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New generic mathematical model for WWTP sludge digesters operating under aerobic and anaerobic conditions: Model building and experimental verification

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ABSTRACT

This paper presents a new mathematical model developed to reproduce the performance of a generic sludge digester working either under aerobic or anaerobic operational conditions. The digester has been modelled as two completely mixed tanks associated with gaseous and liquid volumes. The conversion model has been developed based on a plant wide modelling methodology (PWM) and comprises biochemical transformations, physicochemical reactions and thermodynamic considerations. The model predicts the reactor temperature and the temporary evolution of an extensive vector of model components which are completely defined in terms of elemental mass fractions (C, H, O, N and P) and charge density. Thus, the comprehensive definition of the model components guarantees the continuity of elemental mass and charge in all the model transformations and between any two systems defined by the model. The aim of the generic digester model is to overcome the problems that arise when trying to connect aerobic and anaerobic digestion processes working in series or to connect water and sludge lines in a WWTP. The modelling methodology used has allowed the systematic construction of the biochemical model which acts as an initial illustrative example of an application that has been experimentally verified. The variation of the temperature is also predicted based on a thermal dynamic model. Real data from four different facilities and a straightforward calibration have been used to successfully verify the model predictions in the cases of mesophilic and thermophilic anaerobic digestion as well as autothermal thermophilic aerobic digestion (ATAD). The large amount of data from the full scale ATAD and the anaerobic digestion pilot plants, all of them working under different conditions, has allowed the validation of the model for that case study.

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1. Introduction

Sludge is the solid product generated during wastewater treatment. As a result of population growth and new water pollution legislation, sludge production has increased all over the world. Mesophilic anaerobic digestion is employed worldwide as the oldest and most important process for sludge stabilization. Nevertheless, current and increasingly stricter regulations concerning sludge treatment requirements with respect to its final disposal on land have generated research on alternatives to mesophilic anaerobic digestion which is incapable of achieving sludge pasteurisation (Ward et al., 1998; Oles et al., 1997).

Any operational strategy for sludge digestion has its advantages and disadvantages. In general, a two-phase digestion permits the physical separation of different groups of microorganisms to optimise their conditions for their different growth kinetics, as proposed by Pohland and Ghosh (1971). The Dual Digestion system (DD) formed by a thermophilic aerobic digester followed by a mesophilic anaerobic digester is claimed to have several advantages with regard to the processes alone (Huete et al., 2006a). However, other case studies show that the small gain in Volatile Solids (VS) removal efficiency does not justify the higher operation cost of a two-phase system (Bhattacharya et al., 1996). Concerning the system operational conditions, the thermophilic conditions offer the advantages of pasteurisation to meet the regulations for Processes to Further Reduce Pathogens (PRFP) and the increase of the rates for particulate matter hydrolysis and biomass decay (Mason et al., 1992). Aerobic digestion, studied in depth by Hamer and Bryers (1985), has the self-heating capacity of reaching optimum thermophilic conditions, while oxygen limiting conditions in a digester contribute to the production of a considerable amount of volatile fatty acids (VFA) through anaerobic fermentation (McIntosh and Oleszkiewicz, 1997; Häner et al., 1994). Even the ratio of primary to secondary sludge has been claimed to be a factor worthy of consideration for the treatment design (Gavala et al., 2003). All in all, there seem to be many different operational alternatives to compare and analyse in order to optimise sludge treatment depending on its characteristics and the effluent quality requirements. Mathematical modelling and simulation is a useful tool that can help to do this task.

With regard to the aerobic digestion treatment of sludge, limited references have been found dealing with the modelling of the biological process, and most of them are based on the Activated Sludge Models (ASM) (Henze et al., 2000). The most important particularity of the aerobic digestion process is its autothermal capacity. Thus, the biological heat generated in the tank should form part of the model. Vismara (1985) expressed the stoichiometry of biological heat generation in terms of the amount of VS removal. However, when the process began to be designed as a pre-treatment with a very low VS removal, that term turned out to be too imprecise for practical application and the heat generated biologically was related to oxygen consumption (Hamer and Bryers, 1985). A very complete work on dual digestion treatment evaluation and optimisation (Messenger and Ekama, 1993a, b) presented a model of an autothermal aerobic digester with a heat balance which takes into account the biological heat generation associated with oxygen utilisation. Finally, Gómez et al. (2007) presented a new biochemical model for aerobic digestion that introduces the energy balance to dynamically predict the temporary evolution of the temperature in an *Autothermal* Thermophilic Aerobic Digester (ATAD).

In the field of Anaerobic Digestion (AD), the model No1 (ADM1) (Batstone et al., 2002) has depicted much of the knowledge concerning this process modelling. Since its publication, the ADM1 has been analysed and enhanced by researchers from numerical, fundamental and functional points of view. For example, Blumensaat and Keller (2005) validated the model for a pilot scale process for anaerobic two-stage digestion of sewage sludge. However, they also stated that some modifications had to be made to the ADM1 to overcome numerical aspects and an important problem affecting the mass balancing and the incompatibility of the biomass decay and disintegration transformations.

To overcome this problem, a completely balanced ADM1 was presented by de Gracia et al. (2006) as an example of a methodology to develop and analyse the stoichiometry of dynamic structured models. This approach, based on the definition of all the components in elemental mass fractions and charge density, turned out to be very useful at bringing to light possible fundamental errors (Huete et al., 2006b; Sötemann et al., 2005), to facilitate the fulfilment of closed mass balances in all the transformations and to simplify the connections between models. Thus, this approach was developed and enhanced until a rigorous methodology to model biochemical conversion processes (the so-called Plant Wide Model (PWM) methodology) was obtained (Grau et al., 2007a). This was verified by means of a common case study in Grau et al. (2007b). This methodology allows the direct connection of models for different processes and makes it possible to establish a systematic mathematical procedure for the automatic estimation of influent characteristics in Wastewater Treatment Plants (WWTPs). This procedure was developed in parallel to complement this PWM methodology, as it requires a rather large number of model components (Grau et al., 2007c).

The main motivation of the work presented in this paper is to develop a generic model of a sludge digester capable of simulating digesters operating under aerobic or anaerobic conditions and, consequently, to facilitate the connection of unit-process models to simulate, for example, two-stage digestion systems or the interrelationships between the water and sludge lines in a WWTP. For this reason, the PWM methodology (Grau et al., 2007a) has been used to construct this model in order to be able to directly connect digesters with different operational conditions and also to be suitable to be connected to any other unitary processes, including the water line systems. The dynamic evolution of temperature has also been described in the model based on the work presented by Gómez et al. (2007). With this model we should be able to study the optimal alternative for sludge digestion considering different objectives: sludge stabilisation, sludge pasteurisation and global plant wide optimisation.

This paper describes the new model and shows the analysis of the predictive capacity of the model performed with abundant experimental data. The automatic characterisation of three different kinds of sludge has been carried out by means of the automatic procedure mentioned above (Grau et al., 2007c).

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