THERMOPHILIC AEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE

Milenko Roš, Gregor Drago Zupančič

National Institute of Chemistry, Hajdrihova 19, SI-1000 Ljubljana, Slovenia

Received 20-02-2002

Abstract

Aerobic thermophilic stabilization and degradation of waste activated sludge from wastewater treatment plant was studied. The main parameter of research was the organic fraction reduction (expressed as VSS). The experimental part of the study was divided into two parts. In first, the goal was determination of the most beneficial operating temperature. Batch experiments were, performed at temperatures of 20, 37, 40, 45, 50 and 55 °C. The most beneficial temperature for aerobic digestion of waste activated sludge was found to be 50 °C. The second part of experiments studied the continuous process. Experiments were performed at 50 °C where VSS degradation was studied. It was found that VSS degradation was 29.7% at a retention time of 5 days, and 48.2% at a retention time of 10 days. A simple first order kinetic model was applied. From the batch experiments in the first part the model parameters were calculated. From the parameters calculated from the batch study, the behaviour of the continuous process was predicted. Comparison of model and experimental results showed a very good match for retention times up to 8 days. At retention times above 8 days the experimental data showed better results.

Introduction

Sludge digestion is the most common process for waste sludge treatment. The anaerobic mesophilic process is that most widely used. Less common is the use aerobic digestion. Generally, the anaerobic process is the subject of research, due to the biogas evolved as a by-product of such a process. Degradation of volatile suspended solids in the conventional mesophilic anaerobic process is about 40% at retention times between 30 an 40 days[1-3]. The aerobic process is generally used at smaller wastewater treatment plant and mostly at ambient temperatures; its degradation rate is even smaller, about 30 – 40 % at 50 days retention time.[1, 4, 5] In the thermophilic range sludge degrades at a higher degradation rate. The aerobic digestion of biological sludge is a continuation of the activated sludge process under endogenous conditions.[6] When a culture of aerobic heterotrophic microorganisms is placed in an environment containing a source of organic material, the microorganisms will remove and utilize most of this material. A fraction of the organic material removed is utilized for the synthesis of new microorganisms, resulting in an increase of biomass. The remaining material will be channelled into metabolic energy and oxidized to carbon dioxide, water and soluble inert material, providing energy for both synthesis and maintenance (life support) functions. Once the external source of organic material is exhausted, the microorganisms will begin endogenous respiration where cellular material is oxidized to satisfy the energy requirement for life support. If this condition is continued over an extended period of time, the total quantity of biomass will be considerably reduced and the remaining portion will exist at such a low energy state that it can be considered biologically stable and suitable for disposal in the environment.

The aerobic digestion process, as stated above, consists of two steps; the direct oxidation of biodegradable matter, and endogenous respiration where cellular material is oxidized. These processes can be illustrated in the following equations:

$$organic\ matter + NH_4^+ + O_2 \rightarrow cellular\ material + CO_2 + H_2O \qquad \textbf{Eq. 1}$$

$$cellular\ material + O_2 \xrightarrow{bacteria} digested\ sludge + CO_2 + H_2O + NO_3^- \qquad \textbf{Eq. 2}$$

The first equation (Eq. 1) describes the oxidation of organic matter to cellular material. This cellular material is subsequently oxidized to digested sludge. The process described in the second equation (Eq. 2) is typical of the endogenous respiration process and is the predominant reaction in aerobic systems. The inclusion of primary sludge in the process can shift the overall reaction to Eq. 1, because primary sludge contains little cellular material, so the final result may be an increase of total biomass. Therefore the aerobic process is recommended for excess activated sludge only where longer retention times are possible.

Using typical formula $C_5H_7NO_2$ as representative of the cell mass of a microorganism[4], the stoichiometry of the aerobic process can be represented by the following equations:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + energy \qquad \textbf{Eq. 3}$$

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + 3H_2O + NO_3^- + H^+ + energy \qquad \textbf{Eq. 4}$$

Eq. 3 represents a system inhibiting nitrification; nitrogen appears in the form of ammonia. A system in which nitrification occurs is represented by Eq. 4. These equations indicate that theoretically 1.42 kg of oxygen is required per kg of active cell mass in the non-nitrifying system, whereas 1.98 kg/kg is required when nitrification occurs. The actual oxygen requirement for the aerobic digestion process depends on factors such as the operating temperature, inclusion of primary sludge, and the solids retention time.

The operating temperature of the aerobic digestion system is the main parameter in the process. Because aerobic digestion is a biological process the effects of temperature can be estimated by the following equation[1, 4, 7, 8] in Figure 1:

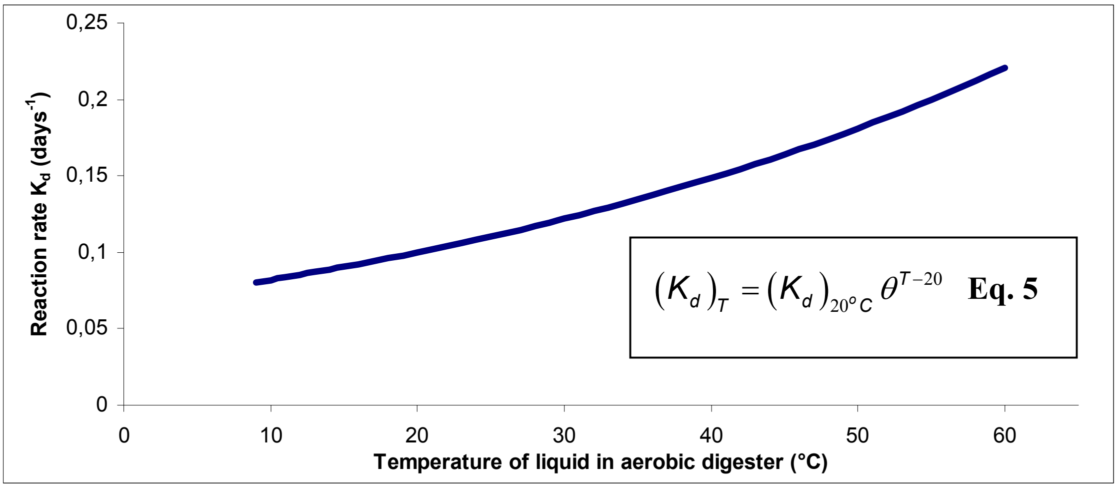

Figure 1 – Aerobic digestion reaction rate as a function of temperature

The reaction rate constant (K_d) represents the destruction rate of volatile suspended solids during the digestion process. An increase in the reaction rate constant (K_d) generally occurs with increase in the temperature of the system and implies an increase in the digestion rate. Temperature coefficients (θ) ranging from 1.02 to 1.10 have been reported, with 1.023 as the average[1, 4, 7, 8]. Although Figure 1 shows the function up to 60 °C its relevance is limited to the range between 10 °C and 40 °C.

The rate of biological processes generally increases with temperature (Figure 1). Hartmann[9] found a maximum volatile solids destruction rate at 30 °C, with a reduction in rate at higher temperatures. This is in contrast with the data in Figure 1, and indicates the importance of obtaining data applicable to the particular sludge with the system operating at higher temperature, which is also the topic of this paper.

Another concern in aerobic digestion is aeration. When the COD loads are much higher than in the conventional activated sludge process, aeration must be very intensive. Another problem appears when digestion is moved to the thermophilic range. For effective aerobic biological degradation the difference between solubility of dissolved oxygen (DO) and the actual oxygen concentration in the reactor must be at least 6 mg/l[4, 9-11]. If the difference is smaller the degradation of organic compounds becomes slower or even partly inhibited. That is why temperatures over 50 °C are not appropriate for aerobic treatment of waste sludge (Figure 2).

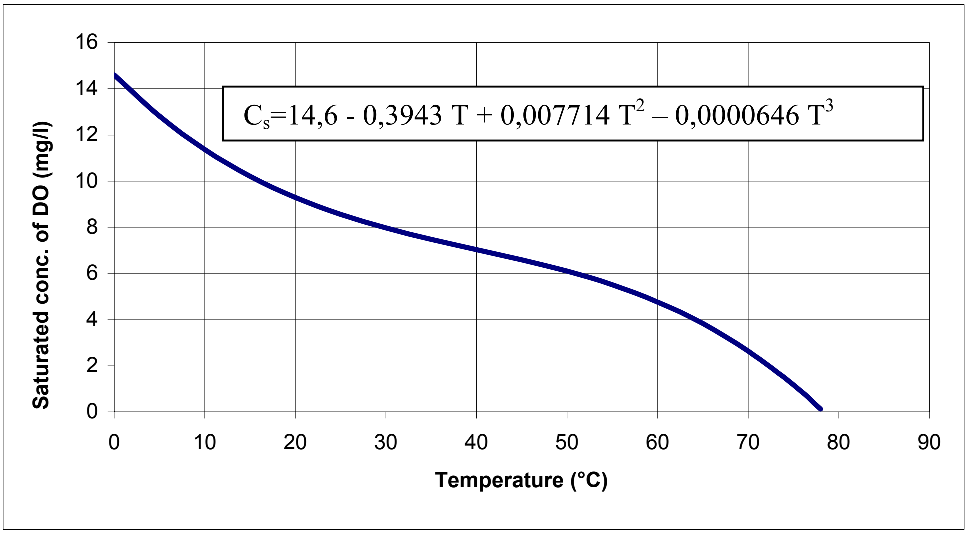

Figure 2 – Oxygen solubility in water at normal pressure

Most aerobic digesters are operated as continuous flow, completely mixed aeration reactors and are designed on the basis of volatile suspended solids (VSS) reduction. The most often used model was presented by Adams[11]. In this model it is assumed that the loss of degradable volatile solids (only a fraction of total VSS) through endogenous respiration follows the first order relationship:

$$\left(\frac{dX_d}{dt}\right)_R = K_d \cdot X_{de}$$ **Eq. 6**

The continuous flow completely mixed digester is shown in Figure 3.

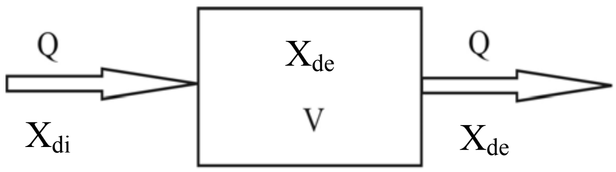

Figure 3 – Flow chart for a completely mixed aerobic digester

The material balance expression for degradable VSS entering and leaving the system is:

$$\begin{bmatrix}\text{net rate of change}\\ \text{in degradable VSS}\\ \text{in digester}\end{bmatrix} = \begin{bmatrix}\text{rate at which}\\ \text{degradable VSS}\\ \text{enter the digester}\end{bmatrix} - \begin{bmatrix}\text{rate at which}\\ \text{degradable VSS}\\ \text{are lost from}\\ \text{the digester}\end{bmatrix}$$

And in mathematical form:

$$\left[\frac{dX_d}{dt}\right]\cdot V = Q \cdot X_{di} - \left[\left(\frac{dX_d}{dt}\right)_R \cdot V + Q \cdot X_{de}\right] \qquad \textbf{Eq. 7}$$

Assuming steady state conditions, substituting $(dX/dt)_R$ from Eq. 6 and considering that $V/Q = \theta_c$, the equation takes the following form:

$$\theta_c = \frac{X_{di} - X_{de}}{K_d \cdot X_{de}} \qquad \textbf{Eq. 8}$$

Introducing relations:

$$X_{de} = X_e - X_n \qquad \textbf{Eq. 9}$$

and

$$X_{di} = X_i - X_n \qquad \textbf{Eq. 10}$$

and substituting for X_{di} and X_{de} from Eq. 9 and Eq. 10, the final form of Eq. 8 is:

$$\theta_c = \frac{X_i - X_e}{K_d \cdot (X_e - X_n)} \qquad \textbf{Eq. 11}$$

The terms K_d and X_n are determined for a particular sludge experimentally through batch studies.

In the experimental work we studied aerobic thermophilic stabilization and degradation of waste activated sludge from a wastewater treatment plant at different temperatures (20, 37, 40, 45, 50 and 55 °C). The aim was to define the most appropriate temperature and sludge retention time for aerobic digestion.

Experimental

Figure 4 shows a cube shaped Plexiglas aerobic reactor with pyramidal bottom having a mixing device on top of the reactor, a temperature regulation device behind the reactor and a dosage flask on a stand to the right of the reactor.

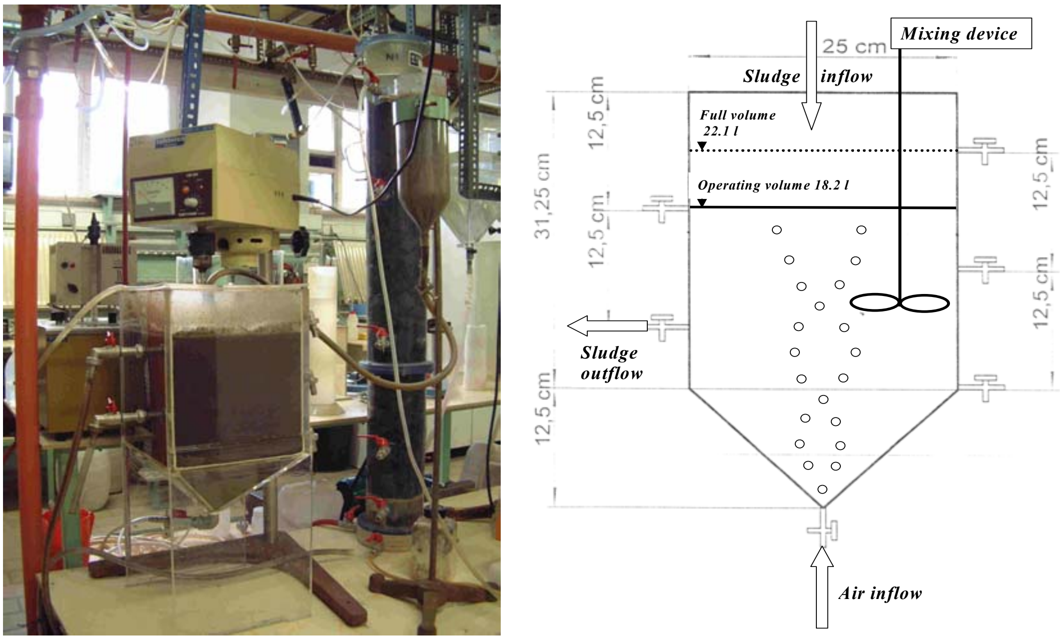

Figure 4 – Aerobic reactor used for experiments.

The total volume of the reactor is 22.1, although only 18.2 l were used in practice because of extensive foaming that appeared while operating under high loads. The reactor inlet is on the top, and the outlet is at the side. Aeration is introduced in the pyramidal bottom. The maximum flow rate of the air into the reactor is 550 l/h. The reactor is heated by hot water.

The main parameters considered in the experiments were volatile suspended solids (VSS), pH, oxygen concentration and temperature. The sample volume was 25 ml. VSS were analysed by Standard Methods.[12] For evaluation of suspended solids in the system the following expression was used:

$$\begin{bmatrix}\text{removal rate of}\\ \text{suspended solids}\end{bmatrix} = \frac{[\text{all suspended solids supplied}] - [\text{all suspended solids leaving the system}]}{[\text{all suspended solids supplied}]}$$

The first series of experiments were performed in the batch mode. The goal was to determine the best operating temperature and model parameters for K_d and for X_n. The experiments were conducted at temperatures of 20 °C, 37 °C, 40 °C and every 5 °C until inhibition occurred. From the data gathered the average K_d was calculated as recommended in Metcalf and Eddy.[7] X_n was determined from long term batch studies with a 60 day retention time[13], assuming that almost all of the degradable material was consumed.

The second series of experiments were performed in the semi-continuous mode. Retention time was set from 5 to 10 days and the results were compared to the theoretical model.

The sludge used in the experiments was collected from a municipal wastewater treatment plant of 200000 PE.

Results and discussion

The first series of experiments were conducted at temperatures of 20, 37, 40, 45, 50, and 55 °C. The results are shown in Figure 5. The best VSS degradation was achieved at 50 °C (62.3% in 17 days). If the results are plotted as VSS degradation in 17 days as a function of temperature, the relation to temperature becomes more obvious (Figure 6).

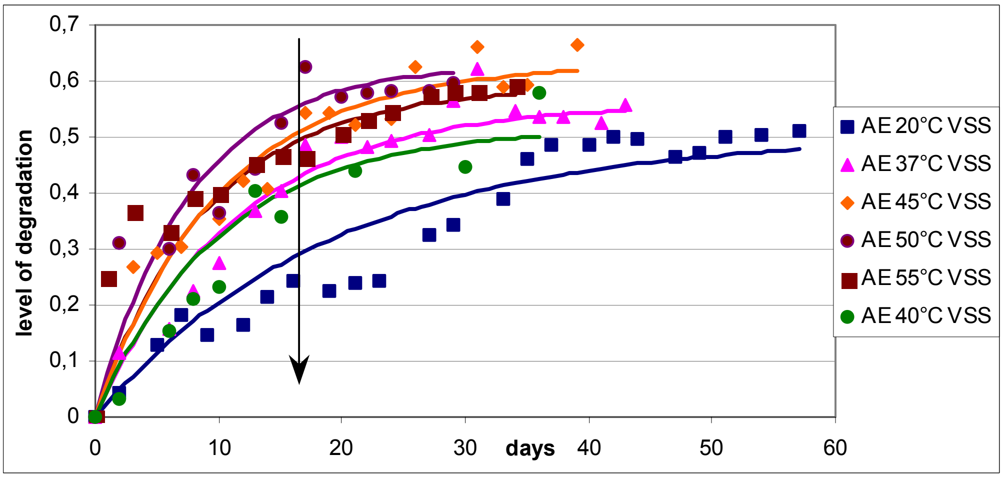

Figure 5 – Results of aerobic batch experiments

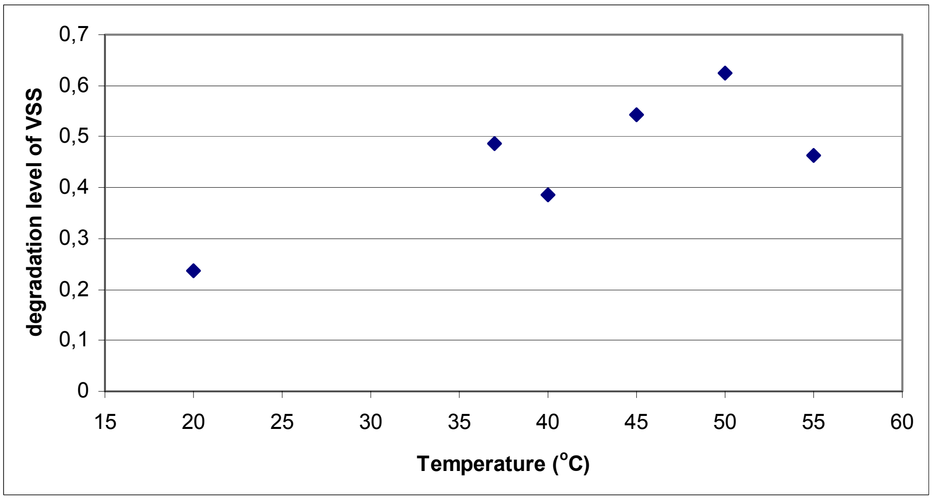

Figure 6 – Temperature dependence of aerobic degradation (cross-section of Figure 5 at 17 days as a function of temperature)

Assuming that degradation follows the function in Eq. 6, parameter K_d can be calculated from the results obtained and shown in Figure 5. The results are presented in Table 1.

Table 1 – K_d of aerobic degradation at different temperatures

	20 °C	37 °C	40 °C	45 °C	50 °C	55 °C
K_d (day^{-1})	0.038	0.066	0.062	0.084	0.125	0.116

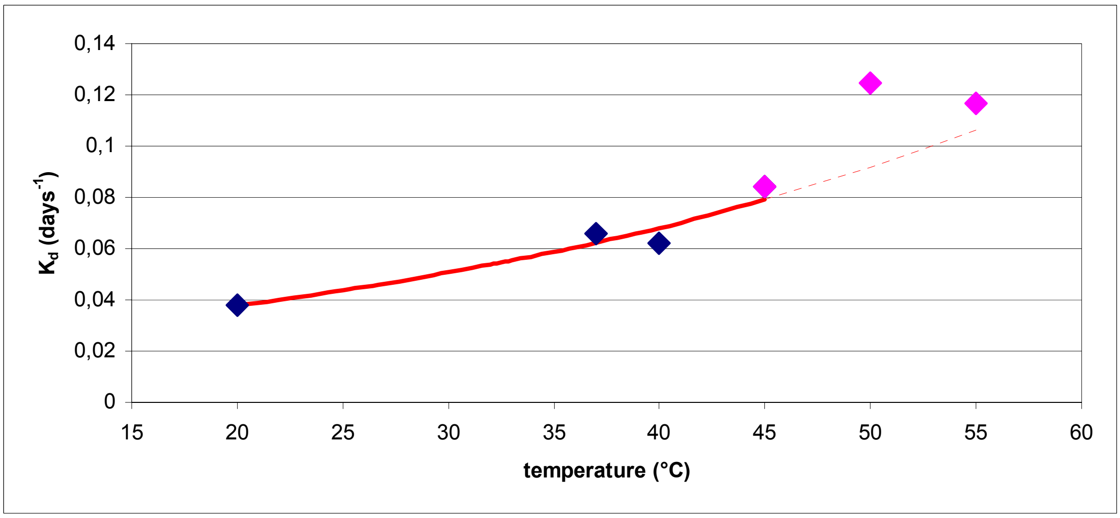

Figure 7 – K_d as a function of temperature

Figure 7 shows the temperature dependence of K_d. In the range between 10 °C and 40 °C it can be considered to follow an exponential function, as cited in the literature.[4, 7-9] Also, the recommended values are about the same (0.04 to 0.06 day^{-1}). At temperatures in excess of 40 °C K_d increases rapidly to its maximum at 50 °C, which is 3 times the normal average value in the temperature range between 10 °C and 40 °C.

To fully define the model, the parameter X_n must also be determined. A study[13] of the total biodegradability of VSS in sludge showed that the degradable part of VSS varies between 67 and 77 % of total influent VSS. The different fractions of VSS in TSS cause variation of the total degradability. Usually the VSS content of sludge is from 75 to 85% of TSS. When the VSS content is higher then the degradable part is also higher.

Having determined all the parameters, a model for continuous digestion (Eq. 11) with the following starting conditions can be established:

K_d =0.1318 day^{-1}, X_n=0.23 X_i (0.77 is the degradable fraction), X_i=8.0 g/l.

The influent concentration is chosen to be the same as in all the continuous experiments where the TSS concentration was 10 g/l and VSS was between 75 and 85% of TSS. The results of the model are presented in Figure 8.

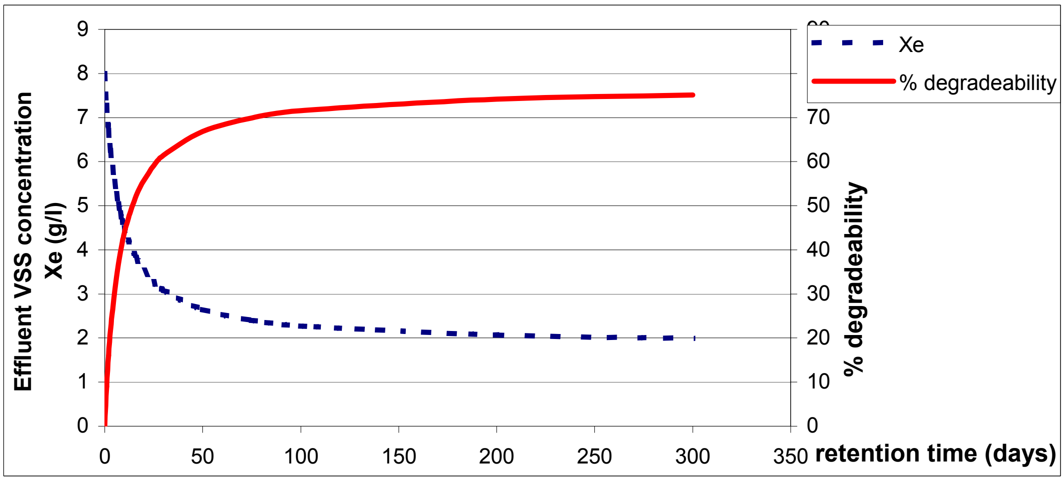

Figure 8 – Model for continuous aerobic digestion

In the second part we conducted continuous experiments with retention times of 5, 6, 7, 8 and 10 days. The results obtained were better than expected from the model; at lower retention times the model is quite accurate, while at higher retention times the experiments show better degradation. The numbers are compared in Figure 9.

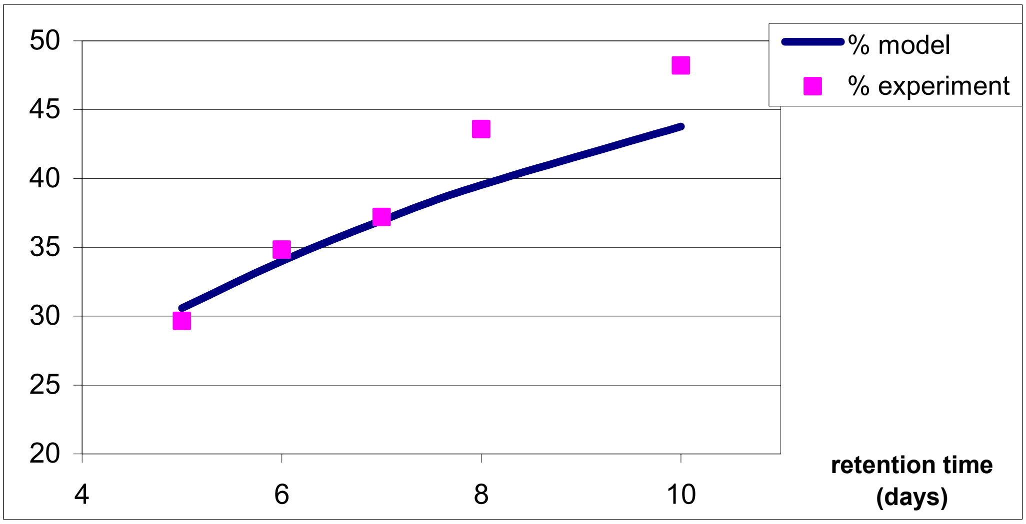

Figure 9 - Degradation levels of aerobic digestion: model and experiment

Experiments were not conducted at higher retention times since the general rate of removal had been achieved. Also, experiments could not be conducted at retention time of under 5 days, because the problem mentioned above with aeration appeared. System aeration was in sufficient, and the process was completely slowed down. It simply was not possible to sustain the oxygen requirements at such high loads. The values of dissolved oxygen were a very good indicator of process quality. If the value was above 0.5 mg/l, good process quality was assured (Figure 10)

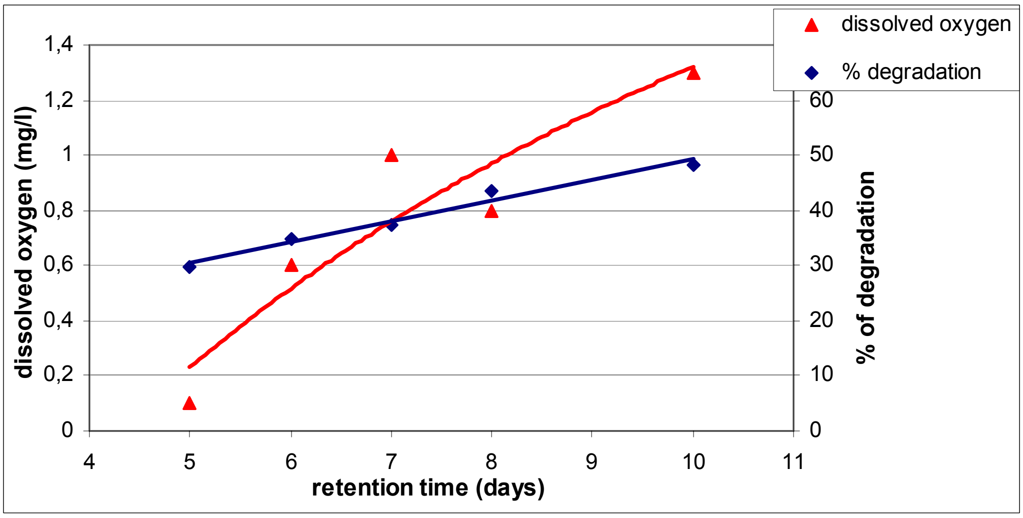

Figure 10 – dissolved oxygen and % of degradation in aerobic digestion as a function of HRT

Considering the model parameters, the results showed that the influent degradable VSS concentration had no impact on the level of degradation. The only parameters influencing the result were the ratio of the degradable portion X_n/X_i (a lower ratio gave better results) and of course K_d (a higher K_d gave better results). However, in the model it is assumed that there is always enough oxygen present to sustain the process. Experiments showed a high sensitivity to a lack of oxygen. Therefore, when dealing with higher concentrations of sludge, more efficient aerators have to be provided, because the operation biomass occupying the reactor volume is greater. Eventually a limit is reached, no matter how good the aerators are, and the process is inhibited due to lack of oxygen. Also, the effect of foaming has to be considered, which is proportional to aeration, and at high loads and extensive aeration becomes a problem, because most of the active biomass can be washed out. Therefore, the reactors must be closed vessels, which is also desirable to preserve the heat necessary for the process and to prevent evaporation of water (in open vessels 5 to 7 volume % of water had to be compensated daily, due to evaporation).

Conclusions

The aerobic digestion of excess waste activated sludge was studied. The most favourable temperature of digestion was established to be 50 °C in the thermophilic range. In this range a general VSS removal rate of 40% was reached at low retention times. At a retention time of 10 days the removal rate was 48.2%, which is more than usually reported in conventional aerobic digestion.

A simple first order relationship kinetic model was introduced. After determining the main model parameters in batch studies, the model was able to predict behaviour in the continuous process. Model results and experiment matched very well at retention times up to 8 days; above 8 days experimental data shows higher mineralization. Although the difference increases with retention time, the practical value of the model is in obtaining reasonably good results for aerobic digestion of various sludges just from batch studies. The disadvantage of the model is that it does not account for the aeration needs of such a process. Aeration has to be considered specially and carefully, because aerobic digestion is very sensitive to lack of oxygen, especially in the thermophilic range of temperature.

Nomenclature

HRT	Hydraulic retention time $[\text{days}]$,
TSS	Total suspended solids $[\text{mg/l}]$,
VSS	Volatile suspended solids (organic solids) $[\text{mg/l}]$,
$\left(\frac{dX_d}{dt}\right)_R$	The rate at which degradable solids are lost as a result of endogenous respiration, $\left[\frac{\text{mass}_{\text{VSS}}\ /\ \text{volume}}{\text{unit time}}\right]$,
K_d	The decay rate constant for degradable fraction of VSS determined in a batch reactor, $\left[\frac{\text{mass degraded VSS/unit time}}{\text{mass of active degradable VSS in the system}}\right] = \text{unit time}^{-1}$,
X_d	The concentration of degradable VSS remaining at time t $[\text{mass/volume}]$,
Q	The volumetric flow rate $[\text{mass/volume}]$,
X_{di}	The concentration of degradable VSS in influent $[\text{mass/volume}]$,
X_{de}	The concentration of degradable VSS in effluent $[\text{mass/volume}]$,
V	Digester volume
X_i	The total VSS concentration in influent $[\text{mass/volume}]$,
X_e	The total VSS concentration in effluent, $[\text{mass/volume}]$,
X_n	The concentration of nondegradable portion of VSS that is assumed to stay inert and constant throughout the digestion process $[\text{mass/volume}]$.

References and Notes

1. Borchardt, J. A., *Sludge and its ultimate disposal*. **1981**, Collingwood, Michigan: Ann Arbour Science.
2. Cook E. J., *Anaerobic sludge digestion: Manual of practice No. 16*. **1986**, Alexandria VA: Water pollution control federation: Task force on Sludge stabilization.
3. Gene F. Parkin, William F. Owen, *Journal of Environmental Engineering*, **1986,** *112*, 867-920.
4. Aasheim S. E., *Sludge stabilization: Manual of practice No. FD-9*. **1985**, Washington D.C.: Water pollution control federation: Task force on Sludge stabilization.
5. EPA, *Autothermal Thermophillic Aerobic Digestion of Municipal Wastewater Sludge*, **1990**, Risk Reduction Engineering Laboratory, Washington D.C.
6. Roš, M., *Respirometry of Activated Sludge*. **1993**, Lancaster, Basel: Technomic Publishing Co., Inc. 151.
7. Metcalf and Eddy, *Wastewater engineering: Treatment, disposal, and reuse*, ed. G. Tchobanoglous, **1991**, Boston Massachusetts: Irwin/McGraw-Hill.
8. Larry D. Benefield, C.W.R., *Biological process design for wastewater treatment*. **1980**, Engelwood Cliffs NJ, USA: Prentice Hall.
9. Hartman R. B., *Sludge stabilizattion through aerobic digestion, Journal of Water pollution control federation*, **1979,** 49 p2353.
10. Ramalho, R. S., *Introduction to wastewater treatment processes*. **1977**, London, GB: Academic Press Inc.

11. Adams C. E., W. W. Eckenfelder, R. M. Stein, *Modifications to aerobic digester design, Water research*, **1974**. **8** p213.
12. APHA, AWWA, WEF, *Standard methods for the examination of Water and wastewater*. 20th edition ed., **1998**, Washington D.C.
13. Milenko Roš, Gregor Drago Zupančič. *Dvostopenjska anaerobno - aerobna termofilna stabilizacija blata*. in *Vodni dnevi 2001*, **2001**, Celje: Slovensko društvo za zaščito voda.

Povzetek

Preučevali smo aerobno termofilno stabilizacijo in razgradnjo odpadnega aktivnega blata. Glavni parameter raziskav je bil organski delež blata (hlapne suspendirane snovi). Eksperimentalni del raziskav je bil razdeljen na dva dela. V prvem delu je bil cilj raziskav določiti najugodnejšo temperaturo razgradnje. Preskusi so bili šaržni, izvedeni pri temperaturah 20, 37, 40, 45, 50 in 55 °C. Najugodnejša temperatura razgradnje je bila 50 °C. Drugi del raziskav so bili kontinuirani preskusi, ki so bili izvedeni pri temperaturi 50 °C. Preučevali smo razgradnjo organskega dela blata. Razgradnja organskega dela blata se je gibala od 29,7% pri zadrževalnem času 5 dni, do 48,2% pri zadrževalnem času 10 dni. Uporabili smo tudi enostavni model prvega reda za kinetiko razgradnje. Iz rezultatov šaržnih preskusov smo izračunali parametre modela. Iz izračunanih parametrov šaržnega preskusa smo določili obnašanje kontinuiranega procesa. Primerjava rezultatov modela in preskusov je pokazala zelo dobro ujemanje pri zadrževalnih časih do 8 dni. Pri zadrževalnih časih nad 8 dni so bili boljši rezultati dobljeni pri preskusih.