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Ultrasonic flow field measurement in agitated lab-scale reactors for optimization of anaerobic digesters

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Abstract

In this article, an ultrasonic flow field measurement is coupled with an evaluation similar to a particle image velocimetry (PIV). This *Echo*-PIV is executed to evaluate the flow in a mechanically agitated laboratory scaled reactor representing a real-life cylindrical digestion tower. The resulting flow field inside the reactor with the corresponding power demand of the stirring device gives a foundation for energetic process optimization. To represent different amounts of total solids concentration as found in real digestion towers, distinctive mixing ratios of water and glycerol are used. Furthermore, two different agitation devices are investigated with different operation parameters.

Findings highlighted the applicability and constraints of an ultrasonic measuring approach for investigating flow fields inside a reactor using low- to high viscous fluids. Both the agitation speed as well as the choice of agitation device have an impact on the overall mixing with predominant influence reached with the latter one. Using a more sophisticated helical stirring device instead of a conventional bladed agitation device, results in more uniform flow profiles, with increased average velocities up to 50 % when using high viscous fluids.

Introduction

In order to reduce global warming, renewable energies such as biogas production get more important as an alternative technology to fossil fuels. In order to provide efficient biogas production in digestion towers sufficient mixing is necessary. Therefore, both the energy input, as well as the gas output are variables that have potential to be optimized, in order to establish the biogas production in digestion towers in the range of renewable energies. Since measuring the mixing efficiency in real scaled towers is hindered by different factors such as constructional means, overmixing is frequently used. Depending on the agitation device used, which can vary from conventional bladed stirring devices to more complex geometries as well as impellers, overmixing results in a needless energy demand that can, and above that should, be prevented. In order to provide a template for optimized mixing both CFD simulations, as well as laboratory experiments, can be conducted. Over the past decades many of such simulations investigated different digestion tower geometries with variable process parameters. [1, 2] Furthermore, different approaches for induced mixing into the fluid were investigated [3, 4] Uniform findings show a more even flow profile when using lower rotational speeds in higher viscous fluids in combination with higher stirring surface. However, implementing laboratory scaled experiments could help validate those simulations.

The main focus of this work is the experimental flow analysis of a cylindrical shaped digestion tower. The existing digestion tower (based on one of two towers) is used by the "*Innsbrucker Kommunalbetriebe AG (IKB AG)".* It provides a volume of 4.500 m^3 and is scaled down to laboratory size. With available space of 7.948 liters for a water-glycerol mixture, the used laboratory reactor is the foundation for different experimental setups and process scenarios. The usage of this sludge substituent brings the advantage of no fluctuations in rheological properties as for example found in real sludge. These deviations in total solids concentration (%TS), viscosity η and fluid density ρ are caused by seasonal and geological conditions. [5] To simulate different ratios of %TS the glycerol percentage per weight (wt%) can be varied. Usual ratios between 2.5 and 5.4 %TS can be investigated while not having any impact on the performance of the ultrasonic measurement. [1, 6] Furthermore, investigated scenarios differ in agitation device and rotational speed (rpm). The executed flow field measurement is based on an ultrasonic device originally from the field of medical technics. The usage of a non-invasive measurement does not alter the flow field such as measurements with probes. Furthermore, it is able to evaluate entire flow areas and not only specific points inside the reactor. The ensuing analysis of the ultrasonic measurement is done by software-based cross-correlation of the time-depended translocation of particles inside the reactor. Validations with computational fluid dynamics (CFD) are planned but are not integrated into this work.

Methods

Laboratory reactor setup

In this work, a real life digestion tower is scaled down to laboratory dimensions using a linear scaling factor. Scaling approach is based on constant specific power both in the real-scale and lab-scale reactors. However, constant power is set with the agitation devices. The cylindrically shaped reactor wall is made of acrylic glass to provide optical accessibility. Other parts that shape the final geometry are made using a 3D-printer with semi-transparent material *VeroClear*. This material offers mechanical and chemical properties similar to acrylic glass. Illustrated in figure Figure 1 the reactor, with inner diameter of 220 mm, provides an fluid volume of 7.948 liters.

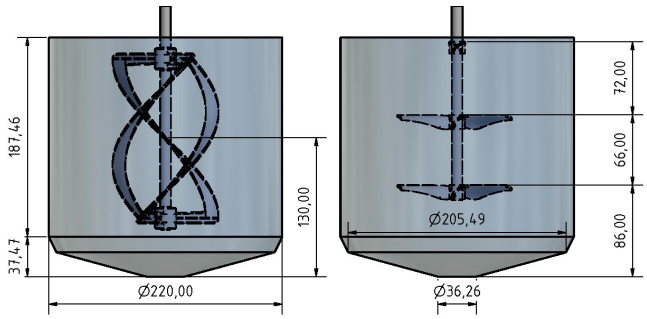

Figure 1: Laboratory scaled reactor with 1) helical and 2) Scaba agitation device (dimensions in mm)

Centric clockwise mixing is induced by a Heidolph RZ 2102 with variable speed control and integrated torque measurement.

Agitation devices

The impact of different mixing devices is investigated with two different agitators. As shown on the right reactor in Figure 1, a bladed agitation device as used in real scale reactors is scaled using the approach of same specific power as described in the Penney-Chart. [7, 8] Reference for constant specific power is the very same stirring device used in the existing template digestion tower. This stirring device consists of two 3-bladed segments, as well as one 2-bladed segment with 0.12 m and 0.09 m in diameter *d*, respectively. The segments are 3D-printed and attached to a steel shaft. The second stirrer in the left reactor in Figure 1 is a helical agitation device as found in chemical laboratory applications R3003.1 provided by IKA. Diameter, stirrer-height *h* and type are displayed in Table 1.

Table 1: Data for two different mixing devices used for mechanical agitation [9]

Mixing device	Type	*d*	*h*
R3003.1	IKA Helical stirring device	0.1 m	0.1628 m
Scaba	3-segment bladed agitation device	0.12 m / 0.09 m	0.152 m

Rheological substituent for the slurry manure

To provide consistent rheological properties a mixture of glycerol and water is used as sludge substituent. Mixtures are set to provide same dynamic viscosity as found in real manure used in digestion towers. Table 2 shows specific ratios of water and glycerol that represent different percentages of %TS resulting in specific dynamic viscosities and fluid densities. Ratios above 5.4 %TS are rarely found in practical application. [1, 6] Despite that, also the ultrasonic measuring quality decreases if a mass-fraction of 75 wt% glycerol is exceeded. In order to reduce the needed sonic gain on the ultrasonic device, seeding particles based on polyamide flakes with a average diameter of 0.005 µm are used. [5] These particles are dispersed in water and induced into the reactor before measuring to prevent sedimentation over longer periods of time.

Table 2: Data for sludge substituent using a water-gylcerol mixture at T = 21 °C, reference %TS concentration taken from [1]

Glycerol / water	η	ρ	*%TS*
0 / 100 wt%	0.00098 Pa s	997.83 kg m^{-3}	-
50 / 50 wt%	0.0058 Pa s	1126.3 kg m^{-3}	2,5 %
75 / 25 wt%	0.0343 Pa s	1193.7 kg m^{-3}	5,4 %
85 / 15 wt%	0.11368 Pa s	1222.7 kg m^{-3}	7,5 %
100 / 0 wt%	1.2901 Pa s	1260.1 kg m^{-3}	>12 %

Ultra Sonic measurement setup

Because of the desired non-invasive characteristics as well as further experimental setups that do not allow measuring methods such as conventional particle image velocimetry (PIV), flow measurement is executed using an ultrasonic measuring approach. For this approach a *GE Logiq 300* ultrasonic examination device, initially as applied for the field of medical examinations is used. [10] In order to provide best resolution in the experimental setup a *GE 739L* linear measuring head is used. With set parameters this head features a penetration depth of 0.1 m while providing a sampling frequency above 24 possible frames restricted by the used frame-grabber. To prevent unwanted refractions at material transitions conventional ultrasonic gel is used. [11] The measuring head is aligned orthogonally to the reactor wall in order to measure the projected velocity consisting of both radial as well as tangential components. For measuring axial flow fields the head can be rotated 90 °. However, those flow fields are not integrated in this work and will be part of future investigations. Evaluation of the gathered ultrasonic frames is done via MatLab related Add-In PIVLab using FFT window deformation algorithm with incrementing sequencing style. [12] Average velocities are calculated in the region of interest which covers the whole ultrasonic measuring field at increasing reactor height increments of 0.01 m. Measuring planes start at 0.03 m because of structural design. Measurements are carried out for approximately 30 seconds to capture at least 1000 frames per experiment at ambient temperature *T*.

Results

Experimental investigations not only have shown the distinct differences between the two agitation approaches, but also the capability of ultrasonic flow field measurement for this application in general. Figure 2 depicts the basic flow evaluation with calculated absolute vectors consisting of both tangential and radial components. The stirring shaft can be seen at the bottom and the reactor wall on the top of the image. Because of the measuring method the vectors are projected in X-Y-plane. Therefore, the third vector component in Z-axis is not incorporated.

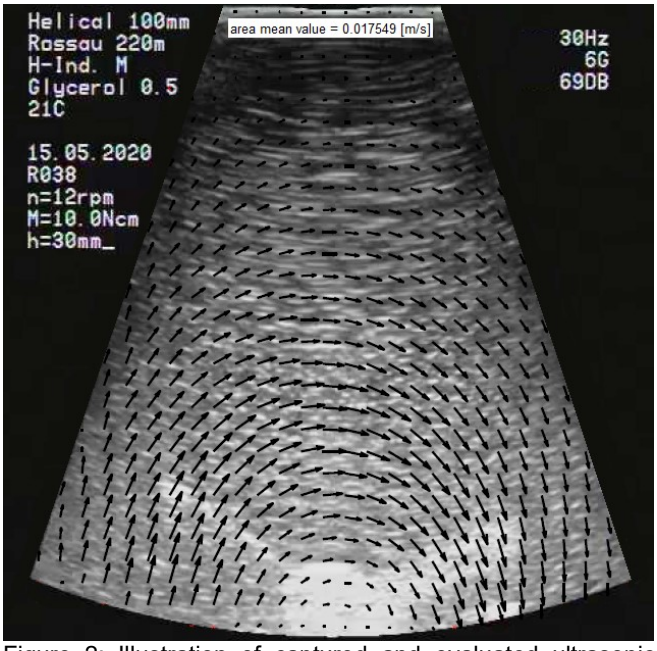

Figure 2: Illustration of captured and evaluated ultrasonic flow field in X-Y-plane. 50 wt% glycerol-water mixture with a helical stirring device (100 mm) at 12 rpm is used. (h = 0.3 m, w_{glyc} = 50 *wt*%, T = 21 °C, η = 0.00098 Ns m^{-2}, ρ = 997.83 kg m^{-3})

Because of material and their corresponding density transitions between reactor materials, fluids and internal installations such as agitation devices, increased sonic gain is necessary that can lead to interfering echo effects. Especially when using pure water those interferences alter the vector field calculated with the software as seen in wider error bars in Figure 3 for pure water. This sonic feedback is less prominent for mixtures with 50 wt% and 75 wt% glycerol/water as illustrated in smaller error bars in figures

Figure 4 and 5. Nevertheless, the measurement method is able to highlight the differences between the two distinctive agitation devices. Results show the differences of average velocities at different heights, with a more uniform vertical flow profile for the helical device. This is coherent with former CFD simulations that go along with this work. [1, 2] When comparing both diagrams in Figure 3 it is evident that, despite the more uniform flow profile, the helical device is also able to produce higher average velocities at lower rpm.

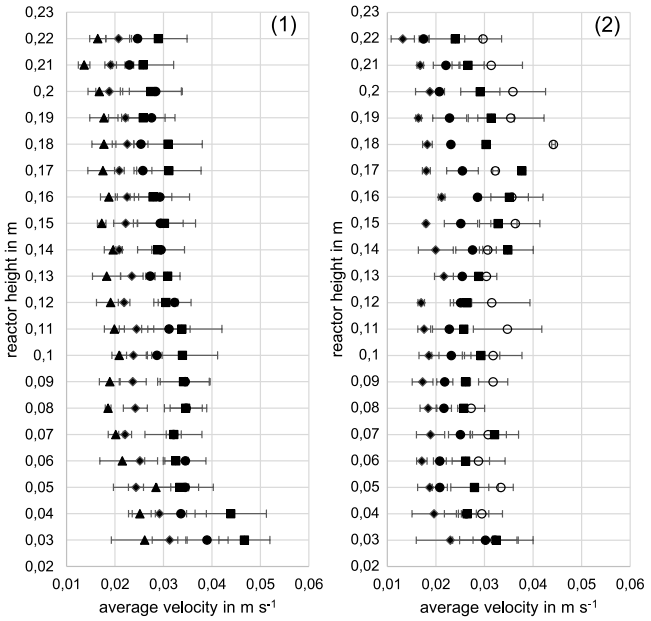

Figure 3: Flow field evaluation in pure water with different agitation speeds using (1) a helical stirring device (100mm) and (2) a Scaba device. (w_{glyc} = 0wt%, T = 21 °C, η = 0.00098 Ns m^{-2}, ρ = 997.83 kg m^{-3}) ▲: 12rpm, ♦: 15 rpm, ●: 20rpm; ■: 25rpm; ○: 30rpm

As seen in Figure 3 (2), Figure 4 (2) and Figure 5 (2), characteristic peaks in the average velocities are detected at h of approximately 0.07 m. These specific peaks are caused by higher fluid velocities at the height of the individual Scaba agitation segments on the one hand and because of the characteristics of the measuring method, respectively. Since the agitation device rotates through the measurement field it is also measured by the ultrasonic device itself. This is due the chosen sequencing style as described earlier. Because of the higher rotational speed of the agitation device itself in relation to the fluid, the resulting velocity field is higher than the actual fluid flow velocity. This is due the fact that the rotating blade is seen as a fluid flow by the used program. In order to minimize that increased velocity error different phase-correlated sequencing style can be executed, where the agitation device does not rotate through the measuring field. However, this approach reduces the size of the measuring field. Therefore, it is planned to determine a correction factor that can be used to adapt results in the used increasing sequencing style. In higher viscous fluids such as Figure 4 (2) and Figure 5 (2) the peaks are also found at a height of 0.13 m.

When comparing Figure 3 and Figure 4 the impact of higher viscous mixtures of water and glycerol can be derived. While the flow field in pure water is spread out by higher turbulences, the flow field for the higher viscous fluid is more uniform while having lower average velocities at same rotational speeds for both mixing devices. This distinctive difference in flow profile is most evident when using the highest of the investigated fluid viscosities. Using higher ratios such as 50wt% or 75 wt% glycerol and 30 rpm, the Scaba device only reaches average velocities above 0.03 m s^{-1} at the height of the stirring segments.

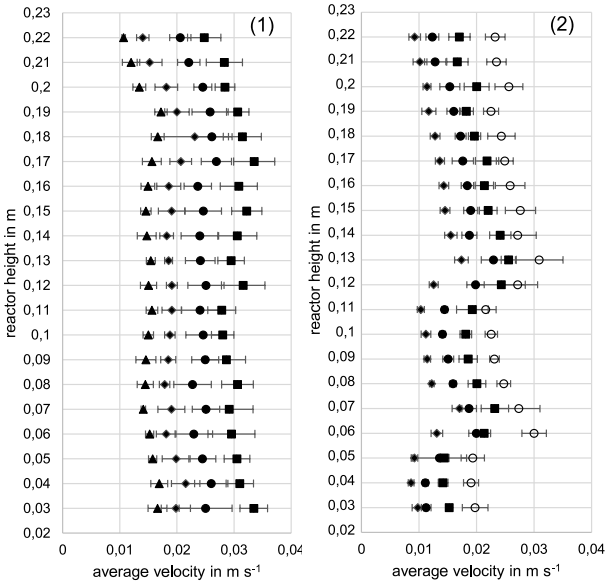

Figure 4: Flow field evaluation in a two-component glycerol/water-mixture with different agitation speeds using (1) a helical stirring device (100mm) and (2) a Scaba device. (w_{glyc} = 50 wt%, T = 21 °C, η = 0.0058 Ns m^{-2}, ρ = 1126.3 kg m^{-3}) ▲: 12rpm, ♦: 15 rpm, ●: 20rpm; ■: 25rpm; ○: 30rpm

The majority of average velocities of the helical stirring device on the other hand are in the range of or above 0.03 m s^{-1} again underlining the more uniform and higher velocity profile. This is still prominent at 25 rpm for the helical device.

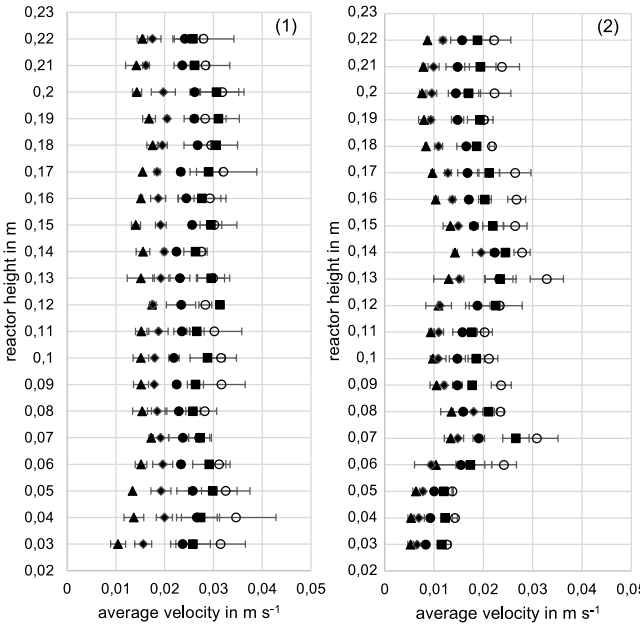

Figure 5: Flow field evaluation in a two-component glycerol/water-mixture with different agitation speeds using (1) a helical stirring device (100mm) and (2) a Scaba device. (w_{glyc} = 75 wt%, T = 21 °C, η = 0.0343 Ns m^{-2}, ρ = 1193.7 kg m^{-3}) ▲: 12rpm, ♦: 15 rpm, ●: 20rpm; ■: 25rpm; ○: 30rpm

As shown in Figure 6 the height-averaged velocities of the scenarios shown in Figure 5 for the helical device compared to the Scaba device are shown for a mixture of 75 wt%

glycerol and 25 wt% water. It can been seen that this overall averaged reactor velocity is increased up to 50%.

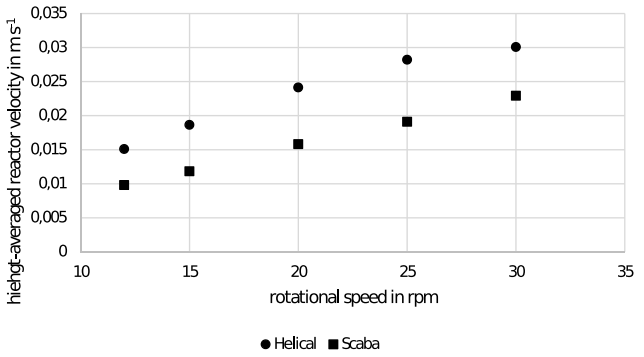

Figure 6: Comparison of the height-averaged velocities inside the reactor for both helical and Scaba at different rotational speeds. Experimental setup shown in Figure 5. (w_{glyc} = 75 wt%, T = 21 °C, η = 0.0343 Ns m^{-2}, ρ = 1193.7 kg m^{-3}

In detail, the helical device offers an increased height-averaged reactor velocity of 53.9 %, 57.7 %, 52.8 %, 47.7 % and 31.3 % for 12, 15, 20, 25 and 30 rpm, respectively. For future work, and in order to obtain a more detailed flow analysis, distinctive flow profiles can be measured at distinctive heights. Such a velocity profile can be seen in figure Figure 7 referencing to Figure 2 along a straight line from at the stirring shaft to the reactor wall.

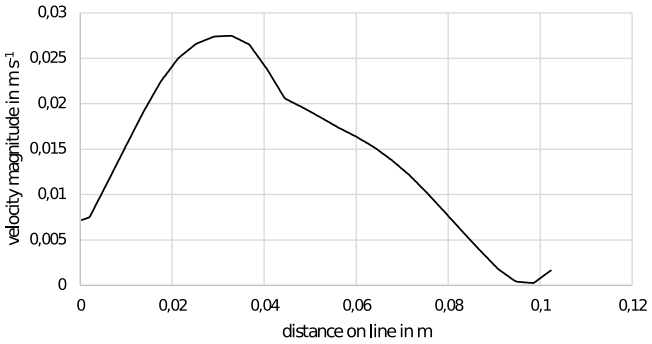

Figure 7: Illustration of the velocity profile along a centric polyline in reference to Figure 2 at a reactor height of 0.3 m. Velocity profile starts at stirring shaft (Distance on line = 0 m) and ends at the reactor wall (Distance on line = 0.11 m).

These plotted average velocities along the line can be compared for every investigated reactor height.

Conclusion

Based on the results as summarized above this work was not only able to highlight the differences of agitation approaches, as well as process parameters on the overall fluid flow, but also the applicability of the ultrasonic flow measurement in lab-scaled reactors. This measuring method offers an interesting non-invasive alternative with a broad area of application for fluid measurement with yet big optimization potential. Furthermore, results have validated former CFD simulation outcome that more complex stirrers can lead to higher average flow profiles with lower rotation speeds. However, power demand as well as structural and mechanical properties where not considered in this work. Without power demand, the improvement of overall mixing efficiency cannot be determined. However, it was shown that especially in higher viscous fluids the more complex helical stirring device delivers better mixing performance.

Future work

This work was the first application of this flow field measurement approach using an ultrasonic device in this very experimental setup. Therefore, a lot of optimization potential both in the setup, as well as in the evaluation and in the validation with CFD simulations is elaborated. Especially the use of area-averaged velocities at different heights may be an interesting approach for a first rough assessment and comparison between two experimental scenarios. However, to provide a more detailed investigation velocity profiles can be extracted that show a velocity gradient inside the reactor. This will be the main approach for further experiments to not only represent a more exact flow field, but also to ensure a better validation with CFD simulations.

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