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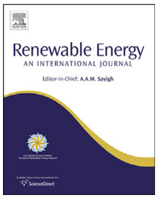

Optimizing low-temperature biogas production from biomass by anaerobic digestion

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ABSTRACT

The influence of selected geometric bioreactor parameters on the performance of continuous-flow-type low-temperature biogas production from biomass by anaerobic digestion was studied to determine the optimal geometric parameters of the digester. A continuous-mode two-stage bioreactor was applied to produce biogas by anaerobic digestion using model dairy wastewater sludge as substrate. The Monod approach was used to find the optimal diameter of the two cylinder-separated stages of the reactor that maximizes the amount of biogas produced per unit of time. Total biogas production derived from the theoretically optimized reactor in the calculation model was 1.6 times higher than that derived for the experimental bioreactor. The methane fraction in biogas increased from 64.5% to 71.2% after optimization, whereas the carbon dioxide fraction in biogas decreased from 34.5% to 27.8%. The optimization of the intermediate cylinder of the digester significantly increased total biogas production (by up to 160%) in comparison with the output noted before optimization.

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1. Introduction

In the absence of air, biogas is produced by micro-organisms through anaerobic digestion. Biogas production from wastewater and different kinds of organic residues in anaerobic digesters has been studied experimentally and theoretically for six decades [1]. Anaerobic digestion is used to treat and recover energy from sludge in wastewater [2], municipal solid wastes [3], agricultural residues and food processing waste [4–6]. The anaerobic digestion technology offers great potential for rapid disintegration of organic matter to produce biogas and conserve fossil energy resources [7]. There is a growing interest in biogas production, and the number of biogas production plants and average plant size continue to increase [8].

Mathematical modeling and optimization techniques have to be applied to increase the profitability of large-scale plants, generate significant benefits without excessive energy use or chemical demand and to scale-up laboratory installations [9,10]. Mathematical model-based simulations of bioreactor runs can explain changes in process variables – biomass, substrate and product concentrations – accompanied by temperature changes inside an apparatus. They can also describe the influence of the nutrient feeding rate on substrate digestion and explain how process parameters, including time, concentration and composition, should be controlled to guarantee the desired response [11]. The models found in scientific literature differ in structure and level of complexity [8,11–14]. Different optimization techniques can be used to improve the performance of the digestion process [15,16]. If a bioreactor (laboratory or technical) is operated in batch mode (unsteady state), the optimization goal is to maximize global biogas production at the end of each batch. In the continuous mode of bioreactor operation (steady state), the goal is to maximize the amount of biogas produced in the apparatus per unit of time.

Bolle et al. [17] and Singhal et al. [18] described hydrodynamic processes in laboratory-scale plug-flow UASB reactors. They studied process behavior using two-compartment [18] and multiple mixed-compartment models [17]. Laboratory-scale installations are often used to study process kinetics before scaling-up to full-scale applications. Batstone et al. [19] demonstrated that the hydraulics of laboratory-scale plug flow-type bioreactors may differ significantly from that of full-scale digesters. They recommended that mixed flow-type models should be used instead of plug-flow reactors for modeling full-scale bioreactors.

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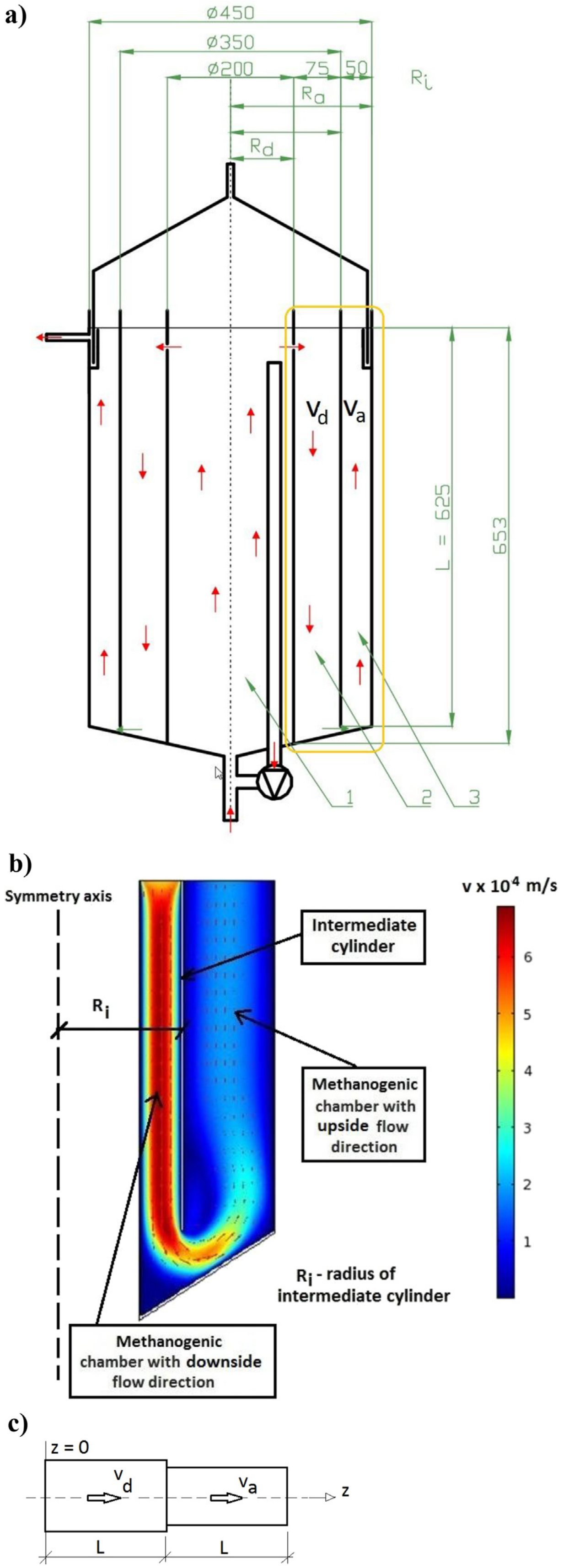

Fig. 1. Experimental design diagram: a) two-stage mixed flow reactor; 1. Chamber hydrolyzer, with full mixing, 2. Methanogenic chamber with downside flow, 3. Methanogenic chamber with upside flow, arrows indicate flow direction in the reactor; b) diagram of liquid flow and velocity distribution inside a methanogenic chamber; c) computational model of the methanogenic part of the bioreactor.

In the present study, a continuous-mode two-stage bioreactor was applied to produce biogas by anaerobic digestion using model dairy wastewater sludge as substrate. The flow rate of the liquid phase at the inlet was kept constant, therefore, liquid flow velocities in each stage of the digester were constant and determined by the cylinders' internal-to-external diameter ratios in each stage of the reactor. As part of a mechanistic framework for investigating mass and energy balances, a set of model equations was adapted to determine the optimal value of the cylinder's diameter with two separate reaction stages to maximize the amount of biogas produced per unit of time. Optimization methods were also used to estimate the parameters in model equations, and simulation parameters, which were elaborated by simple experiment or found in literature, were applied. Therefore, the aim of this study was to determine the influence of a bioreactor's geometric parameters on continuous-flow-type low-temperature biogas production from biomass by anaerobic digestion and to determine the optimal values of the digester's selected geometric parameters. The benefits of applying the general ADM1 model for the optimization of anaerobic digestion are obvious. The ADM1 model consists of many differential equations and various coefficients need to be accurately determined, therefore, vast efforts (laboratory and programming work) are required to ensure the model's effectiveness [20,21]. Since the main aim of the present study was to investigate the possibility of optimizing methane production based on selected geometrical characteristics (radius of the internal cylinder) of the bioreactor as the decision variables, a simplified version of well-established anaerobic digestion models was used in the study. The main aim of this study was to develop a simple but effective mathematical model of anaerobic biomass digestion and to use that model to optimize biogas production efficiency. A similar attempt could be made with the application of a full ADM1 model.

2. Materials and methods

2.1. Raw materials and sample preparation

The study was conducted on anaerobic sludge from an anaerobic dairy wastewater treatment plant. Anaerobic sludge was adapted to process conditions over a period of 60 days. The sampled dairy wastewater was produced from milk powder in the amount of 1 g of milk powder per 1 l of water. The organic compound load on reactor volume was $C = 1$ g COD/l, and the adopted hydraulic retention time (HRT) was 1 day. The main indicators of raw wastewater pollution were determined at: COD $= 1000 \pm 22$ mg/l, BOD5 $= 676 \pm 14$ mg/l, $N_{tot} = 65 \pm 4$ mg N/l, $P_{tot} = 19 \pm 2$ mg P/l.

The most important and most sensitive fermenting microorganisms include *Archaea* of the methanogenic phase. They are responsible for the vast part of methane production, mainly from acetic acid. The predominant microbial species in the tested sludge belonged to the genera *Methanosarcina* and *Methanosaeta*.

2.2. Experimental setup

The study was conducted in a two-stage variable flow reactor shown in Fig. 1. The reactor consisted of concentric chambers serving as the internal hydrolyzer, and two other chambers acted as methanogenic reactors. An intermediate cylinder-separated downflow and upflow suspension zones in the methanogenic part of the bioreactor. Raw sewage was pumped to the hydrolyzer (volume of 20 l). A recirculating pump was used to ensure

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