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Development of Agitation Systems in Biogas Plants: Investigation of Mixing Characteristics, Improvement of Energy Efficiency and Scale-up using CFD

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In the presented work the mixing behavior and performance of the agitation system in biogas plants was studied to support the scale-up process by carrying out Computational Fluid Dynamic (CFD) analysis. The fermentation medium was implemented using an Euler-Euler multiphase approach. The description of specific material properties was achieved by implementing user-defined subroutines.

CFD proved to be a very useful tool for this type of problem definitions. The results of the research work were successfully put into practice: The first facility in scale-up dimensions is already in operation, reducing the net CO_2-emissions by the production of biogas.

1. Introduction

The fermentation of biogenic raw materials to produce biogas can greatly contribute to a renewable energy supply of our society. The purpose of the presented research work is the investigation of the mixing behavior and performance of agitation systems in biogas plants and to support the scale-up process by applying CFD analysis.

CFD can be used to model and predict the actual fluid dynamics in a closed system (Deglon and Meyer, 2006). Thus it may help to plan optimal reactor geometries, position and combination of agitation systems as well as to minimize the energy requirements. Following this strategy, the energy efficiency of such facilities can be increased, reducing the net emission of greenhouse active CO_2. The produced biogas can replace the primary energy source natural gas: After an upgrading step, the biogas can be fed to an existing natural gas grid to be utilized in a wide area (Makaruk et al, 2008).

2. Simulation Setup

In this work, a two-stage fermentation system (main- and post digestion tank) for biogas-production is investigated aiming for an optimal scale-up of the successfully applied technology (Biogest, 2010). The system was designed by *Biogest® Energie- und*

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Wassertechnik GmbH and features a circular ground plan: The main fermenter is positioned outside the postfermenter and is implemented as a circular ring (see Figure 1).

The installation of proper types of stirring units as well as their optimal positioning in the main fermenter is essential for the reliable and stable operation of the biogas production process. In the established system, the mixing of the fermentation medium is achieved by a combination of two slowly rotating propeller stirrers (30rpm, subsequently termed „Biobull“) and one middle-fast revolving plate agitator (42rpm, in the following called „blade-agitator"), see Figure 1.

Figure 1: left: Basic principle of the biogas fermentation plant; 1: main fermenter, 2: post digestion tank, 3: feed system, 4: central pumping station. Mixing devices: center: type „Biobull“, right: „blade-agitator“.

To achieve satisfactory mixing characteristics across the entire width of the main fermenter, the maximum width of the circular ring was found to constitute 4.8 m.

Due to the scale-up to bigger plant sizes, the fermenter volume increases – accordingly the width of the circular ring has to be increased, while the inner diameter of the main fermenter is kept constant. The mixing characteristics in the post digestion tank are unproblematic; therefore the presented work focuses on the investigation of the circular main fermenter. The applied scale-up strategy aims for the attainment of optimal mixing characteristics adopting the approved mixing devices already used in the established setup. The task of the definition of the number of agitators as well as the positioning in the fermenter was worked out by using the methods and possibilities of numerical fluid dynamics.

2.1 Simulation Model

In this work, the commercially available finite volume solver code FLUENT®, version 6.3.26, was used (Fluent, 2010). Due to the complex characteristics of fermentation media, the implementation of proper models for computational fluid dynamics states an extensive challenge (Cui and Grace, 2007). In the present work, the fermentation medium is represented by three distinct phases using the Euler-Euler multiphase approach: the „regular“ fermentation medium, a light phase and a phase with increased density. This setup represents a simplified description of the real fermentation sludge – nevertheless important features of the underlying flow field can be modeled, such as sedimentation, the influence of different viscosities due to variable dry matter contents as well as different particle sizes of dispersed solid matter. The variation of the apparent density of the medium occurs mainly due to the allocation of the dispersed fibres originating from the feedstock, e.g. maize silage (showing a lower density than the liquid content). By conducting simpler and therefore computationally less demanding single-phase simulations (Hennig et al., 2007) it would not be possible to incorporate these characteristic phenomena.

The time-dependent formation of the flow field in the fermenter and the resulting mixing characteristics were evaluated by carrying out time-resolved numerical simulations employing a time resolution of $\Delta t = 0.05$ s.

2.2 Viscosity

Fermentation media in biogas plants exhibit non-Newtonian viscosity behavior (El-Mashad et al., 2005): The resistance against tangential shear shows non-linear dependence on the shear rate. The substrate investigated behaves as illustrated in Figure 3 (continuous line), i.e. the viscosity decreases with increasing shear rate (Metzger, 2002). The shear-thinning effect is caused by particles and fibers that interact in the fermenter-suspension: The shear strain acting in the fluid flow tends to break the 3-dimensional network of dispered matter, resulting in a decrease of the viscosity (Viamajala et al., 2009).

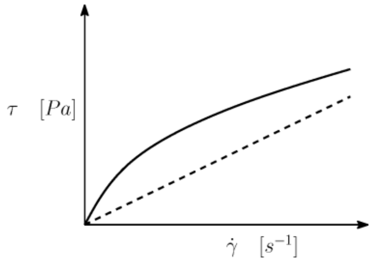

Figure 3: Schematic illustration of viscosity behaviour. Continuous line: shear thinning, dashed line: Newtonian behaviour.

The rheological characteristics of each of the three phases is calculated based on its dry-matter content, the mean fibre length as well as on the local shear rate using the power law model developed by Ostwald-de-Waehle (Seyssiecq et al., 2003) (τ: shear stress [Pa], k: consistency index [Pa·s^n], $\dot{\gamma}$: rate of shear [s^{-1}], n: flow index [-]):

$$\tau = k \cdot \dot{\gamma}^n \tag{1}$$

The model constants k and n are implemented for each of the three phases (see Figure 4). Adapted from experimental results (Wu and Chen, 2008), the viscosity function was modified according to the dry-matter-contents in the phases. To apply this model, the solver code was extended by the implementation of user-defined subroutines.

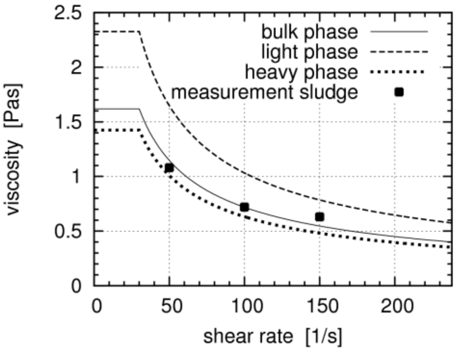

Figure 4: Viscosity vs. shear rate, measurements: (Pohn et al., 2010).

2.3 Turbulence

On the basis of the Reynolds-number of a certain flow field, the intensity of turbulence can be estimated. For non-Newtonian fluids the following equation can be applied (Wu and Chen, 2008) (ρ: density [kg/m³], U_∞: characteristic velocity [m/s], d_h: hydraulic diameter [m]):

$$\mathrm{Re} = \frac{\rho \cdot U_\infty^{2-n} \cdot d_h^n}{k \cdot \left(0.75 + \frac{0.25}{n}\right)^n \cdot 8^{n-1}} \tag{2}$$

Introducing the hydraulic diameter for the rectangular cross-section of the channel it was found that Re = 122, justifying the assumption that the main flow field in the fermenter can be assumed to behave laminar.

In the vicinity of the agitators, the Reynolds-number is approx. 6400. For mixing problems, this value is in the transitional range (Re ~ 10-50000) (Hennig et al., 2007). By applying a laminar model setup, these local turbulence effects near the mixing blades were neglected.

3. Results

The simulation runs were started with initially motionless medium in the fermenter, the three phases were initialized perfectly segregated. Thus, the start-up phase of the fermenter was modeled.

It was found, that after approx. 5 min of operation the overall flow field reaches a steady state (see Figure 5). After this start-up phase, the tangential velocity was found to be 0.22 m/s, resulting in a time of circulation of approx. 3.3 min.

An essential issue of agitation systems in biogas plants is an optimal mixing performance. In this work, the degree of mixing was characterized by the calculation of the standard deviations of the fermentation phase-concentrations (see Figure 5).

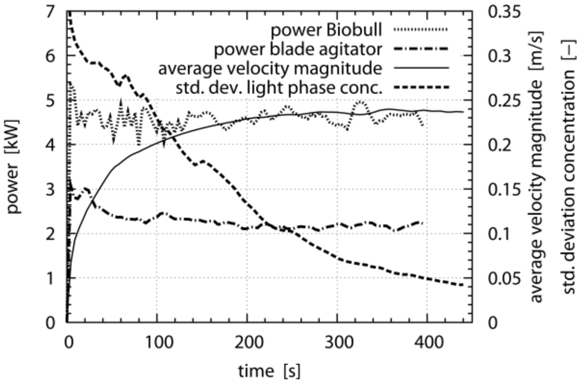

Figure 5: Evolution of average velocity magnitude, power uptake and mixing characteristics in time.

The torque acting on the stirrer shafts was calculated by analyzing the pressure forces on each of the discrete face elements on the stirrer blades (see Figure 6).

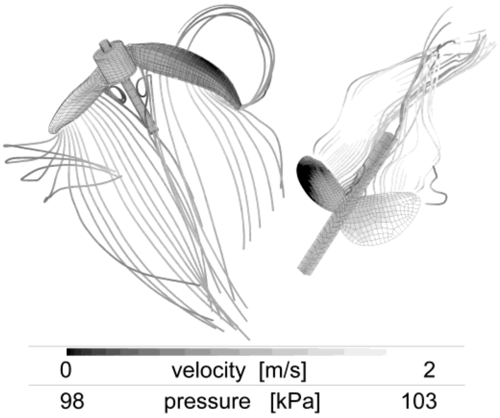

Figure 6: Distribution of the absolute pressure on the surface of mixer impellers. Left: Biobull, right: blade agitator. Pathlines are colored by velocity magnitude.

Applying this approach, the power-uptake of the stirrer-shafts could be calculated. Time-resolved results for 450 s of operation are shown in Figure 5. Excellent agreement was found between the power-uptake in established facilities and the obtained simulation results. The model also reproduced the higher shaft momentum in the initial startup-phase.

The best up-scaled agitator setup was found to feature six mixing devices of type Biobull, positioned evenly distributed on the perimeter of the main fermenter ring. Special attention was given to the discharge direction of the stirrers (orientation of the stirrer shafts) to achieve optimal mixing characteristics all over the fermenter volume. The mixing performance of the up-scaled geometry was benchmarked against the established system – the comparison yielded promising results.

4. Conclusions

To use the full capacity of the available renewable resources for the production of greenhouse neutral energy, the underlying processes have to be designed and operated optimally. By using CFD, the shortcomigs of existing plants can be identified to work out proposals for the optimization of the operating conditions and for the construction and scale-up of new facilities.

The time-dependent formation of the flow field in the fermenter and the resulting mixing characteristics were evaluated by carrying out time-resolved numerical simulations. Based on the results obtained for the established plant size, promising setups of the geometric configurations for the up-scaled main fermenter were defined and again examined by CFD. The best setup was found to include 6 slowly rotating mixing devices positioned evenly distributed along the perimeter of the circumferential main fermenter.

The results of this research work were successfully put into practice by Biogest® Energie- und Wassertechnik GmbH, the first technical-scale facility in scaled-up dimensions is in operation since December 2009.

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