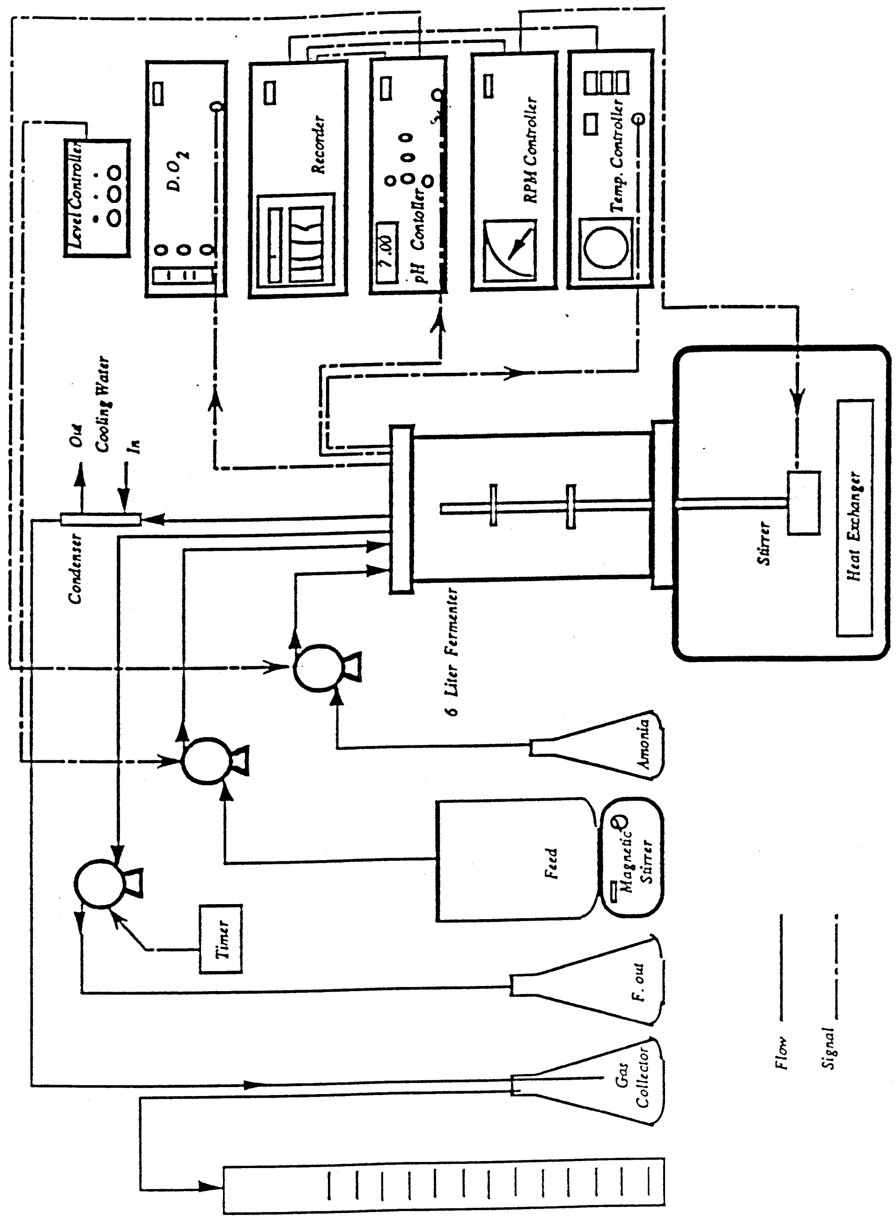


*Figure 1.* Schematic diagram of experimental setup.

### 2.2. EXPERIMENTAL WORK

Laboratory thermophilic anaerobic digestion experiments were conducted for about four months using 6-L continuous-flow, completely mixed, cylindrical fermenter and wastewater sludge from the Ardiya plant. A schematic diagram of the experimental setup is shown in Figure 1. Stirrer speed was set at 300 rpm and the temperature was kept constant at 55 °C through automatic controllers. Other devices used were pH and level controllers and a dissolved oxygen probe. For start-up, the fermenter was filled with 6 L of digested sludge (41 000 mg/I SS, 22 000 mg/I VSS and pH of 7.3) from the Ardiya plant digesters. After one week from filling the digester (batch operation), semi-continuous feeding of the digester started with 15 days HRT (400 mL daily feed flow) and was later changed gradually to 10 days, 5 days and 2.5 days HRT's by changing the daily feed flow accordingly. Experimental runs at each HRT continued for at least ten days to reach steady-state operation based on VSS and COD results. The feed pump was connected to a timer in order to deliver the feed sludge intermittently at equal intervals with a total operating time of two to three hours daily. The effluent withdrawal pump was connected to the level controller in order to keep the liquid volume constant inside the fermenter by pumping the sludge out of the fermenter. The volume of biogas produced was measured by solution displacement in a measuring cylinder. pH was maintained in the fermenter at about 7.0.

A stock of thickened raw sludge obtained from the Ardiya plant was screened through a mesh and was stored in a cold room at 4 °C for daily feeding of the fermenter. Samples were taken daily from the stock and warmed up at room temperature before being fed to the fermenter to eliminate thermal shocks. Each day, samples from feed and effluent sludges were taken from the fermenter for analyses which included SS, VSS, COD and fatty acids. The analyses were conducted according to Standard Methods (APHA, 1985) and a gas chromatograph (Model HP 5710A) was used for fatty acid determinations. Biogas collected was measured daily. Gas sampling was done using a vacuumed glass tube and the gas was analyzed using an Intersmat gas chromatograph with a Porapack Q 80/100 column and thermal conductivity detector.

## 3. Process Modeling and Control

There are some important parameters which must be considered in the operation of anaerobic digesters (Metcalf and Eddy, 1991). Among these parameters, the solids retention time (SRT) is often regarded the most important. SRT is defined as the average time that sludge solids remain in the digestion tank during the treatment, before they are drawn in the effluent. For a system with no sludge recirculation, SRT is calculated as:

$$\mathrm{SRT} = \frac{VX_r}{QX_e} \qquad (1)$$

where $X_r$ and $X_e$ are reactor and effluent concentrations of biomass, respectively and $V/Q$ is hydraulic retention time (HRT). In a well mixed tank $X_r = X_e$, so in this case:

$$\text{SRT} = \text{HRT} = \frac{V}{Q} \tag{2}$$

where $V$ is the volume of digester contents and $Q$ is the flow rate of the influent sludge. SRT can be changed by keeping a constant $V$ and changing $Q$. It is not a control objective, but because of its direct effect on stabilization, it should be controlled.

Obtaining a very accurate mathematical model for anaerobic digestion is difficult due to the complexity of the digestion and the hydrodynamics of the process. Anaerobic digestion is a three phase process, because of gas evolution, and availability of solids. Presence of different types of bacteria, multi-step nature of substrate removal, and great number of parameters which affect the digestion process, make it even more difficult to build a complete model. There are some complex models, which take into account most of these parameters in different ways, such as those presented by Graef and Andrews (1974) and Maeda (1985). On the other hand, Hill (1990) developed a set of simplified, predictive design equations for methane production from livestock waste using anaerobic digestion. However, a simplified model based on the single microbial culture equation as proposed by Monod (1942) could be sufficient to design a system for treating the sludges of municipal origin. Also most of the parameters involved are self regulatory and introducing them in the overall model will increase the interaction between different parameters. Monod microbial growth kinetics is given by Equation (3):

$$\mu = \frac{\mu_{\max} S}{K_s + S} \tag{3}$$

where,

| | | | |
|---|---|---|---|
| $\mu$ | = | growth rate | ($\text{day}^{-1}$) |
| $\mu_{\max}$ | = | maximum growth rate | ($\text{day}^{-1}$) |
| $S$ | = | substrate concentration | (mg COD/1) |
| $K_s$ | = | half saturation constant | (mg COD/1) |

Maximum growth is a function of temperature and different correlations for it are presented in the literature. For the purpose of this study, the Hashimoto *et al.* (1981) correlation is selected:

$$\mu_{\max} = 0.013\text{T} - 0.129 \tag{4}$$

where $T$ is temperature in °C. Equation (4) is valid for the temperature range of 20–60 °C. The digester is assumed to be a well mixed continuous flow reactor, so that temperature $T$, substrate $S$, and micro-organisms concentration $X$ are uniform. Then we can develop the material and energy balances around the reactor as follows:

For micro-organisms concentration assuming the death rate and inlet concentration are negligible:

$$\frac{dX}{dt} = \mu X - \frac{Q}{V}X . \tag{5}$$

These are valid assumptions for municipal sludge since conditions outside of the reactor are so different from inside, therefore there is no chance for bacterial growth outside the reactor.

Also there is always a continuous flow of substrate, so little death will occur. For the substrate we have:

$$\frac{dS}{dt} = \frac{Q}{V}(S_i - S) - \frac{\mu X}{Y_x} \tag{6}$$

where $S_i$ is the influent substrate concentration and $Y_x$ is defined as the amount of bacteria formed per amount of substrate utilized (biomass yield) as is given by the following equation:

$$Y_x = \frac{\text{mg } X \text{ formed}}{\text{mg COD removed}} . \tag{7}$$

By doing a heat balance around the reactor, an equation for temperature and heat requirements can be calculated:

$$\rho V C_p \frac{dT}{dt} = \rho_i Q_i C_{pi} T_i - \rho Q C_p T + E \quad [\text{jday}^{-1}] \tag{8}$$

where $\rho$ is the sludge density, $T$ is the temperature, $C_p$ is the heat capacity and $E$ is a term for energy input. Assuming that inlet and outlet density and heat capacity are the same, then Equation (8) becomes:

$$\rho V C_p \frac{dT}{dt} = \rho Q C_p (T_i - T) + E \tag{9}$$

by simplifying Equation (9), we get:

$$\frac{dT}{dt} = \frac{Q}{V}(T_i - T) + \frac{E}{\rho V C_p} \quad [^\circ\text{Cday}^{-1}] \tag{10}$$

and by substituting $G_u$ for the last term in Equation (10), the following equation is obtained:

$$\frac{dT}{dt} = \frac{Q}{V}(T_i - T) + G_u . \tag{11}$$

For gas production, the following equation can be used:

$$G = VY_g \frac{\mu X}{Y_x} \quad [\text{m}^3\text{day}^{-1}] \tag{12}$$

where $G$ is the gas production rate and $Y_g$ is the gas yield. Solution of model Equations (5), (6) and (11) requires that initial values of $S$, $X$, and $G_u$ to be known. For finding these values, Equation (5) should be set equal to zero for steady-state condition and solved simultaneously. Therefore,

$$\mu = \frac{Q}{V} \quad [\text{at steady state}] \tag{13}$$

But Equation (3) can be written as:

$$S = K_s \frac{\mu}{\mu_{\text{max}} - \mu} \tag{14}$$

Substituting $\mu$ from Equation (13) and $\mu_{\text{max}}$ from Equation (4):

$$S = K_s \frac{Q/V}{(0.013T - 0.129) - Q/V} \,. \tag{15}$$

Dividing both the numerator and denominator in right hand side by $Q/V$ yields:

$$S = \frac{K_s}{(0.013T - 0.129)V/Q - 1} \,. \tag{16}$$

Now we set Equation (6) to zero:

$$\frac{\text{d}S}{\text{d}t} = 0 \,.$$

So,

$$\frac{Q}{V}(S_i - S) - \frac{\mu X}{Y_x} = 0 \,. \tag{17}$$

By moving the second term to the right hand side, substituting $\mu$ from Equation (13), and dividing both sides by $Q/V$, the following equation is obtained:

$$X = (S_i - S)Y_x \,. \tag{18}$$

For finding the steady state value of $G_u$, Equation (11) is set to zero.

$$\frac{\text{d}T}{\text{d}t} = 0$$

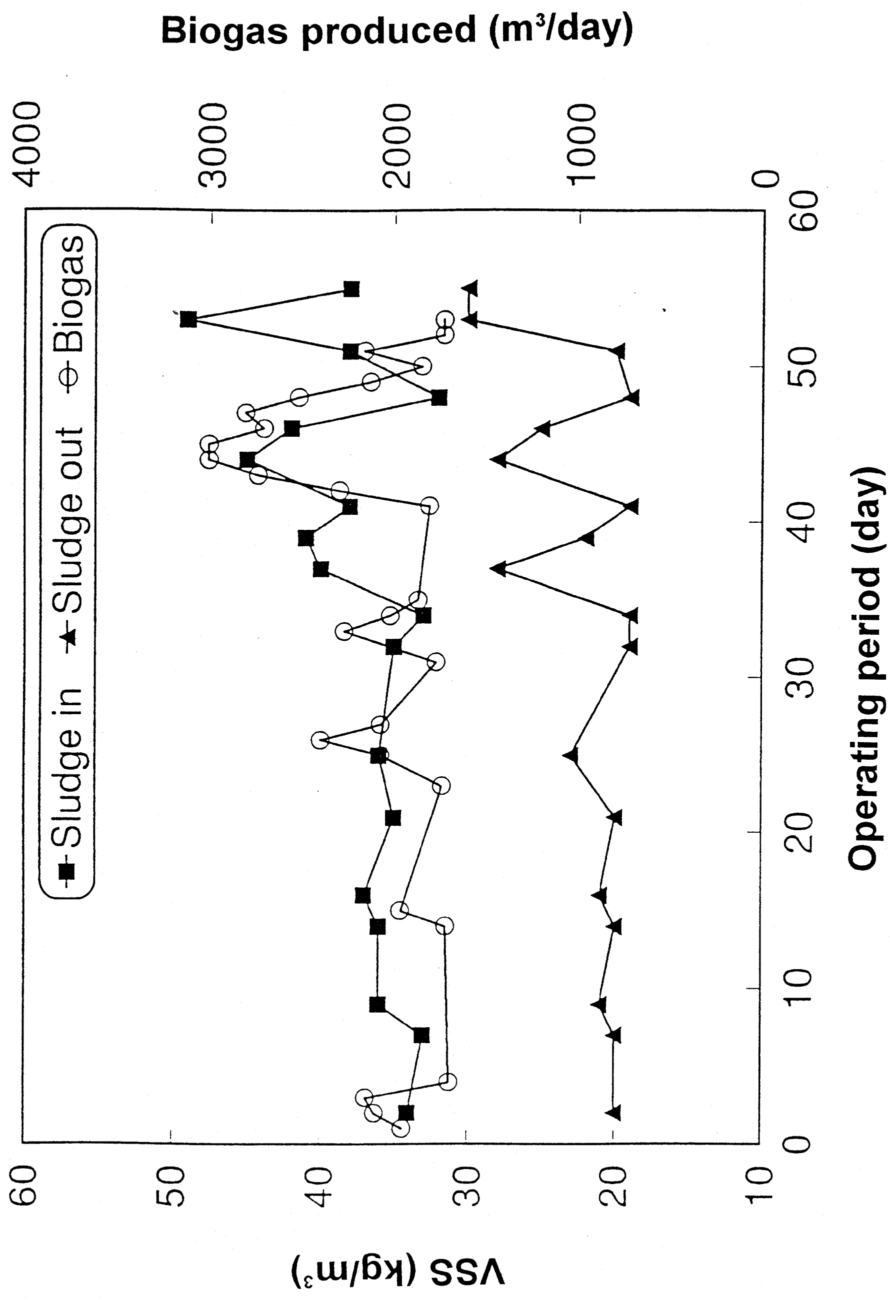


*Figure 2*. Performance of the anaerobic sludge-digester at the Ardiya wastewater treatment plant.

so,

$$\frac{Q}{V}(T_i - T) + G_u = 0 \tag{19}$$

or,

$$G_u = -\frac{Q}{V}(T_i - T)\ . \tag{20}$$

## 4. Numerical Example

A numerical example is used to illustrate the applicability of the model. Some data such as gas production and inlet and outlet substrate concentrations from the anaerobic digestion process are needed. For this purpose, field data obtained from the Ardiya wastewater treatment plant were used, as shown in Figure 2. These data were collected during a two month period of normal operation from three identical digesters, each having an effective volume of 2700 $m^3$. The total gas from the three tanks was measured by one meter. Figure 2 shows the variations in measured gas production rates along with sludge VSS in the digester influent and effluent. No COD measurements were done on the sludge at the plant. Since sludge organic strength was given as VSS in the plant data, while in the model it is expressed as soluble COD, a correlation factor relating the organic substrate in these two parameters is considered for conversion of values. Moreover, gas yield is calculated based on gas composition of 55% methane and 90% actual conversion of COD to methane (Metcalf and Eddy, 1991). So with the theoretical value of 0.35 $m^3$ methane $kg^{-1}$ COD, gas yield is:

$$Y_g = \frac{0.35}{0.55}\times 0.9 = 0.57\ \text{m}^3\ \text{gas kg}^{-1}\ \text{COD}$$

$$= 5.7 \times 10^{-7}\ \text{m}^3\text{gas mg}^{-1}\ \text{COD}\ .$$

Then by substituting these values in Equation (12) we can calculate the COD reduction in the digester based on an average gas production rate of 1965 $m^3$ $day^{-1}$ obtained at the plant:

$$\frac{\mu X}{Y_x} = \frac{G}{VY_g}$$

$$= \frac{1965}{81\times 10^5\times 5.7\times 10^{-7}} = 425.6\ \text{mg L}^{-1}\ \text{d}^{-1}\ .$$

Then from Equation (17), and substituting for hydraulic retention time $V/Q = 30$ days, it can be found that:

$$(S_i - S) = \frac{\mu X}{(Q/V)Y_x}$$

$$= 425.6 \times 30$$

$$= 12768 \text{ mg L}^{-1}$$

Now we can think about a factor '$f$' which correlates between the $S_i$ and $S$ in VSS and COD:

$$(S_i - S) = (37670 - 22440) \times f$$

then

$$f = \frac{12768}{15230} = 0.83835\ .$$

So,

$$S_i = 31580.5 \text{ mg L}^{-1}$$

$$S = 18812.5 \text{ mg L}^{-1}\ .$$

These data are obtained from the digester operating under mesophilic conditions (35 °C). However, if the digester is operated under thermophilic conditions (55 °C) and a hydraulic retention time of 10 days, assuming the same influent substrate concentration ($S_i$) as for the mesophilic digester (Table II), it will be able to handle three times as much the influent sludge flow rate ($Q$) while producing the same effluent substrate concentration ($S$) compared to the mesophilic digester. The steady-state values shown in Table II are generated based on the same kinetic model (Equations (12) and (17)). This demonstrates the advantage of employing thermophilic digestion in an overloaded sludge digestion unit, such as in the Ardiya wastewater treatment plant. Further substantiation of such merits and the ability of the model to manipulate digester operation data had to be made experimentally as discussed in the following section.

## 5. Results and Discussion

The experimental results obtained from the thermophilic anaerobic digester (laboratory fermenter) are illustrated in Figure 3, for HRT's of 15, 10, 5, and 2.5 days. Steady-state operation of the digester was achieved after a start-up period that

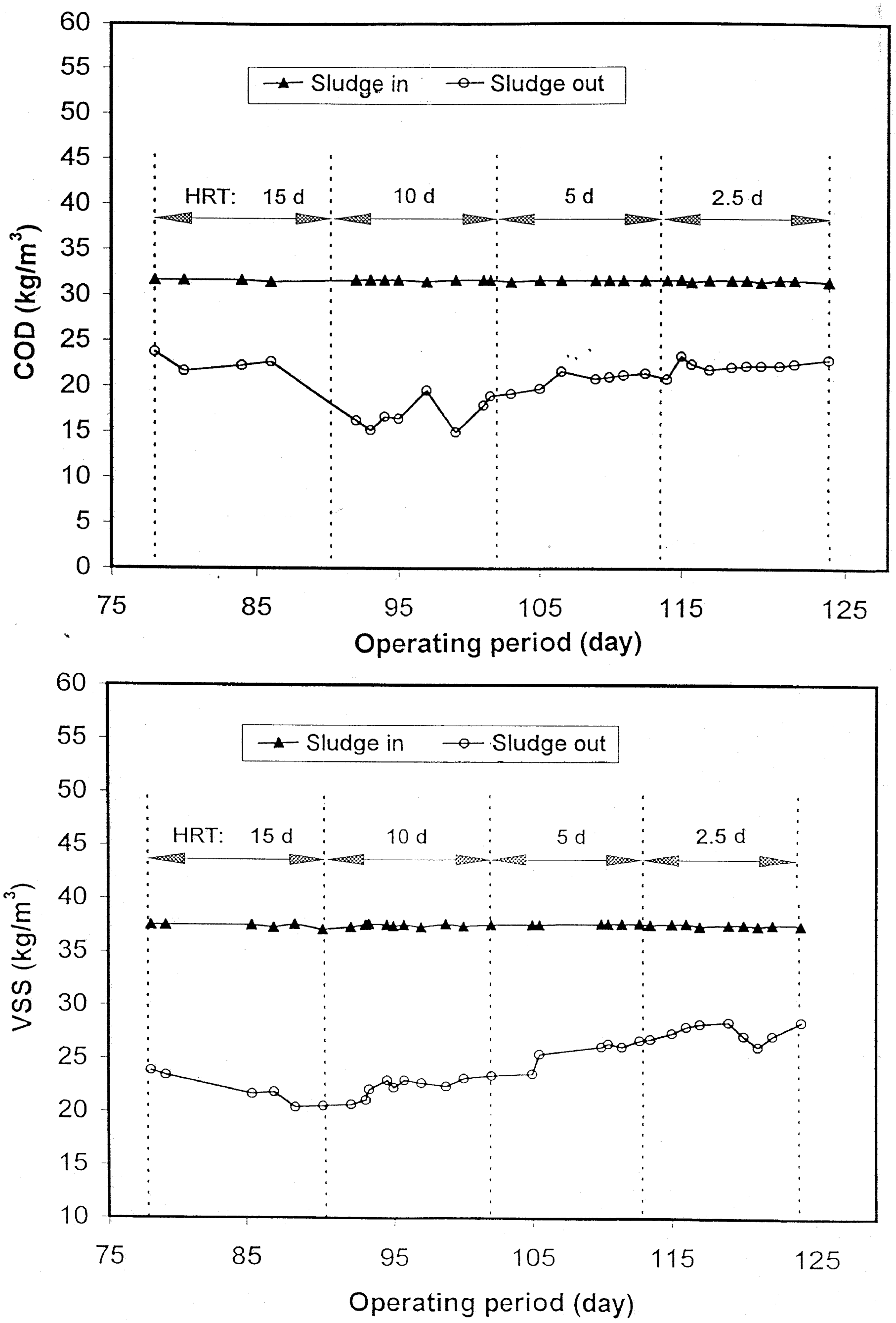


*Figure 3.* Performance of the laboratory thermophilic anaerobic sludge digester.

TABLE II
Steady-state values of model parameters

| Parameter | | Mesophilic | Thermophilic |
|---|---|---|---|
| $Qs$ | $m^3\ d^{-1}$ | 270 (30 day HRT) | 810 (10 day HRT) |
| $V$ | $m^3$ | 8100 | 8100 |
| $G$ | $m^3\ d^{-1}$ STP | 1965 | 5895 |
| $G_u$ | $°C\ d^{-1}$ | 0.0166667 | 2.5 |
| $T_i$ | °C | 30 | 30 |
| $T$ | °C | 35 | 55 |
| $Si$ | mg COD $L^{-1}$ | 31580.5 | 31580.5 |
| $S$ | mg COD $L^{-1}$ | 18812.5 | 18812.5 |
| $X$ | mg $L^{-1}$ | 549 | 549 |
| $K_s$ | mg COD $L^{-1}$ | 165173.8 | 91428.8 |
| $Y_x$ | mg X $mg^{-1}$ COD | 0.043 | 0.043 |
| $Y_g$ | $m^3\ mg^{-1}$ COD | $5.7 \times 10^{-7}$ | $5.7 \times 10^{-7}$ |
| $\mu_{max}$ | $L\ d^{-1}$ | 0.326 | 0.586 |
| $\mu$ | $L\ d^{-1}$ | 0.033333 | 0.1 |

extended for 78 days due to some mechanical problems. The TSS, VSS and COD were monitored for performance analysis. The feed sludge TSS, VSS and soluble COD were 52900, 37000 and 32000 mg $L^{-1}$, respectively. The VSS content of the sludge was reduced by up to 45% during thermophilic digestion. The sludge COD was also reduced by up to 40% depending on the digester HRT. The percentage organic (VSS and COD) reductions obtained show no great difference from those reported for the mesophilic digestion of the same sludge indicating that there is no great variation in the biodegradability of the waste under thermophilic versus mesophilic digestion. This supports earlier findings by Hill (1990). Although the rate of reaction is expected to be higher for the thermophilic than for the mesophilic digestion, the contact time (i.e. HRT) is shorter for the thermophilic digestion which may balance the difference (Hill, 1990).

Figure 4 shows the volatile fatty acids (VFA) as acetic, propionic, i-butyric, and n-butyric acids, and the sum of these acids as total VFA. Acetic acid was the most dominant. The total VFA values for retention times of 10 and 5 days obtained in this study are comparable to the results reported by Smart and Boyko (1973) and Rimkus *et al*. (1982) in full-scale thermophilic digestion studies. However, HRT's of 15 and 2.5 days were accompanied by sharp increase in total VFA which is an indication of instability under these conditions. The lowest total VFA was observed during the 10-day HRT, which is an evidence for optimal operation at this HRT. This is reflected in the relatively lower COD of the digested sludge at 10-day HRT (Figure 3). It seems that VFA is a good indicator of digester performance.

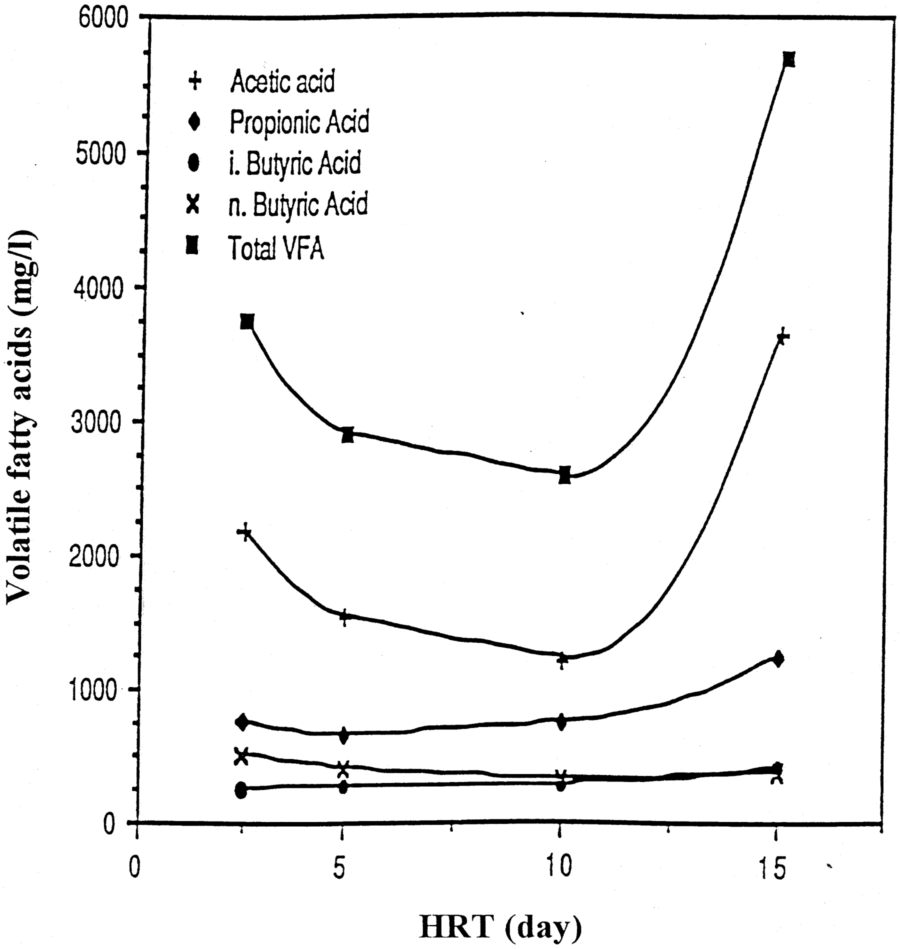


*Figure 4.* Volatile fatty acids versus hydraulic retention time.

Meanwhile, VFA's contribute to the soluble COD content in the digester since each 1 mg $L^{-1}$ of acetic acid gives 1.067 mg $L^{-1}$ COD (Hamoda and Kennedy, 1987).

Figure 5 presents the cumulative volume of gas produced from the digester after steady operation (following the start-up period). The gas contained 55% methane ($CH_4$). It can be seen from the slopes of the lines plotted in Figure 5 that the gas production rates in mL $day^{-1}$ increased as the HRT was decreased from 15 to 2.5 days. This is explained by the increased volumes of feed sludge (substrate) added daily to the digester at shorter HRT's.

Based on the experimental values obtained at HRT = 10 days and using the kinetic model (Equations (12) and (17)) previously stated, results similar to those presented in Table II can be illustrated for the thermophilic digester. This validates the model and demonstrates the advantage of using the thermophilic process for

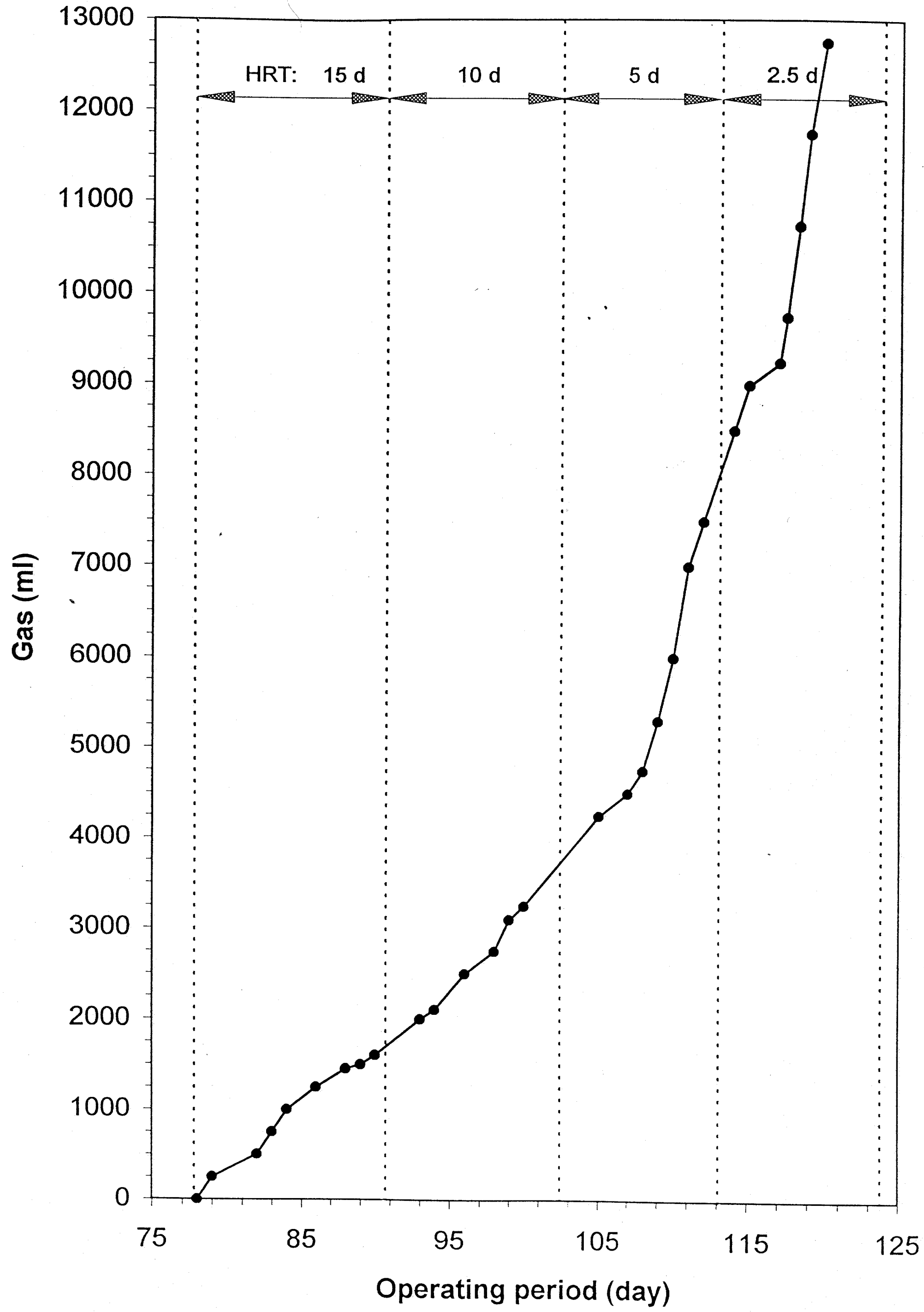


*Figure 5.* Cumulative gas production.

overloaded mesophilic digesters in hot climates. A further advantage is that thermophilic digestion produces a more hygenic sludge for land application since the majority of pathogens are killed at the high temperature (55 °C) employed. However, some disadvantages of the thermophilic sludge digestion include the difficulty in treating supernatant liquor produced and the relative instability of the process. The latter problem can be overcome by applying proper process control strategies (Alatiqi *et al.*, 1994) which demonstrates that thermophilic operation has shorter recovery time after digester upsets.

## 6. Conclusions

The following conclusions can be drawn based on the results obtained in this study:

1. Thermophilic anaerobic digestion is a viable alternative to the mesophilic process especially for overloaded digesters in hot climates.
2. The optimum hydraulic retention time for the thermophilic process appears to be 10 days which leads to substantial savings in digester capacity.
3. A simplified kinetic model has been proposed which can be used for design of the process and manipulation of the digester operating data.

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