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Optimal design and operation of a UASB reactor for dairy cattle manure

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ABSTRACT

Optimal design and operation of a planned full-scale UASB reactor at a dairy farm are determined using optimization algorithms based on steady state simulations of a dynamic AD process model combined with models of the reactor temperature and heat exchanger temperatures based on energy balances. Available feedstock is 6 m^3/d dairy manure produced by the herd. Three alternative optimization problems are solved: Maximization of produced methane gas flow, minimization of reactor volume, and maximization of power surplus. Constraints of the optimization problems are an upper limit of the VFA concentration, and an upper limit of the feed rate corresponding to a normal animal waste production at the farm. The most proper optimization problem appears to be minimization of the reactor volume, assuming that the feed rate is fixed at its upper limit and that the VFA concentration is at its upper limit. The optimal result is a power surplus of 49.8 MWh/y, a hydraulic retention time of 6.1 d, and a reactor temperature of 35.9 °C, assuming heat recovery with an heat exchanger, and perfect reactor heat transfer insulation. In general, the optimal solutions are improved if the ratio of the solids (biomass) retention time to the hydraulic retention time is increased.

1. Introduction

The aim of this paper is to optimize the design and steady-state operation of a planned full-scale upflow anaerobic sludge blanket (UASB) reactor fed with dairy cattle waste with 6 m^3/d available feedstock. The optimization is based on a mathematical model of the reactor comprising a dynamic AD process model combined with models of the reactor temperature and the heat exchanger temperatures based on energy balances. The biological parameters of the AD process model was estimated from experiments on a real pilot reactor using the same feedstock as the planned full-scale reactor.

Three sets of optimization problems are studied: Maximization of the produced methane gas flow, minimization of the reactor volume, and maximization of the power surplus. The biological product considered in the optimization problems is the produced methane gas.

Actually, the real pilot plant in Foss Biolab includes a nitrification reactor used to enhance the quality of the effluent as a biological fertilizer. The planned full-scale plant also includes a nitrification reactor. However, the present study focuses at the energy production – not fertilizer production. Therefore, the AD effluent is taken into account in the present study only through its contribution to the energy balance, and not as a fertilizer.

An early attempt to use a dynamic AD model for optimization of anaerobic digestion (AD) reactors was made by Hill (1983a). In that study, a series of simulations based on the model presented by Hill (1983b) were used to detect the optimum hydraulic retention time (HRT) that maximized the volumetric methane productivity defined as steady-state volumetric methane gas flow divided by reactor volume. The solids retention time (SRT) was assumed equal to the HRT, as in a continuous stirred tank reactor (CSTR).

In the present study, the reactor is a UASB type reactor (Lettinga et al., 1980), having SRT larger than HRT. In UASB type reactors, the dense granulated sludge bed retains the microorganisms, and prevents them from being washed out of the reactor with the effluent. The formation of the granulated sludge is due to flocculation and gravity. Since the SRT is larger than the HRT for UASB reactors, their reactor volume can be made smaller, or, alternatively, their loading (feeding) rate can be higher compared with CSTRs.

Poels et al. (1983) reported experiences from AD processing of swine waste on a farm of typical size for Belgium. They emphasized the importance of insulation and preheating the (cold) influent by the (warm) effluent.

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Bozinis et al. (1996) showed in a simulation study of a hypothetical centralized wastewater treatment plant based on co-digestion of a number of wastewater streams how optimization methods, namely nonlinear programming (NLP), can be used to identify the optimal number of CSTR AD reactors and their volumes that minimize costs. They also showed how to identify the optimal mixing of the wastewater streams that maximize the total COD (chemical oxygen demand) conversion of the plant. Simple steady-state AD process models based on Monod kinetics were assumed.

The methods of formulation and solution of optimization problems for technical systems and industrial plants presented in Edgar et al. (2001) have been useful for the present paper as they are applicable also to biological plants.

The outline of this paper is as follows. A description of the planned AD reactor and the optimization method used are described in Section 2. Optimization results are presented in Section 3. A discussion is given in Section 4, and conclusions are given in Section 5. Mathematical models are presented in Appendix A.

Unless otherwise stated, the numerical values of variables presented in this paper are steady-state values.

MATLAB (The MathWorks, Inc.) is used for numerical computations.

2. Materials and methods

2.1. The AD reactor

The AD reactor is a part of a (planned) full-scale biological plant for nutrient and energy recovery, named Foss Biolab, situated at Foss Farm, Skien, Norway. A small-scale pilot plant has been in operation for about two years. A description of the pilot plant, including its monitoring and control system, is in Haugen et al. (2013a).

The feed to the pilot reactor, which has 250 L liquid volume, is dairy waste diluted with approximately 25% water and filtered with a home-made rotary sieve with mesh-size 1.4 mm. The sieve, or separator, removes larger particles to avoid technical problems (the dry-matter from the sieve is used for vermicomposting). The wet-fraction is used as feed to the AD reactor. Feed characteristics from laboratory analysis are presented in Table 1.

The produced biogas consists of approximately 70% methane.

Fig. 1 depicts the planned full-scale reactor. The figure includes a heat exchanger (however, the pilot reactor has no heat exchanger).

2.2. Mathematical models

The mathematical model used for optimization of the planned full-scale reactor comprises the following sub-models:

Table 1
Characteristics of the reactor feed. (Mean ± standard deviations from laboratory analyses of totally 23 samples collected from the pilot plant approximately twice a week.)

Measure	Value	Unit
TS	44.6 ± 2.2	g/L
VS	30.2 ± 1.0	g/L
tCOD	48.6 ± 1.5	g/L
sCOD	15.5 ± 1.0	g/L
NH4-N	0.95 ± 0.078	g/L
Alkalinity	8.6 ± 0.8	g $CaCO_3$/L
pH	7.55 ± 0.15	log[H+]

1. The modified Hill model of the AD processes adapted to the pilot reactor (Haugen et al., 2013a). For easy reference, the model is summarized in Appendix A.1.
2. A model of the reactor liquid temperature based on energy balance (Haugen et al., 2013a). The model is summarized in Appendix A.2.
3. A model of the temperatures of heat exchanger based on energy balances. The model is derived in Appendix A.3.

The modified Hill model is a relatively simple AD process model, however it has been successfully adapted to the real pilot reactor (Haugen et al., 2013a). The modified Hill model is selected in the present study since it is assumed sufficient for model-based optimization of the full-scale AD reactor. The most interesting alternative model is probably the comprehensive ADM1 model (Anaerobic Digestion Model No. 1) (Batstone et al., 2002), which, after adaptation to the real pilot reactor, may be used in future model-based studies.

2.3. Optimization objectives and variables

Fig. 2 shows alternative optimization variables and objective variables. In the various optimization problems discussed in Sections 3.2, 3.3 and 3.4, various subsets of these variables are used.

2.3.1. Optimization objectives

Fig. 2 defines alternative optimization objective variables (the outputs in the block diagram):

F_{meth}, to be maximized, which is an appropriate objective if the gas is supplied (sold) to a gas grid.
V, to be minimized, which is an appropriate objective to save space and constructional and installation costs.
P_{sur}, to be maximized, which is an appropriate objective if the gas is applied for heating within the farm. P_{sur} is calculated with Eq. (A.20), where all power terms are in units of MWh/y.

2.3.2. Optimization variables and their constraints

In the following, the optimization variables are characterized as either operational or design optimization variables. The former can be changed while the reactor is being operated, while design optimization variables can be changed in the design or constructional phase.

The various optimization variables shown in Fig. 2, and their constraints, are described in the following.

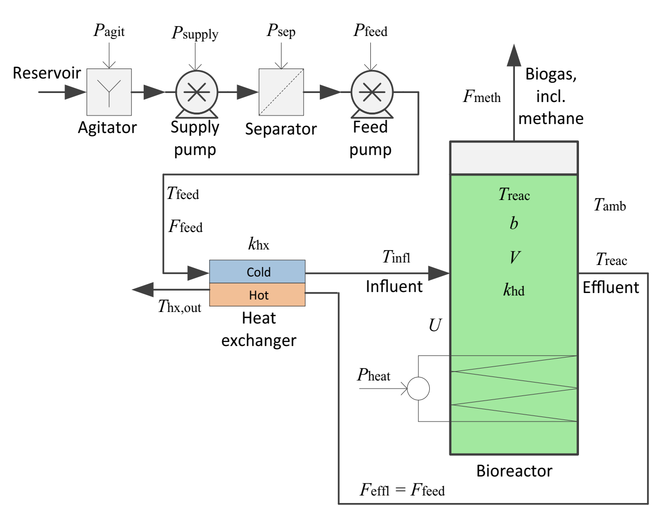

Fig. 1. Planned full-scale AD reactor. (Nomenclature is in Appendix C.)