ON MODELLING THE MIXING IN A DIGESTER FOR BIOGAS PRODUCTION

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Abstract. At the Växtkraft biogas plant the mixing is produced by pumping in biogas and releasing it at the bottom. The mixing inside the digester of a biogas plant is important for good biogas production and since it is complicated to study the mixing inside the digester while it is in operation, this study is based on numerical simulations using a computational fluid dynamic finite volume code. To study the mixing dynamics, five different flow rates of gas (air) injections ranging from 0.1 to 0.6kg/s were simulated. These gas flow rates produced an average liquid speed in the digester between 0.10 and 0.22 m/s. The liquid recirculation impact on the mixing was investigated through the simulation of a case where it is combined with the lowest gas injection flow rate. The results from the simulation suggest that the liquid outlet is situated too close to the gas injection, resulting in energy losses in form of diminished mixing of the digester. A complete redesign of the digester is needed to seriously overcome the mixing limitation.

1 Introduction

Today there is a large potential for biogas production from any kind of organic residue as well as from different crops, farm land residues or graze. In Sweden alone the potential for biogas production is about 17 TWh per year, an amount of biogas that could cover 20 % of the fuel demand of all private cars in Sweden [7]. However, the technology for biogas production is not optimized and thus not fully cost-effective. To be fully commercially competitive with other types of fuels, efficiency improvements of the process is needed.

One important part for possible improvement of the performance is to increase the reaction rate by optimizing the mixing and gas distribution in the digester. The fermentation process relies on a good and even mixing for distribution of microorganisms and nutrition, inoculation of fresh feed, homogenizing of the material and for the removal of end products of the metabolism [3]. This leaves the question of how well the total volume of the digester is being used for the fermentation process and how it can be improved. There is no really good rule of thumb of how much mixing is needed to get a good gas production. A general recommendation from the EPA is a power input of 5 to 8 W/m^3 of digester volume [8]. Many researchers today argue the case that too much mixing could be bad for the process and that a reduction in mixing intensity leads to better reactor performance [6, 9]. The microorganisms themselves are actually sensitive to too intense mixing and can be destroyed because of it [3].

Mixing in a digester can be handled in a number of ways. It can be performed by mechanical mixing of different sorts, hydraulic mixing by using pumps and pneumatically by using the gas itself for mixing the liquid. Mechanical mixing with different kinds of agitators is the most common type of mixing being used in Europe today [3]. Pneumatically forced circulation stands for about 12 % of the used mixing systems in Europe. There are three types of gas-lift mixing being used in digesters, the free and unconfined release of gas from the bottom, confined gas release inside a draft tube and the use of big bubbles to create a piston pumping action [8]. An advantage of the pneumatically forced circulation is that there are no moving parts in the digester that might brake or collect debris and get tangled up.

Research done to study the gas-lift mixing of a digester using a draft tube has revealed that a large portion of the total volume can in fact be poorly mixed [4, 5] and especially the surfaces around the bottom. Studies show that poorly mixed zones can be as large as 33,6 % of the digester volume [5] which leaves room for further improvement of the digester and gas injection configurations. According to research done in this area no significant reduction in the stagnant zones of the bioreactor could be seen while increasing the gas flow to three times its original flow [4], so increasing the amount of gas injected is not a good solution according to these results. In the stagnant zones the mixing of new material and bacteria is low to non-existent and to utilize the digesters total volume and to avoid sedimentation these stagnant zones should be minimized. Deposit of material at the bottom near to the walls of the digester is to be expected according to experiments done to study the gas mixing within a draft tube [5].

In the Växtkraft biogas plant, in Västerås, Sweden, organic waste from households and restaurants is mixed and fermented with crops from graze land. This plant was taken into operation in 2005 and the main parts of the plant can be seen in Figure 1. The solid and liquid waste is mixed with recirculated process water to form a slurry with a dry content matter around 10%. The digestion takes part in a tank of 4 000 m^3. The digester works continuously and the residence time of the material is approximately 20 days. Mixing of the material is done by the compressed biogas itself, today distributed by 12 pipes that enter the tank at the top and release the gas at the bottom of the tank. Gas is then recovered at the top of the digester. The recirculation pipe which is used to add the silage and remove material from the digester is also affecting the mixing of the digester. Svensk Växtkraft AB was a part of the EU-project AGROPTI-gas. The goal of the project was to show how fossil fuel in public transportation (city busses) could be exchanged to biogas and how mineral fertilizer could be exchanged to organic fertilizer, a product of the biogas process. In this project the technical solutions were evaluated. [1, 2]

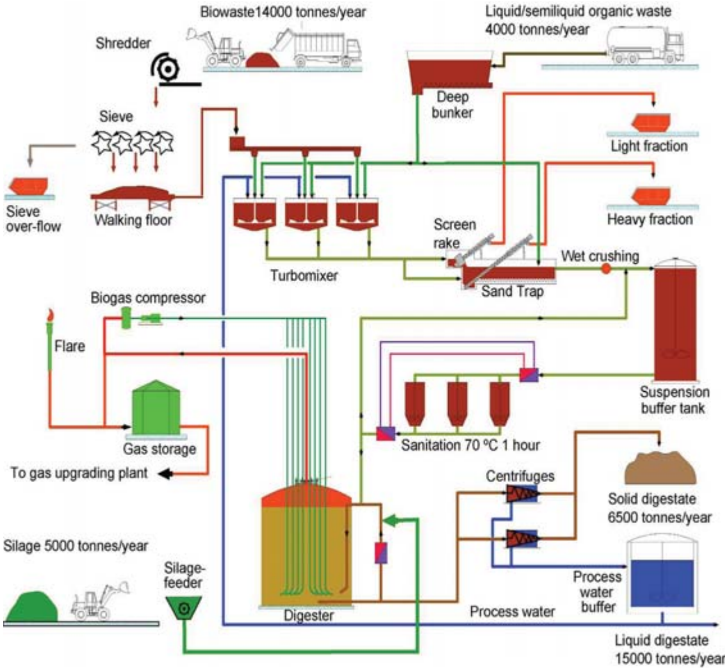


Figure 1. Flow sheet over the biogas plant Växtkraft. The flow sheet shows how the organic material is pre-processed and then added to the digester through a circulation conduit. It also shows the general idea of the gas-lift mixing.

2 Modelling and simulation of a digester for biogas production

Since it is complicated to study the mixing inside the digester while it is in operation, the investigation is based on an advanced CFD study. In this study the unconfined release of biogas from the bottom is simulated to give a better understanding of a digester and the process as a whole. Some work has already been done in this area but for other types of gas driven mixing that can give useful insights in the problems that this type of mixing still exhibits [4, 5]. Because of the difficulties in taking a sample representative of the entire volume of liquid slurry inside the digester and the problems measuring the viscosity a simplified case has been set up using the physical properties of water. This study is a first small step towards understanding and evaluating the digester at the Växtkraft biogas plant. The simulations was made with a CFD finite volume code assuming an axisymmetric reactor geometry and gas and liquid inlets and outlets as suggested by the real plant.

To start the evaluation of the digester six cases were set up (Table 1) with a series of different gas flow rates. The lowest gas flow rate is the closest one to the actual set up at the biogas plant and this gas flow rate is also simulated in combination with the liquid circulation to see what effect it has on the overall mixing.

Simulation	Gas flow rate	% of max flow rate	liquid circulation
1	0.6	100	off
2	0.48	80	off
3	0.36	60	off
4	0.24	40	off
5	0.12	20	off
6	0.12	20	on

Table 1. Setup of the simulations using different gas flow rates and an evaluation of the liquid circulation.

2.1 Digester Geometry

The geometry has been created to resemble the biogas plant Växtkraft to see the effects that changes in the biogas recirculation system would have on the mixing of the digester. The geometry of the digester is assumed to be axisymmetric with a height of 19.5 m and a radius of 8.5 m as shown in Figure 2. The gas injection is also simplified to allow a high quality mesh. As part of the liquid recirculation system a liquid outlet is placed on the bottom next to the centerline axis and the liquid is then reintroduced with an inlet trough the digester side wall close to the bottom.

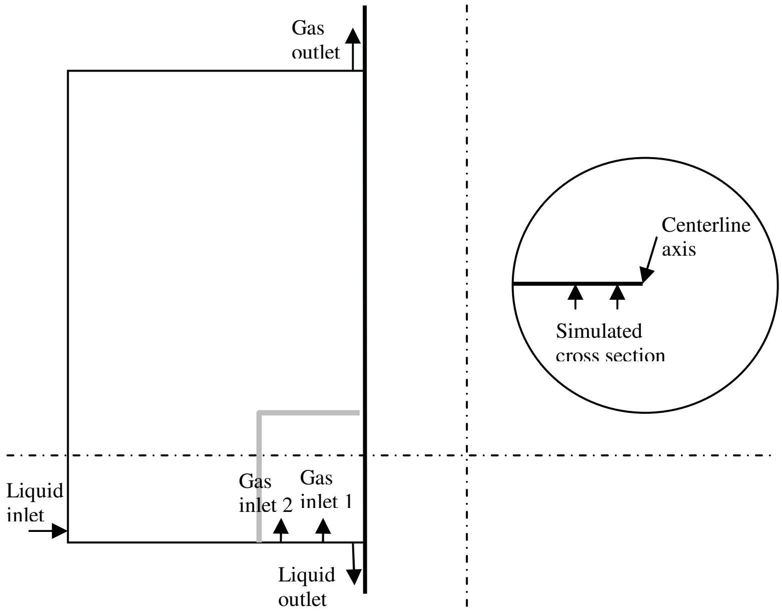


Figure 2. Illustration of the geometry that was used in the simulations (left) and an overview picture of the digester and the simulated surface (right).

Special care was taken to refine the mesh around the inlets and outlets as well as at the neighborhood of the liquid/gas free surface where very high gradient are to be predicted.

2.2 Mathematical model

The numerical predictions allow us to visualize the flow pattern of the liquid and the gas, to examine the mixing, to point out accurately the areas of low recirculation where the sand sedimentation can occur and can be used to study the recirculation time. These parameters are essential to compare one digester configuration with another. Sand deposits on the bottom could also affect the mixing of the digester as well as it would take up valuable space from the fermentation process. In the model an overall picture of flow patterns and stagnant zones can be formed and the sedimentation frequency can be evaluated for the different alternatives. The goal of the model is ultimately to help find a way to improve the quality of the mixing.

The Volume-Of-Fluid model is used in this study. It is valid for two or more immiscible fluids (or phases) that are separated by fluid/fluid interfaces. The method is based on a single set of momentum equations and turbulence while tracking the volume fraction of each phase in the mixture.

Material properties. The physical properties are averages of the phasic quantities weighted by the local phasic volume fractions. The effective density and molecular viscosity in a cell are respectively $\rho = \sum \alpha_q \rho_q$ and $\mu_L = \sum \alpha_q \mu_q$ where the index *q* is relative to the fluid phase *q*.

Continuity equations. The continuity equation for phase q is:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right)+\nabla\cdot\left(\alpha_q \rho_q \vec{V}_q\right)=S_{\alpha_q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right] \qquad (1)$$

$\vec{V}_q$ is the velocity of phase q. The terms $\dot{m}_{pq}$ and S_{α_q} are respectively the mass transfer rate from phase q to phase p and the mass source term for phase q which are both equal zero in this mixing first order investigation. The primary-phase volume fraction will be computed based on the following constraints:

$$\sum_{q=1}^{n} \alpha_q = 1. \tag{2}$$

Momentum equations. The momentum equations, shared by all phases are similar to the single phase case:

$$\frac{\partial}{\partial t}\left(\rho\vec{V}\right) + \nabla\cdot\left(\rho\vec{V}\vec{V}\right) = -\nabla p + \nabla\cdot\overline{\overline{\tau}} + \rho\vec{g} + \vec{F} \tag{3}$$

Where $\vec{F}$ represents possible external forces and $\overline{\overline{\tau}}$ is the stress tensor:

$$\overline{\overline{\tau}} = \mu_{eff}\left(\nabla\vec{V} + \left[\nabla\vec{V}\right]^T\right) + \left(\lambda_{eff} - \frac{2}{3}\mu_{eff}\right)\nabla\cdot\vec{V}\overline{\overline{I}} \tag{4}$$

μ_{eff} and λ_{eff} are the shear and bulk viscosities and include both the laminar as well as the turbulent contributions.

Turbulence model. The turbulence of the flow system is modelled using the Reynolds stress model. The Reynolds stresses and turbulent dissipation rate transport equations are similar to the single phase flow case, however, the physical properties are weighted averages similar to the momentum equations. This advanced turbulence model was motivated by the strong recirculations and large meniscus curvature existing in the bioreactor case that we study today.

3 Results and discussion

3.1 Mixing dynamics

To study the mixing dynamics of the Växtkraft biogas reactor five flow rates of gas (air) recirculation were simulated with a gas flow rates of 0.6, 0.48, 0.36, 0.24 and 0.12 kg/s. Between each of the different gas flow rates in this series of simulations there is a 20 % decrease starting from the maximum gas flow of 0.6 kg/s.

By comparing the fully developed liquid flow of the five different simulations an understanding of how much influence the amount of injected gas has on the overall mixing can be gained. The gas flow rates simulated produced an average liquid velocity in the digester which is almost linearly increasing with the gas flow rate as shown in Figure 3.

In this simplified case where the chemical reactions and the various mixture inhomogeneities in the system are ignored, the main mixing contributions are first due to the convective flow induced by the gas injections and secondly the local effect of turbulence related to the gas or to the liquid flow. The turbulent kinetic energy in the digester can complement the picture of the mixing between the fresh feed and the already digested material. The mean liquid turbulent kinetic energy for the simulated gas flow rates is also found to increase almost linearly with the air flow rates. This result is presented in Figure 3.

A higher gas flow leads to an increased average velocity in the entire digester but the energy used to produce that seems to be much larger than the produced effect.

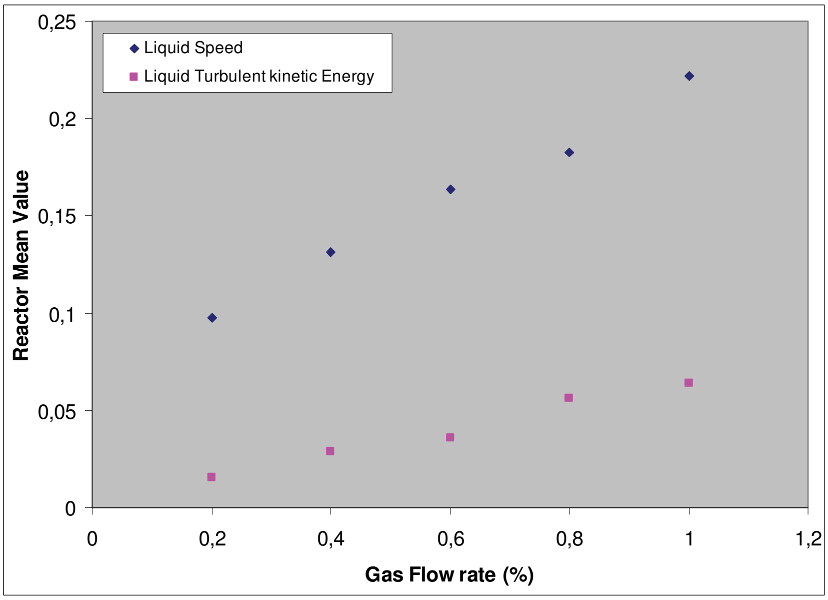
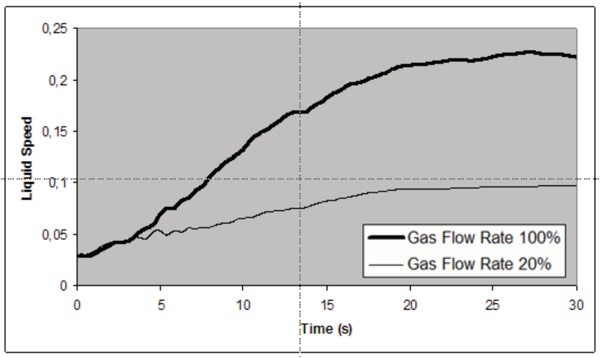


Figure 3. Mean speed and turbulent kinetic energy of the liquid at different gas flow rates.

Figure 4 clearly illustrates that by increasing the gas flow rate 5 times the mean reactor liquid velocity is only doubled. However, the liquid turbulent kinetic energy is 4 times larger as shown in figure 5. This mean that local mixing is strongly improved but the global liquid recirculation in the vessel does not follow and this translates the limitation of the process capabilities as it is today.



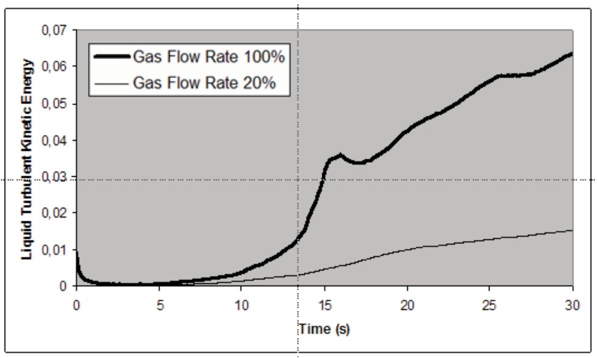
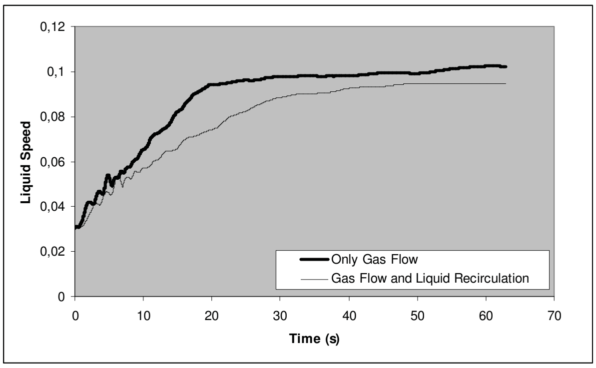


Figure 4. Mean liquid speed

Figure 5. Mean liquid turbulent kinetic energy

The case with the lowest gas flow rate has been simulated with and without liquid recirculation where the liquid is extracted from the bottom core of the reactor and re-injected at the digester side wall bottom as sketched in figure 2. Figures 6 and 7 of the liquid speed and its turbulent kinetic energy show the very limited effect of this operation on the mixing. The liquid extraction at the bottom core of the reactor has even a negative effect on both the global as well as the local mixing.



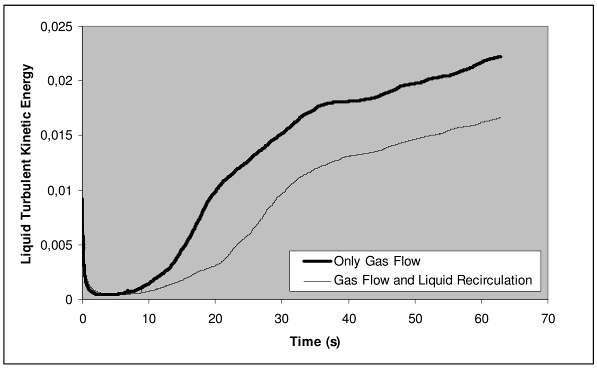


Figure 6. Mean liquid speed

Figure 7. Mean liquid turbulent kinetic energy

The gas-lift mixing facilitates a good vertical movement in the digester core because of the rising gas bubbles and pockets. Intensive radial flow in the digester is created at the liquid free surface.

The push exerted by the rising gas bubbles form a water column above the original liquid surface in the core of the digester creating waves that induce a strong radial flow.

The produced liquid stream in the upper part of the digester is then forced down when it approaches the digester's side wall, creating the recirculation flow back down to the bottom.

The overall velocity magnitude of the liquid and the height of the water column are dependent on the amount of gas injected. Figure 8 shows the gas distribution and the water/air free surface shape for various simulated cases.

The gas that is injected at the bottom rises through the liquid creating a thin stream of liquid and gas moving at high speed in the center line region, but the remaining very large volume of the digester is not affected and is found to be poorly mixed.

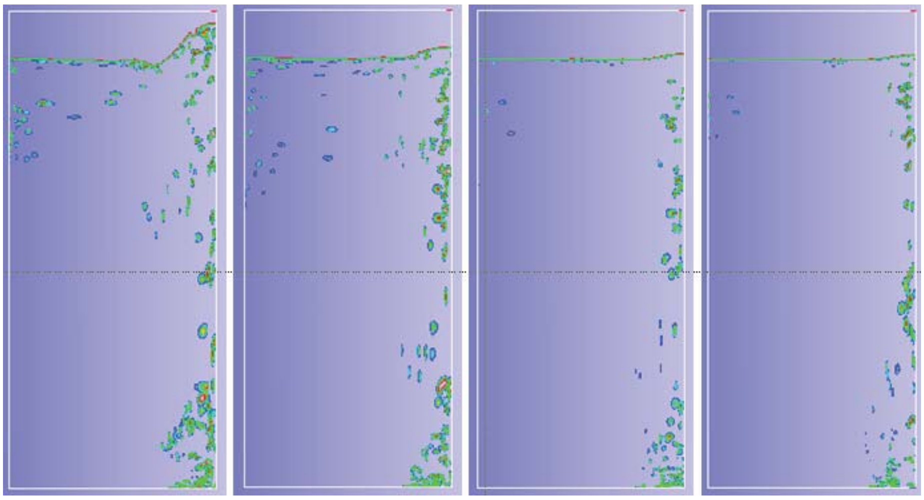


Figure 8. The gas distribution at different flow rates showing the activity at the surface. Starting from the left is the case at 100 % flow rate, 60 %, 20% and 20 % with the liquid recirculation on.

3.2 Liquid recirculation flow pattern

The liquid recirculation is also analyzed to see its impact on the mixing at the bottom center area referred to in figure 2 as the core bottom domain. As mentioned before the liquid is withdrawn from the bottom in the center of the digester and then reintroduced trough the wall close to the bottom. Comparing the simulation with and without the liquid recirculation a loss of energy can be seen in form of diminished liquid flow and a change in the mixing pattern (fig. 9). Positioning the outlet in the center of the digester where the stream of bubble is formed and in close proximity to the gas injectors means that both energy and gas is lost because of the recirculation system and the overall mixing of the digester is affected (fig. 10). The injection of water at the bottom of the side wall has no significant effect on the mixing and quickly dissipates after being injected. Sand sedimentation along the bottom is possible due to the low flow intensity and a good position of the liquid inlet and outlet near the bottom cold help with the removal of these sand particles. The dead zone or very slowly moving liquid zone is becoming larger with the added liquid recirculation.

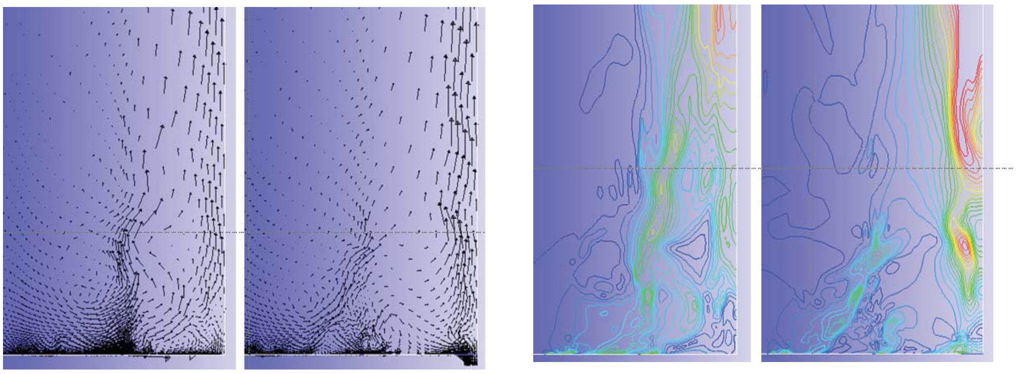


Figure 9. Velocity vectors (left pair) and velocity contours (right pair) of the gas injection and liquid outlet, showing the effect that the liquid outlet has on the flow pattern. The left hand side picture of each pair shows the case where gas injection is 20 % and the right hand side picture shows the activated liquid outlet at same gas flow rate.

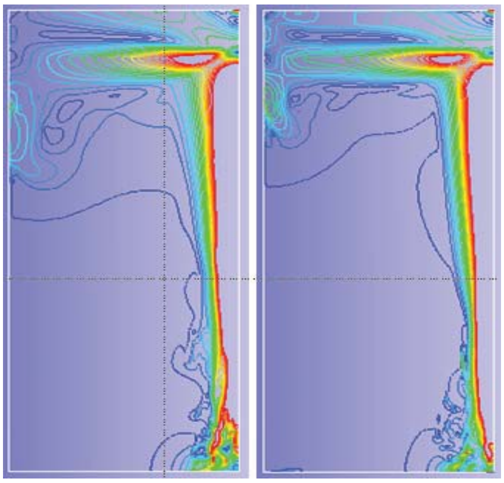


Figure 10. Velocity contours of the entire domain with the gas injected at 20 % flow rate. The picture on the right hand side is showing the result when the liquid outlet is on and the left when it is off.

Before further studies can be done using the CFD simulations, the results must be validated by experimental data. An experimental investigation will be performed in a lab scale model of a digester with gas injection. Validation of the model will be made at ABB corporate research by scaling down the inlet pipes and gas flow to a 1 m^3 Plexiglas tank. In this tank a series of tests will be conducted to see if the flow pattern from the CFD model matches the real life data.

4 Conclusions

Our simulation results suggest that the positioning of the liquid outlet is not optimal for the gas-lift mixing configuration and that energy savings and better mixing can be accomplished by finding a new position for the outlet. The zones with lower circulation are not significantly influenced by fine tuning the gas flow because the volume of the digester is so large compared to the narrow rising bubbly liquid stream. It seams that a complete review of the digester design is necessary to be able to improve seriously the process and probably reduce the energy consumption. Experimental work to validate these results is crucial for further investigations of the digester at the Växtkraft biogas plant.

5 Acknowledgement

The Knowledge Foundation is acknowledged for funding this project, the BioGasOpt project.

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