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Monitoring the mixing of an artificial model substrate in a scale-down laboratory digester

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ABSTRACT

Investigating the mixing process in digesters is a necessary precursor for successful design, operation, and increased efficiency in biogas plants. However, observation of mixing in digesters under real conditions is complex and cost intensive. Based on the theory of similarity a 1:12 scale digester model is set up and an artificial chemical substrate is selected to mimic the rheology of real biomass. Different mixing regimes are configured using propellers and paddle stirrers located in varying positions. Optical and acoustic techniques are employed to observe the fluid dynamics. In this paper, the laboratory setup and the principal results on the flow velocity, power consumption and torque developed during mixing are presented and discussed. The experimental results illustrate the digester mixing quality in various propeller and stirrer configurations, and are used to validate a numeric computational fluid dynamic study.

1. Introduction

Growing energy demands require the continual development of strategies concerning renewable energies. Anaerobic digestion has received increased interest in the panorama of sustainable energies, especially in Germany [1,2]. Anaerobic digestion starts with bacterial hydrolysis of organic materials, followed by a series of complex biological processes, and results in the production of biogas, composed mostly of methane. The process occurs within an enclosed vessel commonly called a fermenter or digester. An overview of research achievements of bioconversion of organic waste to energy can be found in Refs. [3,4]. To maximize gas production, optimal conditions for decomposition of organic materials in the digester are necessary, such as mixing to homogenize the biomass volume [5,6]. Two common digester configurations are continuously stirred tank reactor (CSTR) and plug-flow. The CSTR configuration assumes perfect mixing within the digester, whereas in plug flow digesters the fluid is perfectly mixed radially but not axially. CSTR digesters have the advantage of simplicity in design and operation, and uniformity in temperature and concentration. Plug flow systems can exhibit significant variability in residence times and thermal gradients, which complicate system controls. However, some advantages of plug flow are its lower operating cost, high conversion per unit volume, higher capacity for overloading and horizontal geometry [7–9]. A CSTR digester is studied in this paper. Cost-benefit analyses indicate that mixing is the highest contributor to the total energy consumption in biogas plants [10–12]. Considering the total efficiency of biogas plants, the mixing energy is a parasitic contributor, which needs to be reduced. Thus, the spatial and operational configuration of agitators are fundamental parameters to optimize [13,14]. Testing of different mixing regimes are required to understand mixing characteristics in digesters and achieve high efficiency mixing. Since, it is not economically feasible to perform these tests on an industrial scale biogas plant [15], laboratory scale experiments are an appropriate approach to investigate the mixing in full scale anaerobic digesters. In 1990, Aivasidis and Wandrey [16] concluded that experiments in laboratory on a scaled down digester can provide data to design industrial scale anaerobic digesters. Gallert et al. [17] have confirmed the correlation between a laboratory scale and full scale

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Abbreviations

C1, C2, C3	mixing configurations
D	laboratory digester
L	Nd:YAG laser
DAQ	data acquisition unit
W	workstation
M	mixer motor
S	shaft sealing
Sh	shaft housings
C	camera
TS	torque sensor
T1, T2, T3	temperature sensors
P1, P2	propellers
α, β	shaft inclination angle

digester [18]. More recently, Brunn et al. [19] have explained that the application of laboratory scale experiments to industrial scale is critical in the case of anaerobic waste treatment [20,21].

Generally, mixing of the biomass can be accomplished through injection of gas bubbles, recirculation of substrate via pumps, or mechanical stirring. In the case of gas injection, generated gas is collected, compressed and re-injected at the bottom of the digester [22]. For recirculation, pumps push the substrate between different positions inside the digester. Since in Germany most of the biogas plants are equipped with mechanical stirrers, this mixing method was considered in the present study. The majority of mechanical stirrers is composed of a three-phase electric motor coupled with a stirring element (paddle, blade, anchor, etc.). The motor is height-adjustable and can be mounted outside the digester and connected to the hydraulic element via a shaft or can be submersed inside the biomass. The shaft can be horizontal, vertical or inclined. The mixer can operate at different rotational speeds where the speed is usually inversely proportional to the size of the hydraulic element. To choose the optimum type, number and placement of the mixer several factors have to be considered, such as dimension of the plant, typology of the digester feedstock, cost − benefit analysis, required efficiency of the gas production.

The present study is focused on the development of a new set-up to monitor the mechanical mixing of a substrate. A laboratory scaled-down digester was designed and constructed. All equipment present in the full scale real biogas digester was modelled down and replicated. Two agitator types (propeller and paddle) were installed. The mixing of the substrate was investigated in terms of flow velocity. Two measuring approaches were planned and configured: The fluid flow was measured (1) by optical spectroscopy through the detection of trajectories of additionally injected particles and (2) by acoustic spectroscopy through the Doppler effect of transmitted pulses. Flow velocity was determined for three mixing configurations. A computational fluid dynamics (CFD) model was developed for simulating the fluid flow due to mixing [23,24]. The experimental data was used to validate the computational model.

The paper introduces a new method to monitor flow velocity and power consumption during the mechanical mixing of a substrate in laboratory digesters. Investigations can be made experimentally on real plants; however, it is challenging and resource intensive (expensive instrumentation, limited safety, partial visualization, time and men-power consuming, etc.). Thus, it is helpful to conduct experiments at laboratory scale or using CFD simulations. In this paper, the presented new method results to be relatively easy and low cost and an effective strategy when coupled with CFD simulations. This research is essential in determining the system parameters required to optimize mixing quality, reduce operating costs in biomass digesters, and increase competitiveness of biogas plants.

2. Materials and methods

2.1. Laboratory digester setup

A scale-down laboratory digester made of polymethylmethacrylat, pmma, was designed to replicate the digesters of full-scale biogas plants and consequently constructed to maintain geometric similarity (Fig. 1). The transparency of pmma allowed for the optical observation of flow dynamics in the vessel. The cylindrical laboratory digester had the following dimensions: 1.5 m in diameter, 0.7 m in height and total volume of ca. 1.2 m^3. The dimensions were derived from a real digester with 18 m diameter and ca. 2100 m^3 total volume with a 1:12 size reduction in three dimensions. A wall thickness of 15 mm assured the mechanical stability of the laboratory digester. The lab-scale digester was filled to a liquid depth of 46 cm, which corresponds to ca. 800 l of liquid. All internal structures and all ancillary equipment present in the real biogas digester were replicated in the scale-down model to the same size reduction factor. The laboratory tank was equipped with six access holes (element Sh in Fig. 1-top) for inserting the stirring shafts at different heights and angles. The holes were located at three heights in the wall of the tank (element D in Fig. 1-top): at 16 cm, 32 cm and 48 cm from the bottom and diametrically opposite (see in Fig. 1 the locations of the possible six housings, two opposite facing, of the two shafts). A simmering was used for shaft sealing.

Mixing in the digester was achieved by two IKA Eurostar 100 control overhead stirrers (element M in Fig. 1). Motors for the mixer were placed opposite in the model digester and equipped with variable speed drivers for controlling motor speed via motor input frequency.

Three tmg Gerabert GmbH Pt100 temperature sensors, with accuracy/resolution of 1 °C/0.1 °C, were installed at different locations within the tank (elements T1-T3 in Fig. 1-bottom). The sensors were attached to a 34972A Keysight unit system, equipped with a 34901A 20 channels multiplexer module for data acquisition and logger switching (element DAQ in Fig. 1).

2.2. Propeller and paddle mixing setup

Different agitator heights and angle configurations could be achieved using the six access holes (elements Sh in Fig. 1-bottom) placed on the wall of the laboratory tank. Two IKA Eurostar 100 control overhead agitators were installed, which were located opposite in the digester (elements M in Fig. 1). Three agitator types were used: a small and large propeller mixer, which have three wings and characteristic diameter of 7.5 cm and 12.5 cm respectively (see Fig. 2-top); and one mixing paddle, comprised of four 4.5 cm × 7 cm rectangular plates (see Fig. 2-bottom). As starting point of the study, three mixing configurations were selected and investigated (C1-C3 depicted in Fig. 3). In C1, two large propellers are submerged, and their long axis are horizontal and located 15 cm from the bottom. In C2, one large propeller is submerged with horizontal long axis 15 cm from the button and a paddle is located 23 cm from the bottom. In C3, a small propeller is submerged, with horizontal axis 15 cm from the bottom, and a large propeller is located 38 cm from the bottom with incline long axis forming a $\beta = 30^\circ$ angle with the plane of the liquid surface. In C1-C3, the