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ANAEROBIC TREATMENT SYSTEMS

A Dynamic Model for Anaerobic Filter

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ABSTRACT

Anaerobic filters are frequently used to treat medium to high strength wastewater (2000–20000 mg/L COD), but have fewer applications to low strength wastewater (< 1000 mg/L COD). In order to understand the applicability of anaerobic treatment for low strength wastewater, such as domestic sewage, a dynamic mathematical model was developed. This Monod-type kinetic model, which predicts treatment efficiency and gas production, was used to describe literature observations and is offered as a predictive tool.

Key Words: Anaerobic filter; Domestic wastewater; Dynamic model; Low strength wastewater; Mathematical model; UASB reactor.

INTRODUCTION

Anaerobic treatment has traditionally been used for treatment of sludges and high strength wastewater. This was due to the need for elevated temperatures for

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slow growing methanogens. The invention of new anaerobic systems such as the anaerobic filter (AF), upflow anaerobic sludge blanket (UASB) and hybrid reactors (a combination of UASB and AF) has reduced or eliminated the need for elevated temperatures by maintaining long solids retention time (SRT) independent of the hydraulic retention time (HRT). This change enabled treatment of low strength wastes such as domestic wastewater.

The anaerobic filter uses a rock or synthetic media for biomass growth. The wastewater flows through the media, and biomass is retained on the media, which makes the hydraulic and solids retention times independent. Coulter[1] was the first to develop AF process, but it was not used until 1969 when Young and McCarty[2] studied the treatment of a protein–carbohydrate wastewater (1500–6000 mg/L COD) at 25°C, at organic loading rates (OLR) of 0.96–3.40 kg COD/m^3d. The UASB is an alternative process, developed primarily by Lettinga et al.[3,4] and retains biomass in granular sludge beds, which decouples the hydraulic and solids retention times. The UASB process is now widely used except in the United States, where it and other anaerobic wastewater treatment technologies are unpopular.

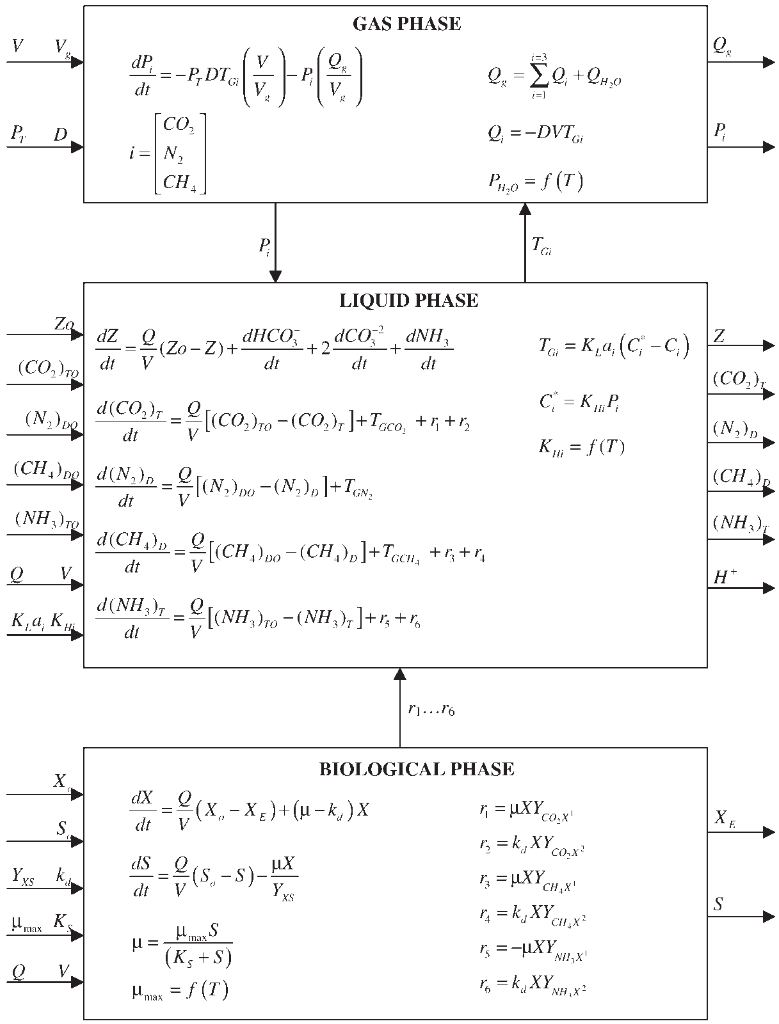
The objective of this paper is to describe a dynamic model that can be used for anaerobic filters, and demonstrate treatment efficiency of domestic wastewater. This predictive tool is offered to improve process acceptance.

MODEL DEVELOPMENT

Anaerobic treatment of waste is a complex biological process involving several groups of microorganisms.[5–7] In general complex wastes are stabilized in three basic steps: hydrolysis, acid fermentation, and methanogenesis. In the acid fermentation step the organic waste is decomposed into lower fatty acids such as acetic and propionic by acid forming bacteria. In methanogenesis these fatty acids are broken down into CO_2 and CH_4 by methanogens.[8] The growth rate of the methanogens is low and is usually the rate-limiting step. Long SRT is required to retain the slow growing methanogens.

The following model is a dynamic model describing anaerobic treatment using anaerobic filters. The model predicts treatment efficiency as well as gas production and composition. The model assumes methane formation from acetate is the rate-limiting step. Therefore, the model is simplified to methanogenesis, and hydrolysis and fermentation steps are not considered. This is a valid assumption for highly degradable low strength wastewater. The model is based in part on earlier models developed by Andrews[9,10]. The model is restricted to low strength influents, and does not require the more advanced concepts that separate substrates and biomasses into different pools.[11–16] The model includes the physical, chemical, and biological interaction between gas, liquid, and biological phases. The model is composed of 10 ordinary differential equations. The general material balance equation (Accumulation = Input − Output + Production − Utilization) was used for the corresponding 10 state variables: substrate, and biomass in the biological phase; CO_2, N_2, and CH_4 partial pressures in the gas phase; alkalinity, dissolved CO_2, N_2, CH_4, and NH_3 in the liquid phase. The equations are shown in Table 1.

Table 1. Model flow diagram.



Stoichiometry

A generalized stoichiometric relationship showing the conversion of acetic acid (CH_3COOH) to methane and carbon dioxide with the synthesis of biomass ($C_5H_7NO_2$) and the decay of biomass is given respectively in Eqs. (1) and (2).

$$\begin{aligned} CH_3COOH + Y_{XS} \cdot Y_{NH_3X^1} NH_3 \rightarrow\ & Y_{XS} C_5H_7NO_2 + Y_{XS} \cdot Y_{CO_2X^1} CO_2 \\ & + Y_{XS} \cdot Y_{CH_4X^1} CH_4 + aH_2O \end{aligned} \tag{1}$$

$$C_5H_7NO_2 + bH_2O \rightarrow Y_{CO_2X^2} CO_2 + Y_{CH_4X^2} CH_4 + Y_{NH_3X^2} NH_3 \tag{2}$$

Biological Phase

The rate of change of substrate concentration (S) in the reactor at any time depends on the influent (S_o) and the utilization of substrate for biomass growth. Monod-type kinetics is used to describe the utilization of substrate.

The rate of change of biomass (X) concentration in the reactor is a function of the influent (X_o) and effluent (X_E) biomass concentrations and the biomass growth and decay in the reactor. In AF the biomass concentration in the reactor is much higher than the effluent biomass concentration as the biomass is retained in the packing media.

The production and utilization rates of dissolved CO_2, CH_4 gases, and NH_3 during biomass growth and decay are shown by r_1, r_3, r_5, r_2, r_4, and r_6 respectively.

Liquid Phase

The net rate of CO_2, CH_4, and N_2 transfer (T_{Gi}) between the liquid and gas phases can be expressed by two-film theory. Henry's Law was used to determine the concentration of the gases in the liquid phase at equilibrium with the partial pressure of the gases in the gas phase. Henry's Law constants (K_{Hi}) are a function of the temperature.

The rate of change of alkalinity (Z) in the reactor depends on the influent alkalinity (Z_o) and the change of bicarbonate, carbonate, and ammonia concentrations in the liquid phase. The rate of change of total carbonic acid concentration in the reactor is a function of the influent carbonic acid concentration and gas transfer rate of dissolved carbon dioxide and the rate of dissolved carbon dioxide production during biological growth and decay. The N_2 gas does not undergo any biological or chemical reaction in the reactor, and it is stripped from the influent.

Methane gas is produced by the biomass and is stripped from the liquid to the gas phase. For low strength systems, the mass of dissolved nitrogen in the influent can be large compared to methane that is produced. Nitrogen is stripped from the influent to the gas phase in the reactor because it changes from being in equilibrium with 79% nitrogen gas fraction to essentially zero in the digester gas. The mass of stripped nitrogen is sufficient to reduce the methane percentage when using low strength (i.e., low methane production) wastewater.

Gas Phase

The rate of change of partial pressures of CO_2, CH_4, and N_2 gases (P_i) in the gas phase are a function of the gas transfer rate and the outflow (Q_g) from the gas phase. The partial pressure of H_2O (P_{H_2O}) changes with the temperature.

RESULTS AND DISCUSSION

Kobayashi et al.[17] and Abramson's[18] AF data were used to calibrate the model. Figure 1 show the calibration graph for removal rate and effluent substrate

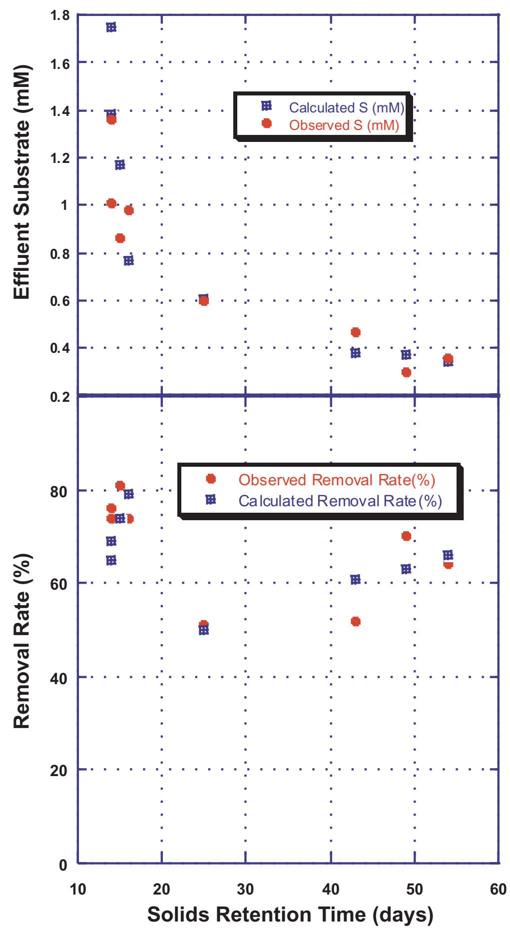


Figure 1. Effluent substrate concentration (top) and removal rate (bottom) vs. SRT.

concentration as a function of solids retention time. Pairs of points are shown, with one member representing the observed data, and the second member representing the simulation for those conditions. The simulations are not on a smooth line, as shown in later figures, since each data point was collected at different temperatures, hydraulic retention times, and influent substrate concentrations. Model predictions of the gas composition of the effluent as a function of influent substrate concentration and solids retention time are given in Figs. 2 and 3. The model accurately predicts the high nitrogen partial pressure for low strength wastewater.

CONCLUSIONS

The dynamic model was able to predict treatment efficiency from previous pilot scale AF studies. Furthermore, the model simulates the gas composition of the

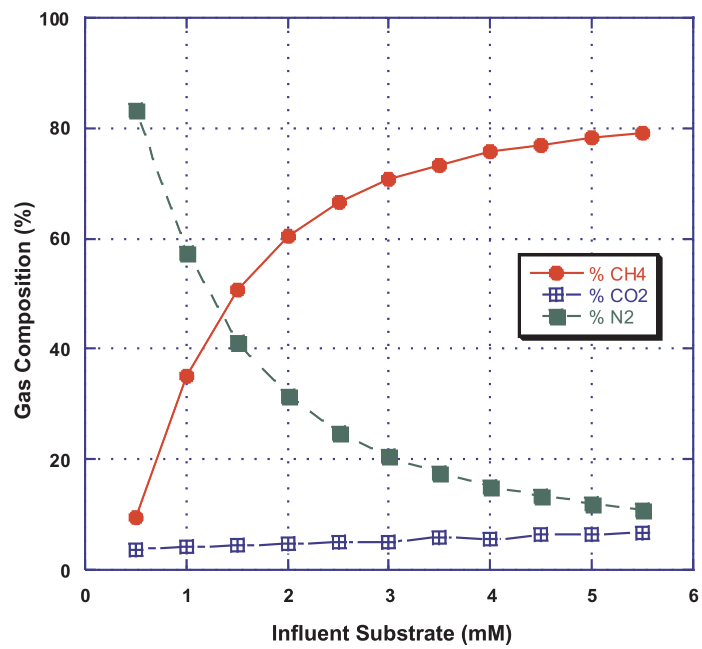


Figure 2. Simulated gas composition vs. influent substrate concentration (symbols represent calculated values).

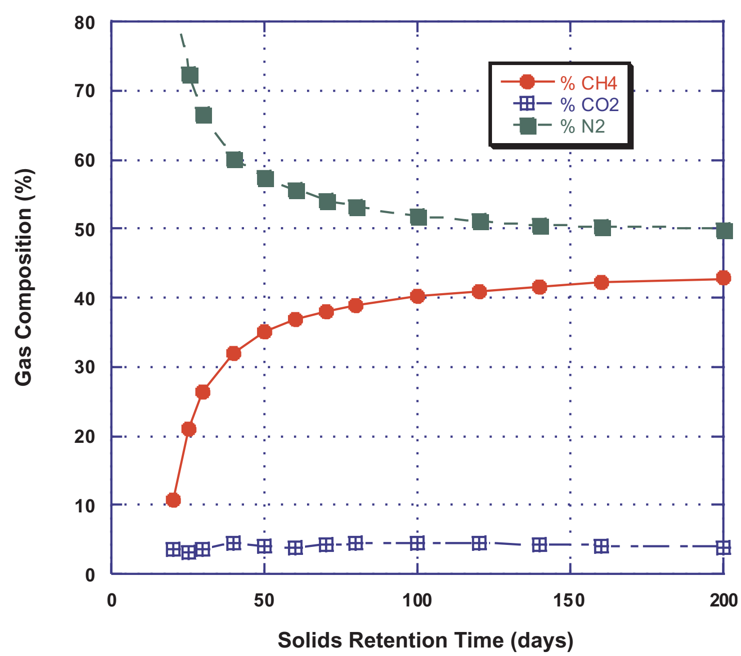


Figure 3. Simulated gas composition vs. SRT (symbols represent calculated values).

effluent from influent characteristics. The previous data and the model suggest that 24 h HRT is required to achieve greater than 60% COD removal. Methane composition will be less than 50%, when influent substrate concentrations are less than 130 mg/L COD at ambient temperature of 20°C.

Hopefully, the reported predictions from the dynamic model will enhance the use of anaerobic treatment in the United States and other areas where anaerobic wastewater treatment is less frequently used.

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