LANDTECHNIK 75(2), 2020, 35–50

DOI:10.15150/lt.2020.3230

LANDTECHNIK
AGRICULTURAL ENGINEERING

Flow velocities and flow profiles in a thoroughly mixed biogas fermenter

Philipp Kress, Hans-Joachim Nägele, Andreas Lemmer, Bastian Kolb

The mixing of fermentation substrate using mechanical stirrers is considered one of the most important processes in biogas-production. However, this is associated with high energy use, resulting in high costs for the operator of the biogas facility. Lately, the improvement of the stirrers as well as the stirring-management has been attracting more attention. Numerous scientific studies attempt to examine and specify the rheology, biology and flow velocities in the fermenter using simulations and experiments on the laboratory scale. Nevertheless, the results still show considerable discrepancies between laboratory and practical outcomes. Studies on the practical scale were carried out at the research biogas facility of the University of Hohenheim in order to fill the gap between those research disciplines. The flow velocities at various spots in the fermenter were determined using a magnet-induced measuring system comparing different dry matter contents and viscosities of the fermentation substrate. The results show that a dry content increase from 7.74 to 10.75% during the experimental period is followed by a decrease in flow velocity from 8.71 to 63.77 $cm \cdot s^{-1}$ down to 0.05 to 37.36 $cm \cdot s^{-1}$. Therefore, the average flow velocities on the same stirrer setting were reduced due to the increase in dry matter content by an average of 70%. Complementary experiments proved that an increase of the dynamic viscosity can diminish the stirring induced circulation at the bottom and the surface to metrologically undetectable levels. This paper supports the thesis that the reduction of the flow velocities can cause “dead zones” in the fermenter.

Keywords
Biogas fermenter, flow velocity, mixing quality, mixing

The mixing of the fermentation substrate in the fermenter is not only important for the process – but also economically – one of the most significant processes in biogas production. A homogeneous distribution of fresh substrate in the fermenter is the foundation for a fast degradation and, therefore, high substrate-specific gas yields. Furthermore, a homogeneous substrate distribution leads to an even volumetric load in the entire fermenter volume which has a positive influence on the process stability. Meanwhile, the technical and economic expenses of mixing the biogas fermenters are very high at this. According to studies – referring to the generated electrical energy of the CHP Unit – the proportionate energy consumption of biogas facilities ranges from 5 to 21% (Gemmeke et al. 2009). The stirrers take up between 6 and 58% of that, usually half of the total energy consumption. Therefore, the stirrers are the largest power consumers in biogas facilities (Lemmer et al. 2013). With an overall yearly electrical energy production of 51.6 billion kWh (BDEW 2017) by biogas facilities in Germany, total costs of EUR 559.1 million per year arise when assuming an average 7.5% of the energy is consumed (Scheftelowitz et al. 2015) and an electricity price of 0,28 €/kWh (BDEW 2017) for an average energy consumption share of 51.6% (Nägele et al. 2012) of the stirrers. This sum has to

received 2 July 2019 | accepted 26 March 2020| published 4 May 2020

be spent exclusively for mixing of the fermenters in Germany and, therefore, offers a great potential for saving operating expenses.

The built-in agitator technology in the biogas facilities can be divided into different modes of action: mechanical, hydraulic or pneumatic. Mechanical stirrers are the most commonly installed agitator technology in German biogas facilities (Schulze und Eder 2006). Mechanical stirrers consist of a three-phase electric motor which is connected to an agitator blade. Here the installation point of the electric motor as well as the mount of the entire stirrer can be located either outside or inside the fermenter. The agitator blade itself can be operated at different circumferential speeds using the frequency converter. The speed at which the agitator blade is operated is inversely proportional to the size of the agitator blades (Wiedemann et al. 2016). An adjusted stirring regime, as described by Lemmer et al. (2013), can be used as a starting point for energy-saving measures. In practice, an assessment of the mixing quality can only be made by visual inspection of the substrate surface, laboratory analysis of a sample of the fermenter content or by evaluation of the biogas production (Lemmer et al. 2013). Despite the above described high energy-saving potentials of stirring energy, data on the efficacy of stirrers in biogas facilities in practice is scarce. In research, the studies are mostly carried out in laboratory scale using Computational Fluid Dynamics (CFD), computer tomography, Electrical Resistance Tomography (ERT) (Lomtscher et al. 2017a,b) and Computer Automated Radioactive Particle Tracking (CARPT) (Lemmer et al. 2013). No work known to the authors compares data collected in the laboratory with measurement data in practice to draw conclusions for the usage of stirring technology or the operation of stirrers. In industrial stirrer development, new agitator blades are usually developed using simulations. To test the final feasibility, the agitator blades are subsequently put to the test in a practical trial with the customers. An explicit measurement of the flow velocities usually does not take place, because practical biogas facilities lack the measurement technology. Instead, parameters such as biogas production and process disturbances are referred to in the assessments. Tests with simulations or tomographical trials, emulating a biogas facility in laboratory scale, describe local flow velocities in the range of $0.22\ m \cdot s^{-1}$ (Lomtscher et al. 2017b) to $0.32\ m \cdot s^{-1}$ with a dry matter content of 12.1% (Wu 2011) when using renewable resources. Still, no conclusions could be drawn through dry substrate determination about the flow properties. However, different fibre lengths with the same dry matter content can influence the flow properties and thus the flow velocities as well. For fibre lengths of 38.5 mm (dry matter = 10.1%; $K = 91.1\ Pa \cdot s^m$; m = 0.11) and 26.1 mm (11.1%; $K = 24.6\ Pa \cdot s^m$; m = 0.31), flow velocities of 1 to $3\ cm \cdot s^{-1}$ and 3 to $13\ cm \cdot s^{-1}$, respectively, were measured by Jobst et al. (2015). Prechtl (2005) showed that “Dead zones” can occur due to insufficient mixing quality.

The aim of the present work was to record flow profiles of the fermentation substrate in the fermenter on a practical scale using an electromagnetic sensor head at the biogas research facility “Unterer Lindenhof” of the University of Hohenheim. This showed the influence of the dry matter content and the dynamic viscosity in relation to the shear rate of the fermentation substrate, on the flow velocities. Furthermore, the occurrence of “dead zones” were investigated. Continuous feeding and the associated increase in dry matter content and viscosity provide a comprehensive data basis for the flow velocities. The measured process-defining parameters were the dry matter content, organic dry matter content, pH value as well as the concentration of volatile organic acids. The fermentation substrate can be described in more detail by connecting the dry substance content with dynamic viscosity and the shear rate.

This was the first time that studies about the occurring flow velocities were carried out on a fermenter on a practical scale where flow profiles could be created. Values determined on a laboratory scale can be compared with these results in order to consolidate their validity. The measured values obtained in this spatial resolution are unique for a fully technical container and therefore represent an important step towards a better understanding of the technical boundary conditions during the mixing of biogas fermenters as well as the fermentation process.

Material and Methods

Facility Technology and Input Materials

At the research biogas facility "Unterer Lindenhof", two fermenters operated in parallel are available for studies on a practical scale. The two structurally identical fermenters are made of reinforced concrete with a concrete ceiling, which is supported by a central support. They only differ regarding the equipment with different long axis agitators as well as the feeding and heating technology (Lemmer et al. 2008). The fermenters each have a gross volume of 923 m^3 with an internal diameter of 14 m and a height of 6 m. The investigations of this study were carried out on fermenter 1, which is equipped with a long axis agitator (LAR) (type Biogator HPR I, 15kW, REMA, Germany) and a submersible mixer (SMM) (type 4670, 13kW ITT Flygt AB, Sweden) (Figure 1). The diameter of the agitator blade of the LAR is 1.600 mm. For infinitely variable control, the LAR is controlled by a frequency converter. In standard operation, a rotational speed of 75 revolutions per minute is designated, which corresponds to a circumferential speed of 6.9 $m \cdot s^{-1}$. The SMM is equipped with a propeller with a diameter of 766 mm and, due to its design, is driven directly by an electric motor at a rotational speed of 365 min^{-1}. This corresponds to a circumferential speed of 14.6 $m \cdot s^{-1}$. In regular operation, these agitators are operated in cycles: The average stirring time per hour is 20 minutes.

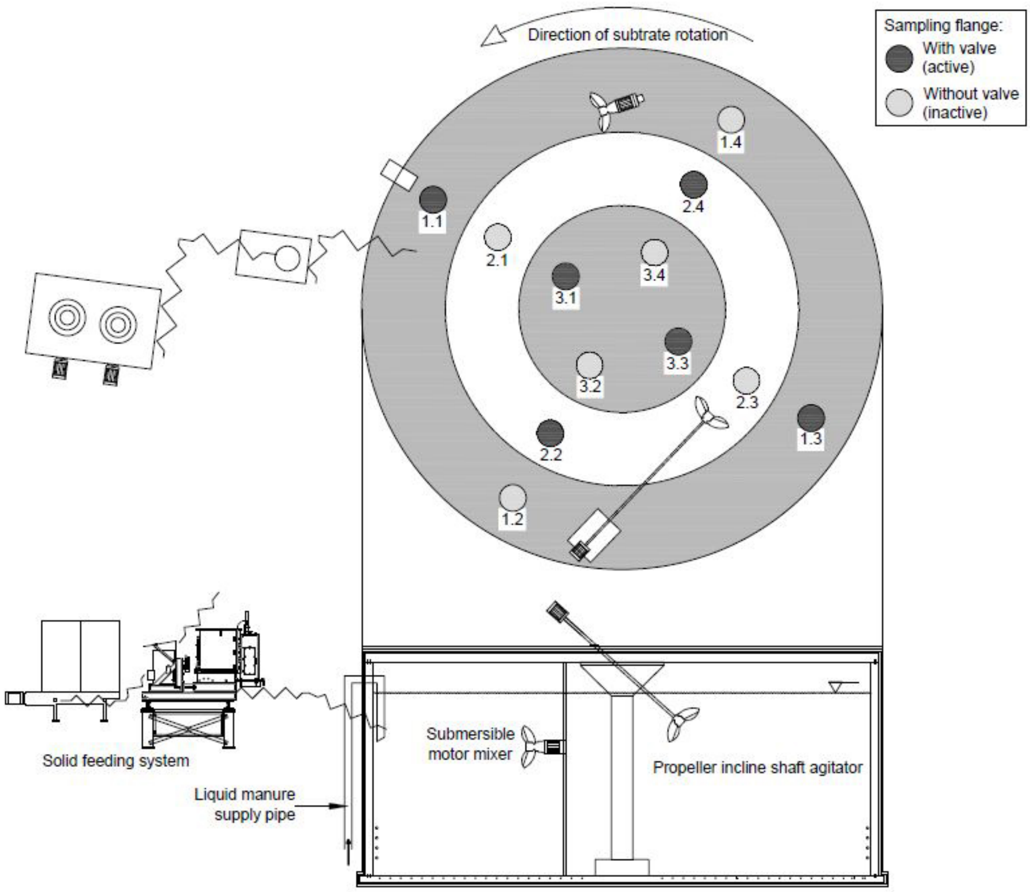

Figure 1: Sectional drawing and top view of fermenter 1 with the existing measuring sluices as well as the installed stirring technology and the feed system with Strautmann Biomix and MeWa Bio-QZ

For sampling as well as the use of external measuring technology, twelve sampling openings are installed on the concrete roof of the fermenter, which are equipped with gas-tight sluices. As already described in previous investigations by Lemmer et al. (2008) and Kress et al. (2018), six of the twelve sluices were used for the series of measurements. A vertical mixer (type Biomix 2000, Strautmann GmbH & Co KG, Germany) is installed at the fermenter for dosing the input materials. The substrates are first fed from the dosing unit via screw conveyors to an impact reactor (type Bio-QZ, MeWa GmbH, Germany) for mechanical treatment. After a processing time of 20 s per batch, the shredded material is automatically conveyed to the fermenter via dosing screws. Before the start of the test series, the fermenter was emptied, cleaned and then filled exclusively with the liquid phase of the separated biogas substrate from the biogas facility with a dry matter content of 7.74%. The intended organic loading rate after the start-up phase was between 2 and 3 kg $(m^3 d)^{-1}$.

Measuring Technology

Viscosity was used to characterize the fermenter substrate. A pipe viscosity measuring section in the pump room was available at the research biogas facility (Mönch-Tegeder et al. 2015) to measure and describe the changes in viscosity under real conditions. The substrate was pumped from the fermenter via a central pump through the measuring section for measurement. Shear rates of 5 to

220 s^{-1} can be mapped by varying the flow rate in two different pipe diameters, DN80 and DN100, in the measuring section. The measurements of previous years also showed that the minimum viscosity within the measuring range is approx. 0.2 Pa·s. This ensures that a wide variety of substrate compositions, which have different flow characteristics and therefore different shear rates, can be measured. Pressure sensors at the beginning and end of the individual measuring sections in combination with a differential pressure transmitter can be used to determine the differential pressures occurring in the pipe. The calculations of the apparent viscosity, η_{app} in Pa·s (Equation 3), the apparent shear rate, $\dot{\gamma}_{app}$ in s^{-1} (Equation 1) and the apparent shear stress, τ_{app} in Pa (Equation 2) were carried out according to Adhikari and Jindal (2001) as well as Slatter (1997) and applied to the development of the tube viscometer according to Mönch-Tegeder et al. (2015). These are based on the following equations:

$$\dot{\gamma}_{app} = \frac{\dot{V}}{r} \quad \text{(Eq. 1)}$$

$$\tau_{app} = \frac{\pi * \Delta p * r}{8 * L} \quad \text{(Eq. 2)}$$

$$\eta_{app} = \frac{\tau_{app}}{\dot{\gamma}_{app}} = \frac{\pi * \Delta p * r^4}{8 * L * \dot{V}} \quad \text{(Eq. 3)}$$

Ostwald-de Waele's power law model was used to model the flow curves (Equation 4), where *k* describes the consistency factor and *n* the flow behaviour index.

$$\eta_{app} = k * \dot{\gamma}^{\,(n-1)} \quad \text{(Eq. 4)}$$

A portable magnet-induced measuring device of the type Ott MF pro (company Ott Hydromet GmbH, Kempten, Germany) was used to measure the flow velocities in the fermenter. Invasive measurements on a fermenter on a practical scale are a particular challenge, especially for safety reasons. For the safe insertion of the sensor into the reactor interior during the running biogas process, a measuring sluice was therefore developed, through which a guide rod with the sensor head can be inserted and adjusted in any height and position (Figure 2).

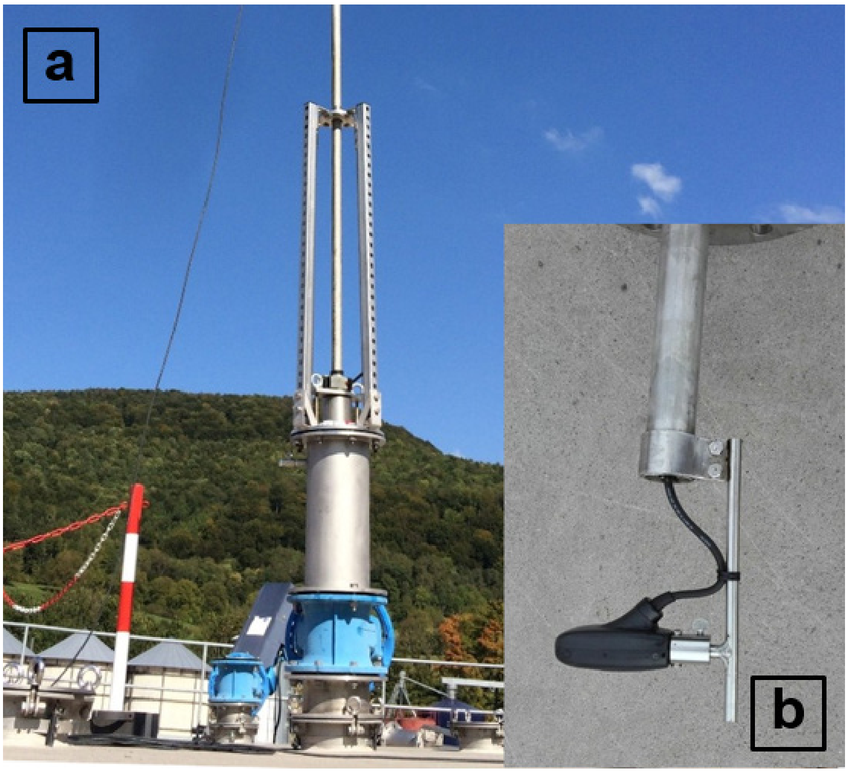

Figure 2: View of the measuring sluice (a) installed on a sampling point and the sensor head on the guide tube (b) (© University of Hohenheim/Philipp Kress)

The magnet-induced measuring system, the basics of which are described in more detail in Baker, R. C. (2016), has the advantage that no moving parts are introduced into the biogas fermenter, so that disturbances of the measurement due to technical blockades are excluded.

The accuracy of the velocity sensor is ±2% of the measured value or 0.015 $m \cdot s^{-1}$ for flow velocities below 3 $m \cdot s^{-1}$. Furthermore, an additional measuring error of 1% deviation per ±10° deviation from the orthogonal can occur if the sensor is not aligned exactly with the flow.

Test Procedure

In order to generate an increase in dry matter content, 2.5 t of cattle manure, 2.0 t of horse manure, 0.2 t of grain and 1.8 t of whole plant silage were divided into 12 rations and fed every 2 hours over a 24-hour period. From the third week onwards, whole plant silage was replaced by grass silage. All materials were used according to availability. Liquid manure was not added during the entire trial period. In order to ensure the most uniform conditions possible during the measurements, the digester was first stirred for two hours on each day of measurement. The rotational speed of the SMM was 365 min^{-1}, that of the LAR 75 min^{-1}. The flow velocity measurements were carried out between the feeding processes, which were carried out automatically every two hours. During the measurements described here, both agitators were operated at a constant position: the SMM parallel to the flow and rotation direction of the fermentation substrate with an axis height of approx. 3.5 m above the bottom of the fermenter, the LAR at an angle of 45° to the substrate surface and 45° to the vertical of the fermenter centre. The measuring points of the velocity measurement were set at 0.5 to 4.5 m above the bottom of the fermenter, with the upper measuring point just below the liquid surface. The Fixed Period Averaging (FPA) filter in the measuring device was used for data acquisition. Here, measurement points were collected in a fixed interval of 250 ms. These could be extracted as an average value over a freely selectable interval, which was set to 1 s. A complete data set for each measuring position and height consisted of 75 measured values, from which the average value was calculated. The measurements were carried out over a period of six weeks on two measurement days per week. The measuring points were randomized before the start of the experiment and sampled according to this scheme. There was no randomisation of the individual measuring heights per measuring point. Measurements were taken at nine heights from 0.5 to 4.5 m in steps of 0.5 m. To record the flow angle, it was measured in 30° steps, with 0° corresponding to the orientation of the magnetic north pole. In order to be able to describe the rheological properties of the fermenter contents during the experiment, a viscosity measurement was carried out in every week of the experiment. This was carried out after the flow measurement. In order to be able to describe the fermentation process more precisely during the test period and to ensure a stable start-up phase, two substrate samples were taken each week. The determination of dry matter (DM) and organic dry matter as well as the analysis of volatile organic acids and buffer capacity were carried out according to VDLUFA standard methods – Volume III (VDLUFA 2007).

Results

Substrate Composition

The average fresh mass, which was fed into the fermenter via the solid matter feeder, was 6,387 kg d^{-1} in the test period (Table 1).

Table 1: Feeding quantities, organic dry matter (oDM) content FM content of the individual substrates

	Solid manure	Grass Silage	GPS	Cereal	Horse manure	Total
FM in kg·d^{-1}	2,316 ± 850	2.294 ± 640	1,642 ± 577	202 ± 2	2,164 ± 648	6,387± 1,715
oDM content in %	16.2 ± 0.8	32.4 ± 5.4	30.1 ± 3.5		23.2 ± 2.7	
Share FM in %	27	27	19	2	25	

The biogas fermenter was filled exclusively with separated, fibre-free thin manure before the start of the experiments. Only solid biomass was added during the trial period. This resulted in a continuous increase of both the dry matter and the oDM content in samples from the fermenter (Table 2). During the test period, acetic acid with a concentration of 0.098 to 0.587 g·kg^{-1} and temporarily low concentrations of propionic acid up to a maximum of 0.057 g·kg^{-1} could be detected in the volatile organic acids. The concentration of acetic acid equivalents (HAC) varied throughout the test period from 0.098 to 0.587 g·kg^{-1}. It can therefore be concluded that the fermentation process was stable throughout the trial (FNR 2013).

Table 2: Results of sample analyses of the fermenter content during the test period to assess the process stability

Measuring week	Test day	DM content %	oDM content %	pH	HAC $g \cdot kg^{-1}$	Acetic acid $g \cdot kg^{-1}$	Propionic acid $g \cdot kg^{-1}$	VFA/ TAC
1	1	7.74	4.99	8.34	0.098	0.098	0.000	0.188
	4	7.85	5.15	8.44	0.309	0.309	0.029	0.206
2	8	8.19	5.46	8.49	0.207	0.207	0.012	0.188
	11	8.56	5.90	8.18	0.587	0.587	0.057	0.211
3	15	9.13	6.20	8.21	0.250	0.250	0.009	0.196
	18	9.45	6.47	8.57	0.242	0.242	0.000	0.201
4	22	8.61	6.72	8.36	0.262	0.262	0.000	0.203
	25	9.83	6.86	8.39	0.264	0.264	0.000	0.210
5	32	9.95	6.90	8.28	0.207	0.207	0.000	0.215
6	36	10.75	7.56	8.11	0.173	0.173	0.000	0.215

Viscosity Measurement

At dry matter contents of 7.74%, no measurement data could be obtained to determine the viscosity, as the minimum viscosity required for the measuring section was not achieved. From the second week of testing on, at a dry matter content of 7.85%, the measurements showed reliable values which could be justified by a constant flow rate of the pump and the resulting constant pressure in the measuring section. In the following test period, a continuous increase of the apparent viscosity could be observed. The increase of 60% at a shear rate of 10 s^{-1} was observed from week two to week six (Table 3).

Table 3: List of the weekly apparent viscosities measured over the 6-week testing period at corresponding shear rates as well as the consistency factor *k* and the flow behaviour index *n*

Shear Rate in s^{-1}	Apparent Viscosity in $Pa \cdot s$				
	Week 2	Week 3	Week 4	Week 5	Week 6
10	1.49	1.36	1.78	2.06	2.39
20	0.84	0.79	1.05	1.23	1.42
30	0.60	0.57	0.77	0.91	1.05
40	0.47	0.46	0.62	0.73	0.85
50	0.39	0.38	0.52	0.62	0.72
100	0.22	0.22	0.31	0.37	0.43
120	0.19	0.19	0.27	0.32	0.37
k	10.3	8.96	10.5	11.7	13.1
n	0.16	0.19	0.23	0.25	0.26
R^2	0.99	0.99	0.99	0.99	0.99

Investigations by Kress et al. (2018) and Mönch-Tegeder et al. (2015) in fermenter 1 showed an apparent viscosity of 6.59 Pa · s at a shear rate of 10 s^{-1} and a dry matter content of 13.61% and an apparent viscosity of 13.61 Pa · s at a dry matter content of 10.1% (Table 4). Thus, the apparent viscosity determined in this test with a maximum of 2.30 Pa · s at a dry matter content of 10.74% appeared to be conclusive for this facility operation mode.

Table 4: Viscosity and dry matter content at a shear rate of 10 s^{-1} from different publications

	Kress et al. (2018)	Mönch-Tegeder et al. (2015)		Present Work
Apparent Viscosity in Pa · s	6.59	1.56	2.68	2.39
DM content in %	13.61	10.1	11.7	10.74

Flow Velocity

In the fermentation substrate with a low dry matter content of 8.02%, the measured flow velocities varied significantly in the range of 6.74 to 87.5 cm · s^{-1}. With an increase of the dry matter content (10.75%) the measured flow velocities slowed down 2.86 cm · s^{-1} (±0.46 cm · s^{-1}) (Figure 3).

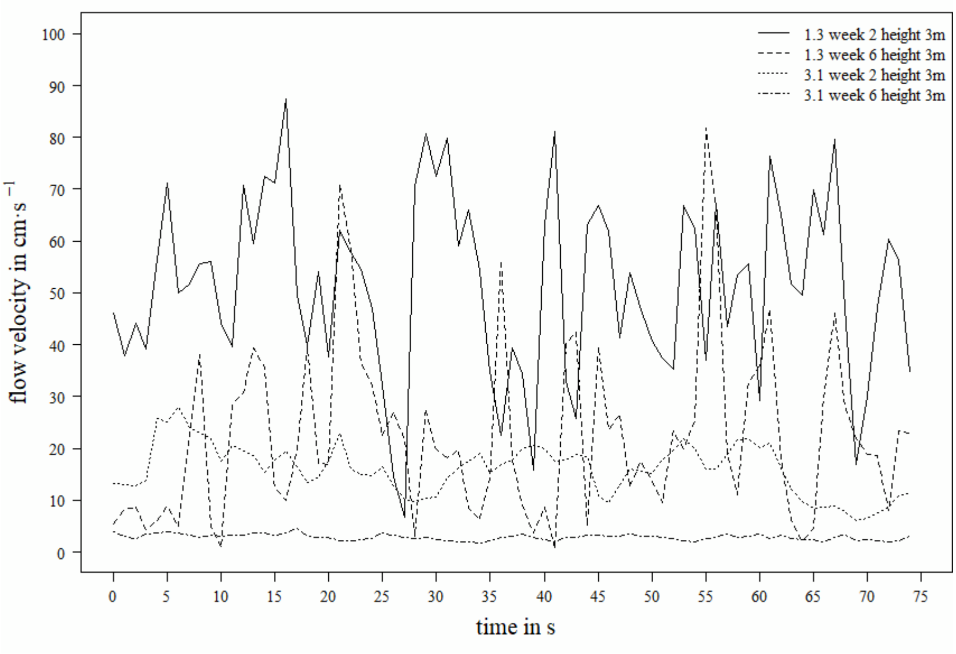

Figure 3: Comparison of the measurement curves of the flow velocities at positions 1.3 and 3.3 over a recording interval in the second week of the test at DM contents of 8.02 and 10.75% (this position is located directly next to the agitator blade of the long-axis agitator).

Due to the low variation in flow velocities during the sixth week of measurement, it can be assumed that the turbulence in highly viscous fermentation substrates was reduced, which at the same time increased the accuracy of the measurement. On the other hand, it can be assumed that turbulent flow conditions with strong variations in flow directions and velocities prevail in low-viscosity fermentation substrates.

The flow velocities measured at measurement sluice 1.1 at different heights from week to week are shown in Figure 4. Overall, the flow velocities of the fermentation substrate decreased with the increase of the dry matter content. The measuring point at measurement sluice 1.1 was in close proximity to the SMM, so that the SMM strongly influenced the flow velocities at this measuring point. The height of the SMM was approx. 3 m above the bottom of the fermenter. With a dry matter content of 9.61% in the fourth week of measurement, the velocities reduced by up to 50% compared to the third week of measurement at this stirrer height, while a reduction of 60–70% was measured at the bottom of the fermenter and at the surface. The influence of the SMM on the flow curve was therefore no longer as pronounced as in the first three weeks of measurement. The effect of changes in the dry matter on the flow velocities was less pronounced from the third week of measurement onwards. Furthermore, the velocity curve was more uniform over the height of the fermenter. The liquid jet and the associated increased flow velocities at the level of the SMM decreased from the fourth week of measurement onwards, at dry matter contents of up to 9.61%, and were hardly detectable at the end of the study in week six. At very high dry matter contents, submersible mixers tend to form a cavern (Rostalski 2009). This means that the agitator does not convey in an axial direction, but instead sucks the substrate radially again, which leads to a kind of short circuit. The flow velocities determined in week six indicate that such a cavern was formed. The velocities decreased by up to 85% over the entire height of the fermenter in the six weeks of measurement.

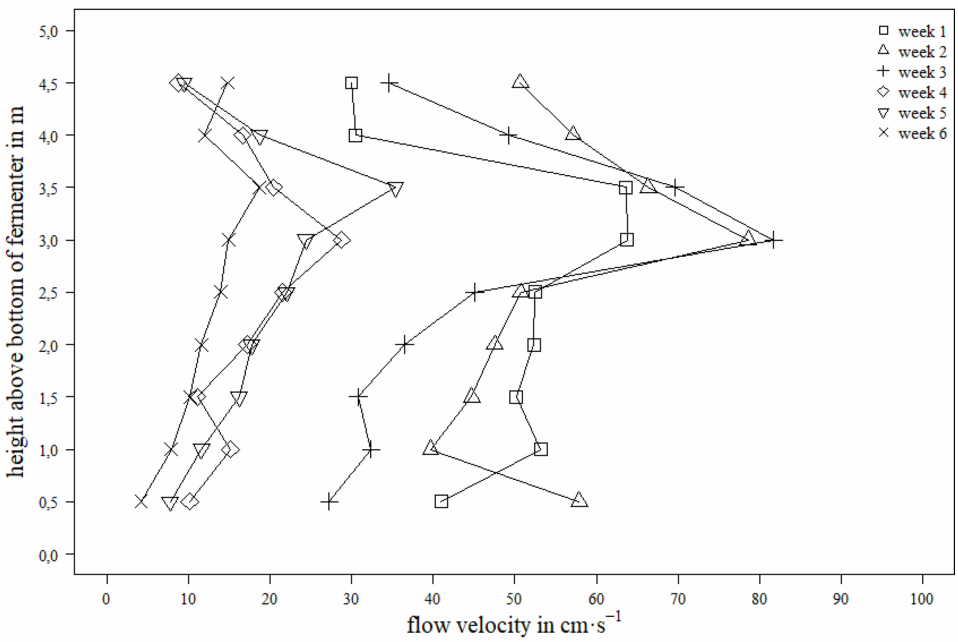

Figure 4: Average flow velocities at measurement sluice 1.1, directly behind the SMM in flow direction, in test week one to six

Directly downstream of the LAR was measuring point 1.3. At a height of 2,5 m the influence of the LAR on the flow curve was clearly marked (Figure 5).

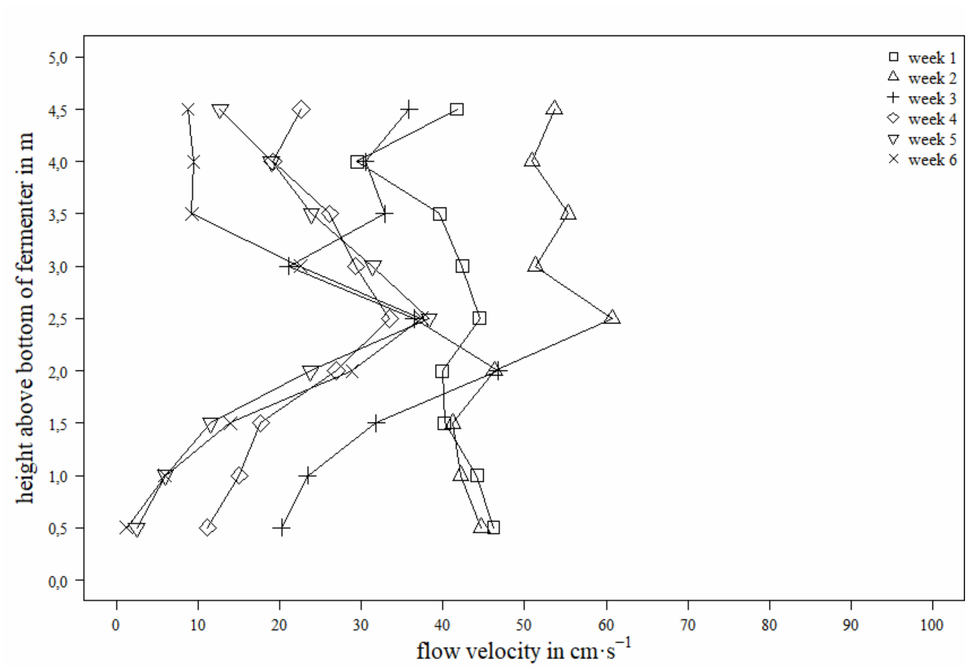

Figure 5: Flow velocities at measurement sluice 1.3, downstream of the LAR, over the entire test period

At a dry matter content of 8.84%, three constant flow velocities of 33.47 to 38.27 $cm \cdot s^{-1}$ were recorded at a height of 2.5 m from the week of measurement onwards. From the second week of measurement onward, a strong reduction of flow velocities near the bottom as well as in the upper areas of the fermenter was observed. In the height of 4.5 m, directly at the surface, a reduction from 53.63 to 8.71 $cm \cdot s^{-1}$ and thus a reduction of 85% was observed. An even stronger reduction took place near the bottom. Here, the flow velocities decreased from 46.17 to 1.19 $cm \cdot s^{-1}$, a reduction of 97.5%. At the same time, the dry matter content in the fermentation mixture increased from 7.74 to 10.75%. In the last week of measurement, the highest velocity over the entire height of the fermenter and all measuring points was detected at measuring point 1.3 with 37.36 $cm \cdot s^{-1}$ (Figure 6).

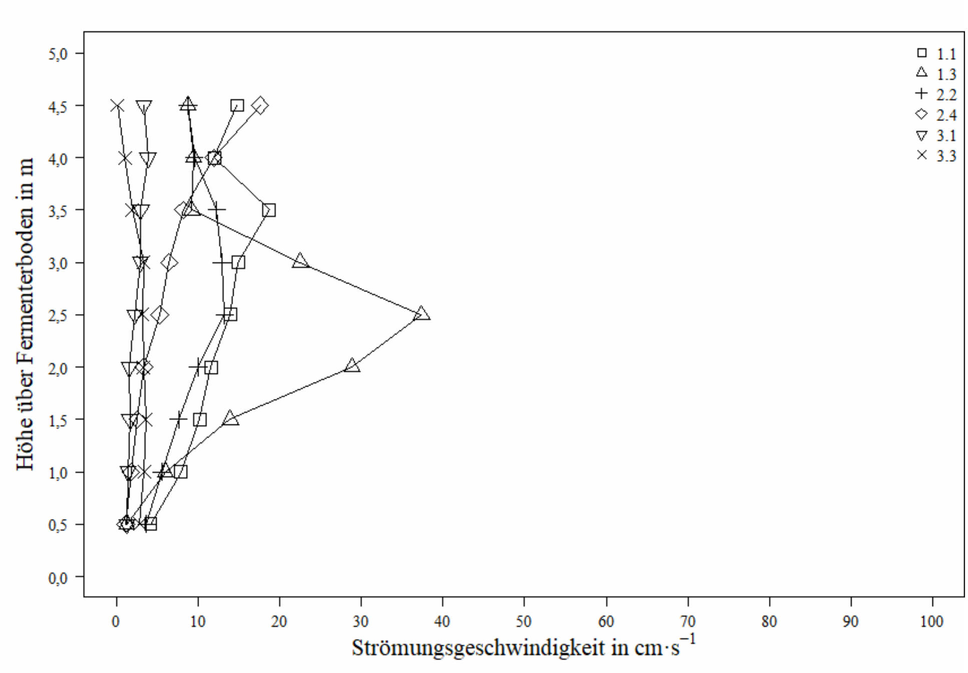

Figure 6: Average measured flow velocities in the sixth week of measurement at all positions

The results of the measurements of flow velocities at all measuring points in the first and last week show clear differences in the scattering of the velocities (Figure 7). In the first week, when the fermentation substrate was still thin-bodied with low-viscosity, the speeds were strongly influenced by the position and height of the agitators and the flow radius (see position 1.1 for an example). In the last week, however, the influence of the agitators and their position on the flow speeds in the higher-viscosity fermentation mixture had drastically decreased. Only at measuring point 1.3, which is located near the LAR, a clear influence of the agitator was still evident. Here, the entering force of the stirrer blade was able to generate corresponding flow velocities in the direction of the measuring point in correspondence with the fermenter wall.

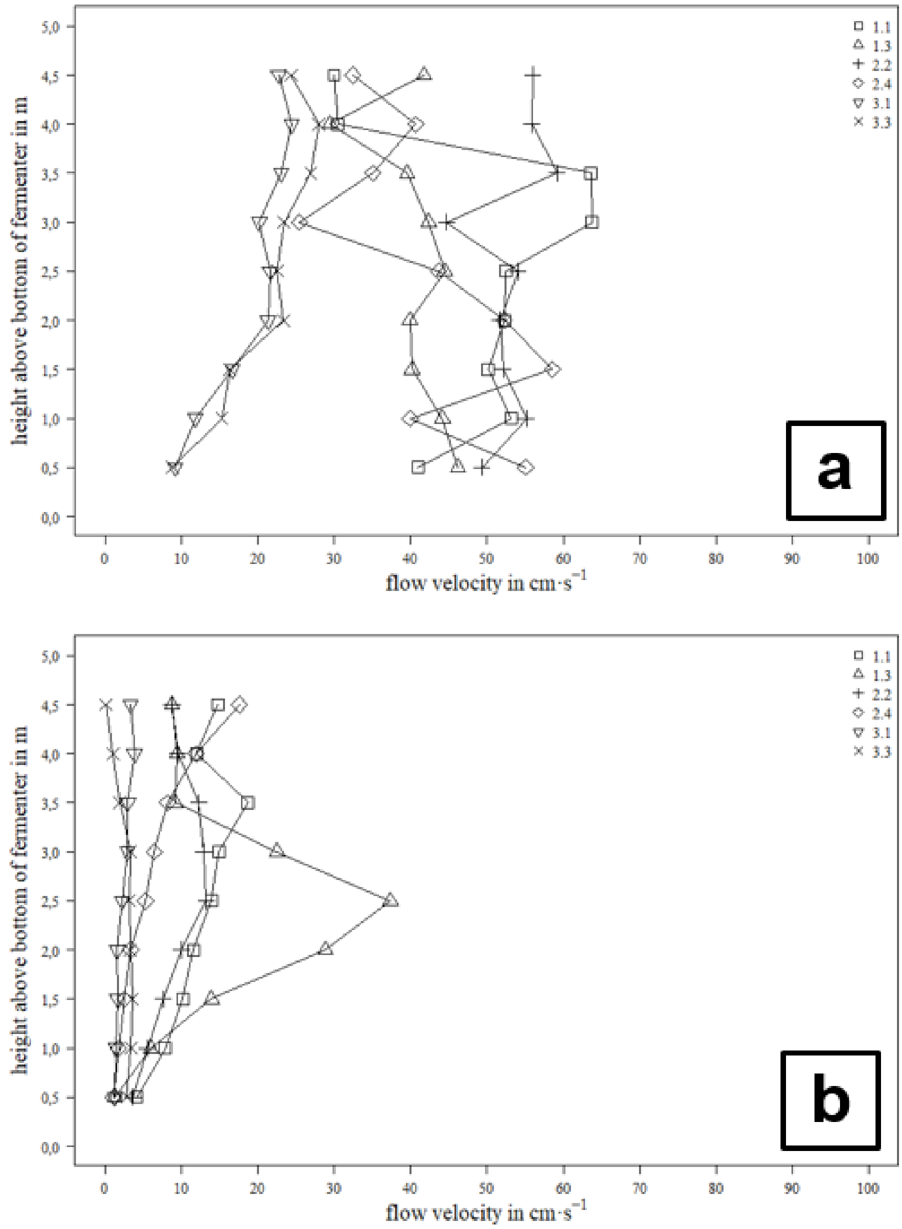

Figure 7: Average flow velocities in the first (a) and sixth week (b) overall measuring positions and fermenter heights

In order to ensure a high mixing quality in the fermenter, those positions where the flow velocities are reduced to near zero are of importance in practice. This could be observed at the lowest two positions of sluices 1.3, 2.4 and 3.1 from the fifth week of measurement onwards, at velocities between 0.96 and 1.72 $cm \cdot s^{-1}$. In the sixth week of measurement, only velocities up to 1.59 $cm \cdot s^{-1}$ were recorded at sluice 3.1, which is not in the direct sphere of influence of the SMM, up to a height of 2 m. In sluice 3.3, at the two upper positions where the LAR is located in the immediate vicinity, velocities of 1.59 $cm \cdot s^{-1}$ were measured in the sixth week of measurement. In comparison to the work of Kress et al. (2018), which was carried out in the same fermenter with a dry matter content of 14.1%, it can be stated that even at speeds below 2.5 $cm \cdot s^{-1}$ there is still a nutrient distribution and mixing of the substrate. "Dead zones", which show insufficient mixing, were identified by Leonzio (2018), but no comparison with the actual prevailing nutrient distribution could be shown. Therefore, no conclusion can be drawn whether low flow velocities lead to "dead zones" and whether "dead zones" at the same time mean that there is no sufficient nutrient distribution. Likewise, performance losses in the biogas process cannot be clearly attributed to "dead zones".

With increasing dry matter content and the associated increase in viscosity, the flow speeds at all measuring positions dropped by up to 98%. Due to the highly viscous fermentation substrate, the range of the agitators changed as well. Thus, the range of the SMM was very pronounced at the beginning of the study and decreased until the end of the test period, as can be seen from the flow velocities at measuring point 1.1 and height 3.0 m. There the velocities at the beginning of the study were at a maximum of 81.78 $cm \cdot s^{-1}$ and decreased to 14.84 $cm \cdot s^{-1}$ in the last week of the experiment.

No statement can be made on the basis of the measurements carried out on the investigated long axis agitator with an installation angle of 45° as to whether flows occur outside the horizontal plane. The measuring sensor used was not suitable for this purpose, as it could only measure horizontal flows. However, it is very likely that vertical flows are also induced due to the installation position of the agitator propeller. The flow behaviour became more homogeneous with increasing viscosity in the course of the investigation. Looking at the whole fermenter, the highest velocities occurred in the middle layers (fermenter height: 1.5 to 3 m) as well as the middle radii (diameter: 4.5 to 9 m). Near the walls, the inner concrete pillar and towards the bottom, the flow velocities decreased strongly. The higher velocities in the middle layers and the middle radius can be explained by the installation position of both agitators and their direction of action.

Conclusions

In this study flow profiles in the fermenter were able to be recorded and the influence of the dry matter content and the dynamic viscosity related to the shear rate of the fermentation substrate were shown. During the test period, the dry matter content of the fermentation substrate increased by 38% in relative terms. The apparent viscosity of the fermentation substrate also increased by 85% with the increase of the dry matter content. The increase in viscosity and dry matter content led to a decrease of more than 97% in the measured flow velocities for the same stirring times and rotational speeds of the stirrers in the test fermenter. With the absolute decrease of the flow velocities, their fluctuation also decreased. This suggests that turbulent flows dominate in low-viscosity fermentation substrates, whereas laminar flow conditions predominate in high-viscosity fermentation substrates. The results presented in this thesis provide the basis for corresponding flow measurements in the practical fermenter for the first time, so that previous results from CFD models, as presented by Koll (2012), can be validated: The maximum flow velocities measured in the present study were very similar to those in Koll's CFD models. However, the results of this work prove that the average speeds over the entire container volume were clearly overestimated with the previous models. Thus, in the area of the middle radii, the velocities are up to 95% (CFD: 20 $cm \cdot s^{-1}$ (Koll 2012) 1.07 $cm \cdot s^{-1}$) lower in practice than in the models, and in the innermost areas of the fermenter in some cases even 99.5% (CFD: 10 $cm \cdot s^{-1}$ (Koll 2012), practice: 0.05 $cm \cdot s^{-1}$) lower than in the models. In both investigations, a strong influence of dry matter on the flow behaviour could be determined. In the CFD models and the practical measurements it was found that the flow velocities are lowest in the centre of the fermenter. This is the so-called teacup effect (Koll 2012).

With the results presented here, flow simulations can be adapted and improved. This can help to make future studies generally more effective and to relate studies in the laboratory or simulations closer to the actual conditions prevailing in practice. This work supports the thesis that "dead zones" must occur due to the velocity distribution in the fermenter. However, investigations on nutrient distribution by Lemmer et al. (2013) and Kress et al. (2018) could not confirm this thesis. Therefore, it must be assumed that other mechanisms contribute to nutrient distribution. Diffusion processes but also occurring temperature differences or rising gas bubbles are possible factors. However, such effects can hardly be investigated in practical facilities, which highlights the need for proof and further investigation through laboratory experiments or simulations.

References

Adhikari, B.; Jindal, V.K. (2001): Fluid flow characterization with tube viscometer data. Journal of Food Engineering 50(4), pp. 229–234

Baker, R. C. (2016): Flow Measurement Handbook - Industrial Designs, Operating Principles, Performance, and Applications. Cambridge University Press

BDEW Bundesverband der Energie- und Wasserwirtschaft e. V. (2017): Erneuerbare Energien und EEG: Zahlen, Fakten, Grafiken (2017). Berlin, BDEW Bundesverband der Energie- und Wasserwirtschaft e. V.

FNR (2013): Leitfaden Biogas – Von der Gewinnung zur Nutzung. Gülzow, Fachagentur Nachwachsende Rohstoffe e. V.

Gemmeke, B.; Rieger, C.; Weidland, P.; Schröder, J. (2009): Biogas-Messprogramm II, 61 Biogasanlagen im Vergleich. Gülzow bei Güstrow, Fachagentur Nachwachsende Rohstoffe

Jobst, K.; Lomtscher, A.; Deutschmann, A.; Fogel, S.; Rostalski, K.; Stempin, S.; Brehmer, M.; Kraume, M. (2015): Optimaler Betrieb von Rührsystemen in Biogasanlagen. In: Tagung KTBL/FNR-Kongress, KTBL/FNR, 22.–23.09.2015, Potsdam, KTBL, S. 140–149

Kress, P.; Nägele, H.-J.; Oechsner, H.; Ruile, S. (2018): Effect of agitation time on nutrient distribution in full-scale CSTR biogas digesters. Bioresource Technology 247, pp. 1–6

Koll, C. (2012): Aufnahme, Auswertung und Beurteilung rheologischer Parameter zur Auslegung und Simulation von Fördereinheiten sowie Rühraggregaten in Biogasanlagen. Masterarbeit, Leibniz Universität Hannover

Lemmer, A.; Bekker, M.; Oechsner, H.; Jungbluth, T. (2008): Forschungsbiogasanlage „Unterer Lindenhof". Landtechnik – Agricultural Engineering 63(2), S. 80–81, https://doi.org/10.15150/lt.2008.778

Lemmer, A.; Nägele, H.; Sondermann, J. (2013): How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters. Energies 6(12), pp. 6255–6273

Leonzio, G. (2018): Study of mixing systems and geometric configurations for anaerobic digesters using CFD analysis. Renewable Energy 123, pp. 578–589

Lomtscher, A.; Jobst, K.; Fogel, S.; Rostalski, K.; Stempin, S.; Kraume, M. (2017a): Scale-up of mixing processes of highly concentrated suspensions using electrical resistance tomography. Flow measurement and instrumentation 53, pp. 56–66

Lomtscher, A.; Jobst, K.; Kraume, M. (2017b): Fibers and particles in stirred systems: influence on the flow velocities. Chemie Ingenieur Technik 89(4), pp. 424–431

Mönch-Tegeder, M.; Lemmer, A.; Hinrichs, J.; Oechsner, H. (2015): Development of an in-line process viscometer for the full-scale biogas proces. Bioresource Technology 178, pp. 278–284

Nägele, H.; Lemmer, A.; Oechsner, H.; Jungbluth, T. (2012): Electric Energy Consumption of the full-scale Research Biogas Plant „Unterer Lindenhof": Results of longterm and full detail Measurements. Energies 5(12), pp. 5198–5214

Prechtl, S. (2005): Optimierte Durchmischung von Biogasreaktoren. ATZ Entwicklungszentrum, Sulzbach-Rosenberg

Scheftelowitz, M.; Daniel-Gromke, J.; Rensberg, N.; Denysenko, V.; Hillebrand, K.; Naumann, K.; Ziegler, D.; Witt, J. (2015): Stromerzeugung aus Biomasse (Vorhaben IIa Biomasse). Zwischenbericht Juni 2015, DBFZ, Leipzig

Schulz, H.; Eder, B. (2006): Biogas-Praxis: Grundlagen, Planung, Anlagenbau, Beispiel. Staufen, Ökobuch

Slatter, P.T. (1997): The rheological characterisation of sludges. Water Science and Technology 36(11), pp. 9–18

Rostalski, K. (2009): Tauchmotorrührwerke in Biogasanlagen – Ein Beitrag zur Effizienzsteigerung. In: Tagungsband zur 18. Jahrestagung des Fachverbandes Biogas e. V. – Biogas: dezentral erzeugen – regional profitieren – international gewinnen. Fachverband Biogas e. V., 03.–05.02.2009, Hannover, S. 59–65

Verein deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten, VDLUFA (2007): Methodenbuch III - Die chemische Untersuchung von Futtermitteln. Darmstadt, VDLUFA-Verlag

Wiedemann, L.; Conti, F.; Janus, T.; Sonnleitner, M.; Zörner, W.; Goldbrunner, M. (2016): Mixing in Biogas Digesters and Development of an Artificial Substrate for Laboratory-Scale Mixing Optimization. Chemical Engineering & Technology 40 (2), pp. 238–247

Wu, B. (2011): CFD investigation of turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters. Water Research 45(5), pp. 2082–2094

Authors

M. Sc. Philipp Kress is a research assistant and **PD Dr. Andreas Lemmer** is a project manager at the State Institute of Agricultural Engineering and Bioenergy, **M. Sc. Bastian Kolb** is a research assistant at the Department of Livestock Systems Engineering at the University of Hohenheim, Garbenstr. 9, 70599 Stuttgart. E-Mail: philipp.kress@uni-hohenheim.de

Dr. Hans-Joachim Nägele is a lecturer at the Zurich University of Applied Sciences, ICBT Institute for Chemicals & Biotechnology, Einsiedlerstrasse 31, CH-8820 Wädenswil

Acknowledgements

This research was funded by the Federal Ministry of Economics and Energy (funding code 03KB101B) as part of the project “FlexFeed – Flexibilisierte Fütterung in Biogasprozessen mit modellbasierter Prozesserkennung im Praxismaßstab”.