A steady state model for anaerobic digestion of sewage sludges

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Abstract

A steady state model for anaerobic digestion of sewage sludge is developed that comprises three sequential parts – a kinetic part from which the % COD removal and methane production are determined for a given retention time; a stoichiometry part from which the gas composition (or partial pressure of CO_2), ammonia released and alkalinity generated are calculated from the %COD removal; and a carbonate system weak acid/base chemistry part from which the digester pH is calculated from the partial pressure of CO_2 and alkalinity generated. From the stoichiometry and weak acid base chemistry parts of the model, for a given % COD removal, the digester gas composition, ammonia released, alkalinity generated and digester pH are completely defined by the influent sludge composition, i.e. X, Y, Z and A in $C_XH_YO_ZN_A$ of the hydrolysable organics; volatile fatty acid (VFA) concentration; and pH. For the kinetic part of the model, four hydrolysis kinetic equations were calibrated against 7 to 60 d retention time anaerobic digesters treating two different sewage sludge types, viz. first order; first order specific; Monod; and saturation. Once calibrated against the two sludge type data sets and taking into account experimental error in effluent COD concentration and gas production (i.e. COD mass balance error), each of the four hydrolysis kinetic equations predicted the % COD removal versus retention time equally well, and predicted COD removal and methane production compared well with measured data. For the different sewage sludge types, viz. a primary and humus sludge mixture from a trickling filter plant, and a "pure" primary sludge, different kinetic rate constants were obtained indicating that the "pure" primary sludge hydrolysed faster and had a lower unbiodegradable particulate COD fraction ($f_{PS'up}$ = 0.33) than the primary and humus sludge mixture (0.36). With the %COD removal known from the hydrolysis part of the model, and again taking experimental error into account (i.e. C and N mass balances error), the stoichiometry and weak acid base chemistry parts of the model predicted the gas composition, effluent free and saline ammonia (FSA) concentration, alkalinity generated and digester pH well for a primary and humus sludge composition of $C_{3.5}H_7O_2N_{0.196}$. From independent measurement of primary sludge CHON composition, this model estimated composition is within 96%, 100%, 95% and 99% of the average measured composition of $C_{3.65}H_7O_{1.97}N_{0.190}$ lending strong support to the developed steady state model.

Keywords: Anaerobic digestion, steady state model, sewage sludge, hydrolysis kinetics, biodegradability

Introduction

Sötemann et al. (2005a) developed an integrated two-phase (aqueous-gas) mixed weak acid base chemical, physical and biological processes kinetic model for anaerobic digestion (AD) of sewage sludge. The COD, C and N mass balances and continuity basis of this model fixes quantitatively, via the interrelated chemical, physical and biological processes, the relationship between all the compounds of the system. Thus for a given sewage sludge COD removal the digester outputs (i.e. effluent COD, TKN, FSA, SCFA, H_2CO_3* Alk, pH, gaseous CO_2 and CH_4 production and partial pressures) are governed completely by the input sludge solids (and dissolved) constituents. In this model, the sewage sludge feed is characterised in terms of total COD, its particulate unbiodegradable COD fraction ($f_{PS'up}$), the short chain fatty acid (SCFA) COD and the CHON content, i.e. X, Y, Z and A in $C_XH_YO_ZN_A$ of the particulate organics. This approach characterises the sludge in terms of measurable parameters in conformity with the COD, C and N mass balances approach. With this approach, the interactions between the biological processes and weak acid/base chemistry could be correctly predicted for stable steady state operation of anaerobic digesters. While not validated for dynamic flow and load conditions, the model has the capability of being applied to such conditions. In this paper this complex dynamic simulation model is simplified to a steady state one for integration into a steady state mass balance model of the whole wastewater treatment plant (Sötemann et al., 2005b).

Steady state models are based on the slowest process kinetic rate that governs the overall behaviour of the system and relates this process rate to the system design and operating parameters. Therefore, steady state models allow the system design and operating parameters, such as reactor volume and recycle ratios, to be estimated reasonably simply and quickly from system performance criteria specified for the design, such as effluent quality. Once approximate design and operating parameters are known, these can serve as input to the more complex simulation models to investigate dynamic behaviour of the system and refine the design and operating parameters. A steady state AD model is therefore useful to:

- estimate retention time, reactor volume, gas production and composition for a required system performance like COD (or VSS) removal,
- investigate the sensitivity of the system performance to the design and operation parameters,
- provide a basis for cross-checking simulation model results, and
- estimate product stream concentrations for design of down- (or up-) stream unit operations of the wastewater treatment plant.

Anaerobic digestion of organics require a consortium of four organism groups (Mosey, 1983; Massé and Droste, 2000;

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