CFD investigation of the flow characteristics of a plug flow anaerobic digester for lignocellulosic biomass methanisation

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Abstract
For the anaerobic conversion of plant biomass to biogas several different types of digester have been installed in practise in recent years. Plug flow digesters are often used when the feedstock treated has high solids content or high viscosity, as this is the case for agricultural lignocellulosic biomass. This study evaluates the flow characteristics of a horizontal digester by computational fluid dynamics (CFD) simulation. The simulation results showed that the fermenter content is under typical operation conditions to a considerable degree mixed in the axial direction and hence plug flow behaviour cannot be expected. The model indicated that axial mixing is mainly caused by the vertical directed paddles of the agitator, which were arranged in an offset pattern of 120 degrees. Different agitator layouts were evaluated by CFD simulations towards their resultant flow patterns in the fermenter. Although real plug flow behaviour did not appear for any improved arrangement of the mixing system, the optimized configuration exhibited significant lower fluid velocity components along the horizontal fermenter axis. Methanisation of lignocellulosic biomass has recently been promoted as a resource of renewable energy production, but it still lacks practical experience in respect to the efficient design of the anaerobic reactor. CFD simulation can represent a powerful tool for the optimisation of anaerobic digesters treating biomass at high-solids content.

Keywords
Computational fluid dynamics; lignocellulosic biomass; energy crops; mechanical mixing

INTRODUCTION

The specific and systematic cultivation of lignocellulosic agricultural biomass for methane generation is from a global perspective still unusual, and is stronger promoted only on the regional level. While the conversion of biomass into fuel ethanol has gained growing attention e.g. in the USA, the focus of several European countries is rather upon biogas technology. A broad variety of plant biomass has been investigated for anaerobic conversion to biogas in recent years (Amon et al. 2007). Present experiences in Germany have pointed out that maize is the most competitive crop for biomethanization (Grieder et al. 2012). Optimized fermentation processes for these new substrates as well as stable plant operation are necessary in order to reach high methane yields and hence a sustainable development in this field. This requires, in turn, detailed knowledge about the conditions within the fermenter. A particular challenge for mono-fermentation of lignocellulosic agricultural biomass exists in the high total solids content of the substrates, leading to higher viscosities and hence causing technical difficulties in mixing of reactor content. To manage with the special properties of the feedstock, like the distinct fibre content, different types of reactor have been investigated. Koch et al. 2009, e.g., have analyzed loop reactors as a single-stage system for biogas production from grass, and demonstrated that such system can effectively avoid the formation of scum layers. Cysneiros et al. 2012 modified for high solids substrates a two-phase system composed of a leach bed as the first step and a methanogenic reactor as second step, by which the leach beds were operated at different feed cycles. The common technologies of biogas production from energy crops can roughly be arranged in completely stirred tank reactors (CSTR), plug flow reactors (PFR) and bioleaching reactors. Reactors following ideal plug flow behaviour have high volumetric unit conversion, and degradation of biomass can easier be controlled as short circuiting is prevented. Inoculation of active biomass is necessary to avoid washing out of microorganisms.

The biological and chemical parameters of the fermentation process have been primarily investigated in the past, so that a broad knowledge base exists. For these issues reliable mathematical models are available, e.g. the Anaerobic Digestion Model No. 1 (ADM 1, Batstone et al. 2002). There are also model applications available for describing the anaerobic degradation of plant biomass (Lübken et al. 2007; Wichern et al. 2009; Thamsiriroj & Murphy 2011). However, in most cases the flow characteristics of the reactor are neglected, or only a very rough estimate is done. Knowledge about the rheological properties of the processed substrate is still limited. Computational Fluid Dynamics (CFD) has emerged as a common analysis tool for fluid engineering, and can be used for the design and optimization of bioreactors. Some examples of use exist for digesters (e.g. Wu & Chen 2008; Karim et al. 2007), but no CFD simulation study has been published so far concerning the mono-fermentation of lignocellulosic biomass.

METHODS

The pilot plant investigated by CFD simulation was a combination of two digesters in series: a horizontal fermenter as the main process step and a vertical fermenter used for recirculation of active biomass to the first reactor. Such horizontal fermenter used for agricultural biogas production is generally described as “plug flow reactor”, which needs to be permanently inoculated by a recycle flow from the second reactor. Both fermenters were built as cylindrical steel tanks and operated at constant 38°C. The stirring device of the horizontal digester was equipped with vertical arranged paddles to allow only radial mixing, while axial mixing should be avoided. The agitator speed was held constant to 7/min. The horizontal fermenter had a liquid volume of ca. 240 L (length = 1.951 mm, diameter = 400 mm) and additional 60 L were reserved as head space.

Figure 1. Pilot plant. Left: Horizontal digester with feeding screw and gas domes. Right: Storage tank for inoculation of the plug flow fermenter.

The pilot system was fed with whole-plant corn silage in mono-fermentation without addition of manure. The mean total solids (TS) content of the substrate was 36.8%, and the volatile solids (VS) content was in average 97.5% of TS. The organic loading rate (OLR) was stepwise increased for the plug-flow fermenter from 0.50 to 3.60 g VS/L/d, corresponding to a hydraulic retention time (HRT) in the PFR of 62 to 13 days (including recycle flow, ratio whole-plant corn silage to recycle flow 1:2 v/v) and 800 to 89 days (without recycle flow). The specific biogas yield ranged from 571 to a maximum of 896 L_N / g VS added.

The density of fermenter content was determined by a round-bottomed flask pycnometer. Shear rate, shear stress and viscosity were determined by a rotational viscometer (HAAKE Viscotester VT 500, HAAKE GmbH, Germany), with a reproducibility of ± 3%.

The flow characteristics were simulated with the software Fluent (Version 6.3.26), Gambit (Version 2.4.6) was used as geometry and mesh generation software.

RESULTS AND DISCUSSION

Main objective of the CFD simulation was to investigate whether mixing within the horizontal fermenter is done only in the radial direction. The rheological properties of fermenter content were experimentally studied. The density of fermenter content was determined to be 1.009 g/L, which is distinctly higher than the values reported for biogas reactors treating manure (1.001 g/L, Wu & Chen 2008) or sludge (1.005 g/L, Karim et al. 2007). A clear relationship between the viscosity and the OLR applied was identified. At low OLR the relative viscosity is higher compared to high OLR. In addition, the relative viscosity decreases at all OLR with rising shear rates. (Detailed information will be given within an extended version of the paper).

The simulated velocity vectors in Figure 2 (left) give an impression of the fluid flow in a vertical plane of the middle part of the horizontal fermenter. The circular motion of the fermenter content induced by the vertical arranged paddles can clearly be recognized. The highest fluid velocity was calculated to be in the range of 0.12 m/s and emerged at the cross-braces of the vertical paddles. However, also a distinct axial flow between the single paddles was simulated. These horizontal components of the fluid flow are obviously forced by the mixing elements, which were arranged in an offset pattern of 120 degrees. Figure 2 (right) shows path lines, outgoing from a virtual plane in the middle of the reactor. This illustration shows that the particles reach the neighboring mixing element after only 300 seconds, which contradicts plug-flow behavior.

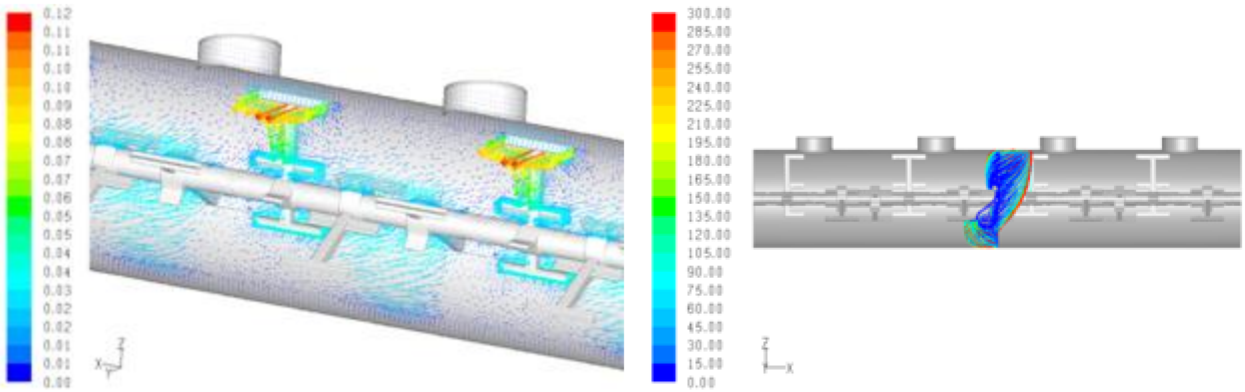

Figure 2. Simulation results. Left: Simulated velocity vectors (readings are in m/s). Right: Path lines outgoing from a sectional plane within the middle part of the model (all readings are in seconds).

CFD simulations were subsequently performed to investigate the effect of different layouts of the digester mixing system. One modification was accomplished in the way that (i) the cross-braces were removed, (ii) both sides of the mixing paddles received the same length and (iii) all paddles were arranged in one plane. Figure 3 describes in analogy to the previous results the resultant flow characteristics. The simulated velocity vectors now show significant lower velocity components in axial direction. Even more clearly the effect of the mixing system modifications turns out with the representation of the path lines. The observed particles remain considerably longer at the origin plane.

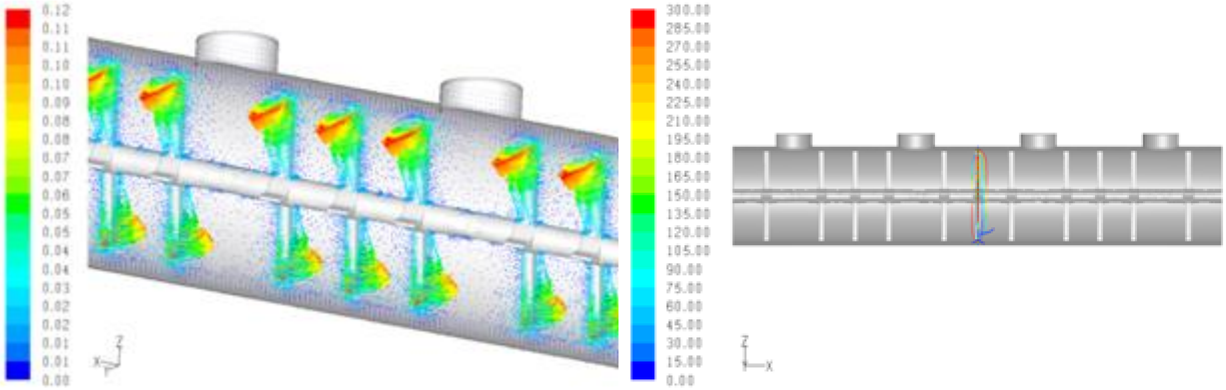

Figure 3. Simulation results for the modified system. Left: Simulated velocity vectors (readings are in m/s). Right: Path lines (readings are in seconds).

CONCLUSION

The combination of a horizontal fermenter and a CSTR in series is commonly used in practise when lignocellulosic biomass is converted to methane. The objective of such reactor layout is to realize plug flow behaviour in the first vessel and by this to maximize biogas production. The CFD simulation in this study clearly demonstrated that the flow characteristic for the investigated horizontal fermenter follows no plug flow behaviour. The model indicated that the mixing device with the arrangement of the vertical paddles in an offset pattern of 120 degrees induces a strong horizontal component of the fluid flow. The CFD model could be successfully used to identify effective modifications of the mixing device to reduce the horizontal components of the fluid flow. The anaerobic conversion of lignocellulosic agricultural biomass to methane is scarcely investigated towards fluid mechanics. CFD simulation can contribute to generate knowledge in this area.

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