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Effect of mixing of waste biomass in anaerobic digesters for production of biogas

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Abstract. Biogas technology is an important renewable bioenergy producer. The biogas generating process needs to be optimized to minimise the energy consumption due to the stirring of biomass slurry. Numerical simulations and laboratory experiments are economically and practically preferred over investigations of industrial scale biogas plants. Additionally, a strategic approach to model the reality in scientific laboratories is to use a rheological valid artificial chemical substrate to replace real biomass. The proposes of this study were (i) to investigate the mixing process in a 1:12 scaled-down home-made laboratory digester filled with a 0.3 wt% water-cellulose solution, (ii) to simulate the mixing process in the laboratory-scale digester using a computational fluid dynamics model, (iii) to validate the model by comparison of the simulation with laboratory experiments results obtained on the laboratory digester. Optical and acoustic measurements on the flow velocity inside the digester during the mixing process of the water-cellulose solutions indicate that the model based on computational fluid dynamics is valid. The data are presented and discussed in the paper.

1. Introduction

Human global energy consumption requires competitive energy forms and continual development of strategies concerning renewable energies. Sunlight, wind, waves and tides, geothermal phenomena and bioresources are common renewable energy sources. Bioresources, commonly known as biomass, produces bioenergy in form of heat, electricity, biofuels and has gained significant interest as an alternative to petroleum fuels, especially in the last thirty years [1].

In comparison to wind and solar power, which are fluctuating energy suppliers, the biomass power has the ability to balance these fluctuating energy producers due to its capacity to produce energy continuously and to realize demand oriented production. Different kinds of processes have been developed to extract energy from biomass, depending on the chemical and physical state of the feedstock itself and, of course, the final use and destination [2]. The most common type of bioenergy is combustion of lignocellulose pre-treated biomass (e.g. wood pellet), oil crops or animal fat. Not only are these sources suitable for heating, but they can also be combined with electricity production. For sludge, liquid and wet organic materials, anaerobic digestion is currently the best-suited option for producing electricity and/or heat from biomass, although its economic viability relies heavily on the

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availability of low cost feedstock. Gasification is also a good renewable alternative for heat and power generation. It consists of the treatment of organic matter at high temperatures without combustion, producing CO, CO_2 and H_2 gas. Biofuels are instead used for the transport sector: bioethanol from starch and sugar crops and biodiesel from oil crops and residual oils and fats, mostly.

Anaerobic digestion systems use waste biomass to produce renewable energy in the form of biogas. To maximize gas production, optimal conditions for decomposition of organic materials in digesters are necessary, such as mixing to homogenize the biomass volume. Cost-benefit analysis indicate that mixing is the highest contributor to the total energy consumption in biogas plants. To reduce this parasitic contributor testing of different mixing regimes is required, i. a. spatial and operational conditions of agitators [3-5]. Since it is not economically feasible to perform these tests on an industrial scale biogas plant, laboratory scale experiments emerge as a convenient and appropriate approach to study the mixing in full-scale anaerobic digesters. Recently we have designed a scaled-down digester [6, 7] and select an artificial substrate [8] with the aim to mimic in our scientific laboratory what is the mixing process in a real fermenter filled with biomass. In this paper, we investigate the mixing process using a 1:12 scaled down laboratory digester, an artificial chemical substrate based on cellulose, optical and acoustic spectroscopies and computational fluid dynamics (CFD) simulations. Indeed, computational simulations using CFD is a powerful tool to assess mixing quality of different system configurations and several model are described in the literature [9-12]. In this paper we use the well-known Ostwald-de Waele power law model for non-Newtonian fluids [13, 14]. Technical challenges and difficulties of mixing configurations can be rationalized in the model to obtain in valuable interval of time important parameters to evaluate the efficiency of the process. The next phase is to scale up the resulting parameters to correlate the dynamic in the laboratory digester to that in the real fermenter of the industrial scale biogas plants.

2. Materials and methods

2. 1. Preparation of artificial substrate

The artificial chemical substrate was prepared using a sodium carboxy-methyl cellulose purchased from Dow Wolff Cellulosics GmbH, Germany, with the commercial name of Walocel CRT 30000TM. Aqueous Walocel solution with 0.3 wt% dry matter content was prepared dissolving 2.5 Kg of powder in 800 l of water at 20 ℃ to obtain rheological characteristics comparable to the biomass slurry [8]. The artificial substrate was mixed intermittently for three days to obtain a homogeneous solution.

2.2 Experimental laboratory digester setup

A 1:12 scaled-down laboratory digester was designed and constructed in polymethylmethacrylat to replicate the digester tank of full-scale biogas plants. Mixing was achieved by two IKA Eurostar 100 control overhead stirrers placed opposite in the tank. The motors are equipped with variable speed drivers for selecting and controlling motor speed. Six access holes on the tank allow to insert the two stirring shafts at different heights (levels) and angles. Three types of agitator were installed: a paddle equipped with four rectangular plates and two propellers with three wings and characteristic diameter of 7.5 cm and 12.5 cm (see Figure 1).

2.3 Setup for optical and acoustic investigation

The mixing process has been investigated in the laboratory digester in terms of flow velocity and flow pattern inside the tank. Optical spectroscopy (Particle Image Velocimetry, PIV) and acoustic techniques (Acoustic Doppler Velocimetry, ADV) have been used.

For PIV measurements, seeding particles (microporous polyamide with average particle diameter of 20 μm) were injected in the water-cellulose fluid and illuminated with a Nd-YAG laser sheet. The trajectories of the particles were captured by a high speed camera in consecutive images. By cross-correlating the images, the fluid velocity was calculated to obtain velocity vector maps, statistics and spatial correlations of the artificial substrate.

For ADV measurements, the water-cellulose fluid velocity was directly measured using a Vectrino Velocimeter operating with the Doppler effect principle and a bistatic sonar, i.e. the ADV velocimeter uses separate transmit and receiver beams, in contrast to standard Doppler profiles. The reflection (echo) from the particles suspended in the water was picked up by four receive transducers.

2.4 Computational fluid dynamics (CFD) analysis

To simulate the mixing process, the commercial computational fluid dynamics (CFD) software StarCCM+ from CD-Adapco Siemens was used. Simulation aspects cover geometry design of the tank, grid generation, selection of physical models and solvers, data evaluation and optimization.

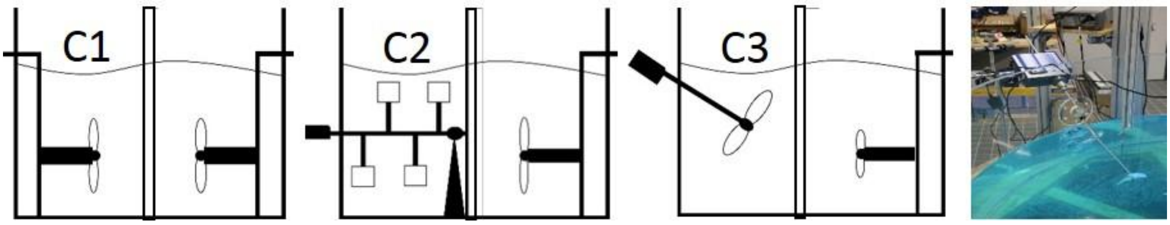

Figure 1. Scheme of the three mixing configurations, which are used in the laboratory digester tank to validate the CFD simulations. C1: two submersed big propellers produce a symmetric flow. C2: one big propeller and one paddle. C3: one small propeller and one incline big propeller. Foto of the incline big propeller mixer used in C3.

3. Results and discussion

3.1 Effect of mixing configurations

To study the mixing process, three combinations of propeller and paddle were configured in the laboratory tank (Figure 1). In general, the efficiency of the mixing process inside a digester depends on a large number of parameters, which are related to the substrate rheology, design of the tank (geometry and size) and stirrers (quantity, locations, direction), and operational procedure (continuous or intermitted substrate feeding, bulk liquid temperature, mixing velocity, and continuous or intermitted mixing). The three configurations, C1-C3, were selected on the basis of four factors: (a) the intention to not be limited to a single mixer but to use different types of mixers, which represent the state of the art in biogas plants, (b) the idea to use configurations comparable to full-scale applications to obtain results which may be valuable to the operational procedures in biogas plants (c) the plan to start with a simple flow dynamic (in C1) and to increase its complexity (in C2 and in C3), and (d) the concept to have symmetrical (C1) and asymmetrical (C2 and C3) flows inside the laboratory digester.

3.2 Effect of flow velocity

The distribution of the homogeneous substrate was evaluated with PIV and ADV measurements on the flow velocity at three levels (height) in the tank with 10 locations each (marked from 1 to 5 and from 6 to 10 in the CFD scenario of Figure 2 and 3). The y components of the flow velocity of the water-cellulose mixture in the ten positions inside the laboratory digester are plotted in Figure 2. The results refer to the mixing configuration C1 of Figure 1.

The results indicate a development of the flow velocity from the wall of the digester to the center. Towards the center, the slower moving fluid is accompanied by less mixing dynamics. Lower fluid velocities were apparent near the center of the digester. This suggested lower quality of the mixing within the region, since slow moving zones represent less mixed zones. The presence of a dead zone in the center is merely related to the movement of the flow in the plane parallel to the bottom of the digester (xy). In the z axis the flow appears slightly eddying and with up and down movement. The velocity values in Figure 2 ranged in the interval 5 - 10 cm/s. The velocity depends on the friction at the wall, then increases to a maximum of ca. 0.1 m/s, and then nearly no flow is present in the central regions.

For the C1 configuration, a symmetry in the flow dynamics was expected between the 1-5 and 6-10 regions, such that the results in positions 1 and 6 should be comparable and also those of positions 5 and 10. This expectation was validated by the PIV and ADV experimental data, which confirm the precision of the used PIV and ADV setups and the accuracy of the experimental procedure. The similarity of PIV and ADV data suggest the possibility of limiting the investigation to only ADV technology. Indeed, the accuracy of the ADV measurements (error of the ±0.5% of the value) is much higher due to the high error of the PIV measurements (±5% of the value).

3.3 CFD evaluation

One main purpose of the present research was to obtain experimental results which could be used to validate a CFD model recently developed. The parametric settings are listed in Table 1.

Table 1. CFD parametric settings for the study of mixing configurations C1-C3.

	parameter	specification		parameter	specification
1	Type of mixer	Submersed 3-bladed propeller mixer	**6**	Height	Positioning up/down of mixer
2	Number of mixer		**7**	Placement in/out	Positioning at different radii
3	distribution of mixers	Placement of mixers to one another	**8**	Elevation angle up/down	Angle mixer orientation vertical direction
4	Digester geometry	Diameter of digester and height of fluid level filled	**9**	Mode of operation	Continuous/time-sequence
5	Side angle	Angle mixer orientation horizontal (sidewards)	**10**	Rotational speed	Mixer rotational speed [rpm]
			11	Rheology	

For computer simulations with StarCCM+, the Non-Newtonian generalized power law was used for the fluid rheology. A consistency factor of 0.05 [Pa•s^n] and flow index of 0.25 were specified. In the CFD calculation, the k-ε turbulence model was used, integrated with steady-state and moving reference frame model (MRF) to implement rotation and static regions.

Data obtained from the PIV and ADV experimental measurements were compared with the CFD calculated flow velocities. In Figure 2 are plotted the results obtained for the y component of the flow velocity in configuration C1.

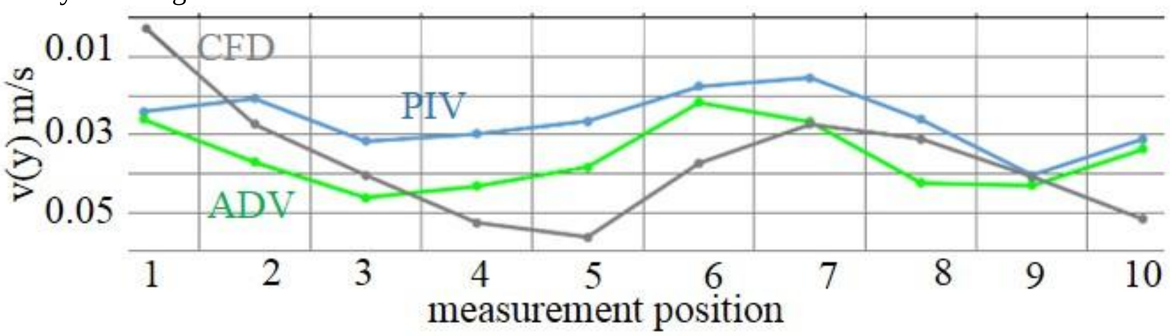

Figure 2. Flow y-velocity results obtained with PIV, ADV, and CFD investigations. Measuring positions 1-10 refer to the ten locations in the digester depicted in Figure 3.

The correlation between the experimental data obtained with PIV and ADV technologies and the theoretical data obtained with the CFD simulation is very promising. CFD simulation is advantageous over laboratory experiments due to the drastically reduced timescale required to visualize flows. Experiments on the laboratory digester were time consuming and limited by the number of configurations and parameters which could be checked. For example, the investigation of the flow dynamic in the 50-250 rpm range at steps of 50 rpm needed weeks of measurements but only hours of computer simulation. The discrepancy in time required is also evident when changing the angle of the shaft of the stirrer from 30 ° to 60 °. However, CFD simulations alone, without any confirmation from experimental results, cannot be justified. Thus, a combination of the two methodologies must be applied.

3.4 Effect of torque moment

Additional measurement of the torque moment on the stirrer-blades indicate the power consumption for each configuration. Values in the range of 0.0045Nm-0.0065Nm (measurement error 0.1% of full scale 1 Nm) were found. The results indicate that the use of the smaller propeller required more energy and produced less hydraulic torque. The consideration that a large propeller is less energy demanding is useful for mixing design and selection of stirring configurations in real digesters.

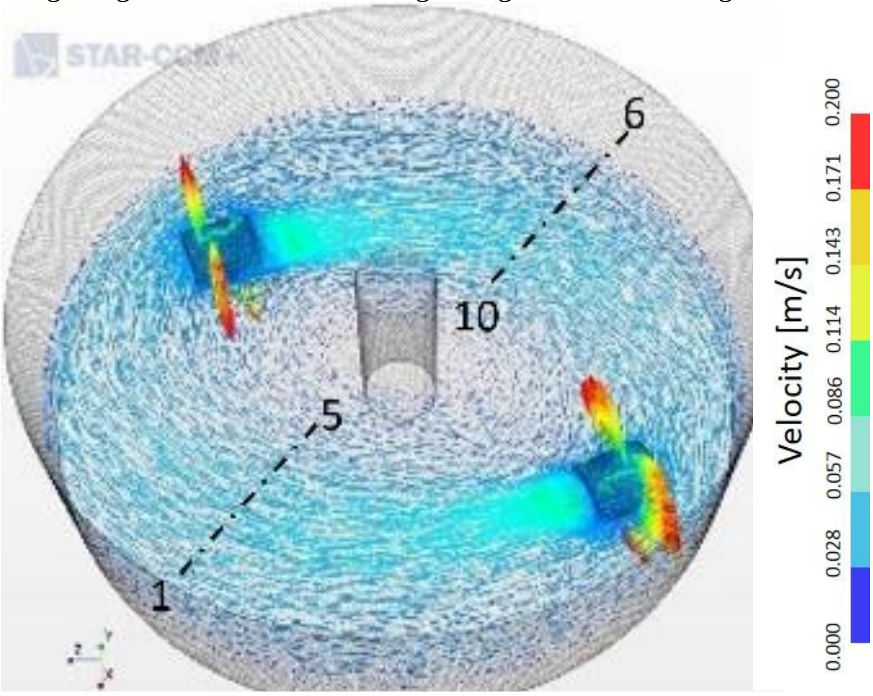

Figure 3. Top view scenario of the flow velocity vector obtained using the CFD model. Positions 1-10 inside the digester refer to the ten measuring locations investigated by PIV and ADV (Figure 2).

4. Conclusions

A scaled down laboratory digester equipped with mixing systems, and optical and acoustic setups was designed and successfully constructed to investigate the mixing behavior of an artificial chemical substrate, used to substitute real biomass. In this paper PIV and ADV laboratory results are shown to determine flow characteristics of sludge in digesters. Results on power consumption, torque moment and flow velocity confirmed the accuracy of the experimental procedure. The data are comparable to CFD numerical calculations so that the laboratory experiments can be used as validation tool to the CFD simulating model. The approach allows at a much lower cost than laboratory experiments or investigations at full-scale.

In real case scenario, the condition will be anaerobic, temperature substrate quality will be different, the microorganisms will be present, etc. These points limit the applicability of any result and model.

On the other hand, researches on industrial scale biogas plant are not economically feasible. There is a need for deeper insight on the complexity of this fascinating biological process. The presented study suggests one possible successful strategy. The next step is studying the transferability of the results obtained with PIV, ADV and CFD on the scaled down laboratory digester to the industrial scale biogas plants. A full examination of this scaling up process is in plan to be conducted in future studies.

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