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Hydraulic modeling of a confined gas recirculation mixing system for a CSTR anaerobic digester

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Abstract

Hydraulic numerical modelling and experimental work was used to develop a mixing system, that is able to satisfy the biological requirement of micro bacteria and create a homogeneous solution inside the digester.

A review was conducted on the different mixing methods used commercially for CSTR's as well as the influence of mixing intensity and intervals on anaerobic digesters. The gas recirculation method, operating in a two-phase plug-flow regime mixing method was selected and a one-dimensional explicit, transient numerical model was developed that could predict the liquid mass displaced by a gas plug. An experimental study followed the numerical modelling of the digester mixing system to capture the effect of various geometrical constructions of the plug-flow generator in two empirical equations to predict the mass and frequency of plug released. With the numerical model and experimental results a full scale mixing system was developed for a 1 600 m^3 digester. The benefits of the proposed mixing system over the mechanical draft tube method include the following: no moving parts inside the digester, tedious downtime of clogged rotating equipment is eliminated and only requires 7 % more power per unit volume.

Key words

Anaerobic digestion, digester mixing, gas recirculation, plug generator, draft tube, two-phase flow

1. Introduction

Anaerobic digestion is a multi-biological process whereby anaerobic microorganisms break down complex organic substances in the absence of oxygen. The breakdown of complex organic substances (consisting of carbohydrates, proteins and lipids) by the micro-bacterial community inside the digester can be characterised in four stages, namely; hydrolysis, acidogenesis, acetogenesis and methanogenesis. The micro-bacterial stages inside the digester are also influenced by different environmental and process operating factors and can either enhance the deration or inhibit the process and gas production (Eliyan, 2007 and Schön, 2009).

In the first two stages hydrolysis and acidogenesis bacteria degrade the organic fraction into soluble intermediates and soluble monomers operating at an optimum pH range between 5.2 and 6.3. In the second two stages acetogenesis and methanogenesis bacteria convert the soluble monomers into biogas operating in an optimum pH solution range between 6.6 and 7.2 (Moo-Young, 2011).

This study will only focus on mixing for an anaerobic continuous stirred rector, one of the process operating factors affecting the performance of a digester.

Mixing is an important process operating factor, which essentially acts as a transportation mechanism for the microorganisms inside the digester, increasing the surface contact area of the organic substances to the microorganisms and can lead to an increased rate of micro-bacterial productivity. Mixing a digester is important in order to create a homogeneous solution inside the digester which prevents a crust layer forming on top of the digestate and increases the effective volume of the reactor (Karim *et al.* 2005a, Turovskiy & Mathai, 2006, Augusto de Lemos Chernicharo, 2007).

Mixing of a digester can be classified into three main categories namely, method, intensity and intervals. Mixing method can be sub categorized as mechanical, gas and hydraulic recirculation. Mixing intensity can be sub categorized into vigorous, gentle and minimal. The last main category can be sub categorized as continuous and intermittent. In order to design a mixing system for an anaerobic reactor, the three main categories listed above should be studied carefully, as mixing has a large effect on biogas production rate and the pH inside the digester (Augusto de Lemos Chernicharo, 2007).

The method of mixing a reactor is based mainly on the type and design of the reactor. In this study the focus was on methods used to mix a CSTR experimentally and commercially. An illustration of the different methods used experimentally and commercially are summarised in Figure 1 below.

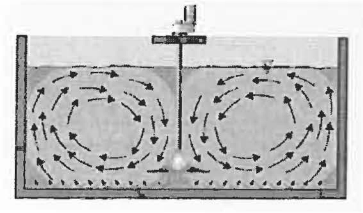
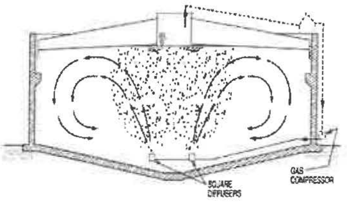
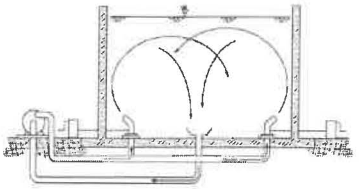
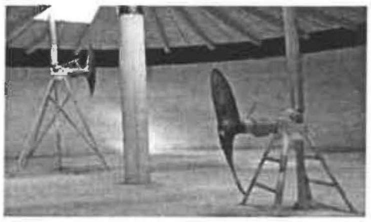
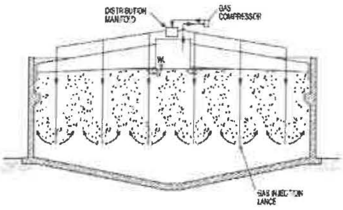
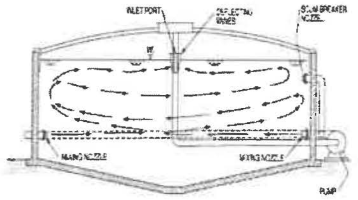
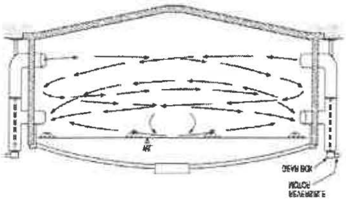
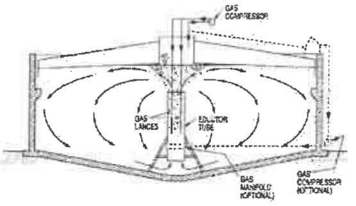
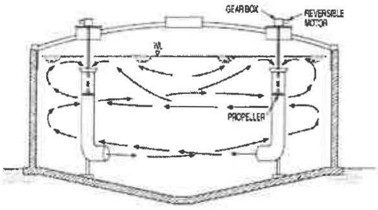
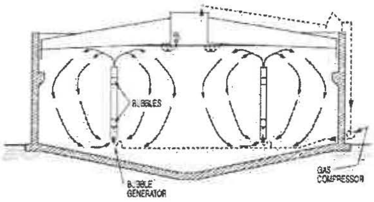
Mechanical	**Gas recirculation**	**Hydraulic recirculation**
Vertical paddle stirrer (unconfined) 	Gas diffusers (unconfined) 	Slurry recirculation (fixed nozzles) 
Horizontal paddle stirrers (unconfined) 	Gas lance (unconfined) 	Slurry recirculation (rotating nozzles) 
External draft tube (confined) 	Bubble column (confined) 	
Internal draft tube (confined) 	Bubble piston (confined) 	

Figure 1: Mixing methods used for CSTR (Turovskiy & Mathai, 2006)

Several research studies in the past focused on increasing the effective volume of a digester and quantifying the amount of mixing needed for a digester (Azbar and Speece, 2001). The parameters that are mainly used to quantify the mixing inside a digester today are: digester volume turnover time (DVTT), averaged velocity inside digester (v_{avg}), unit power (UP) and the normalised mixing intensity (G). According to Turovskiy and Mathai (2006), the desired ranges for theses mixing parameters in a

CSTR are a DVTT, UP and G in the ranges of 0.8 to 1.2 h, 5.2 to 7.9 W/m^3 and 50 to 85 s^{-1} respectively, all of which are determined experimentally.

The DVTT is a measure of the anticipated digester volume turnover time of the mixing system in hours and can is calculated by dividing the reactor volume (in m^3) by the mixing flow rate (in m^3/h). The UP is a power-to-volume ratio (in W/m^3) that is normally used to compare different mixing methods based on power consumption where the ratio is mixing power (in W) over the the volume of the reactor (in m^3). Normalised mixing intensity inside the reactor (G in s^{-1}) can be determined using equation 1 below, where μ is the dynamic viscosity of the sludge (in Pas).

$$G = \left(\frac{P_{mix}}{V\,\mu}\right)^{\frac{1}{2}} \qquad (1)$$

In more recent years, CFD simulations have been used to optimise the digester effective volume and to compare different mixing methods. One of the more recent studies on CSTR mixing systems, done by Wu (2010a), simulated mechanical draft tube mixing vs. the slurry recirculation mixing method. These results from Wu (2010a) indicated the following points to obtain the same average velocity in the reactor:

- Pumping upward through the draft tube was 30.7 % more efficient than pumping downwards
- The egg-shaped digester turned out to have a power saving of 55 % over the cylindrical digester
- The DVTT, UP and G of the cylindrical reactor were 0.4 h, 6.6 W/m^3 and 90 s^{-1} respectively, whereas those of the egg-shaped digester were 0.85 h, 2.97 W/m^3 and 65.5 s^{-1} at 0 % TS
- The mechanical draft tube had a power saving of 49.7 % with a UP of 2.4 W/m^3 and G of 58.89 s^{-1}, compared to the UP of 4.77 W/m^3 and G of 83.02 s^{-1} in the slurry recirculation method

Wu (2010b) continued his research by comparing a bubble column, gas diffusers, mechanical draft tube and the slurry recirculating method in a cylindrical digester using ANSYS Fluent 12.0. The result indicated that, at a TS content of 5.4 % and an average velocity in the reactor of 0.08 m/s, the mechanical draft tube was most efficient (0.52 h, 4.1 W/m^3, 71 s^{-1}). It was followed by the bubble column method, with a 29 % increase in UP (5 W/m^3, 78.4 s^{-1}) and then by the slurry recirculation method, with a 43 % increase in UP (5.9 W/m^3, 85.17 s^{-1}). The gas recirculation method using the gas diffusers was excluded due to insufficient mixing.

The effect of mixing on the biological enactment of a digester has also been noted by many researchers but the optimum intensity and intervals are a subject of much debate. From experimental work on a scale size digester, Stroot *et al.* (2001), Karim *et al.* (2005a), Karim *et al.* (2005b) and Kaparaju *et al.*, (2008) confirmed that an intermittent (2 hours on 2 hour rest) gentle mixing intensity lead to an increase in biogas production especially at increased total solid contents (TS) of 10% and Karim *et al.* (2005a) also proposed that the gas recirculation mixing method be used for large-scale digesters.

From experimental and numerical studies it indicated that mechanical daft tube mixing in an upwards direction was the most effective mixing method. The problem with all the mechanical rotating equipment used for mixing is clogging of the impellers due to the fibres in municipal sludge. In the case of devices such as horizontal paddle stirrers and slurry-recirculation pumps located inside the digester, these fibres lead to recurring maintenance of these devices and tedious downtime. The second most effective method for mixing was the gas recirculation bubble column, as proposed by Wu (2010b) and Kaparaju *et al.*, (2008).

2. Selection of mixing method

The application of two-phase flow to convey liquids has been used in industry for centuries and is known as an "airlift pump". The pump characteristics of an airlift pump have recently been studied by Kassab *et al.* (2009). The study was based on a numerical 1D steady state mass momentum balance model validated against experimental work conducted and published with the following results:

- As the SR ratio increases, the efficiency increases at a constant gas flow rate
- The maximum efficiency does not occur at the maximum flow rate
- The maximum efficiency of the pump was found to be in the slug or slug-churn flow regime

The studies concluded with Figure 2 obtained from the experimental work, which indicates the phase transitions with increasing air flow rate operating at a submersible ratio (SR) of 0.4, a length of 3.75 m and an internal diameter of 25.4 mm.

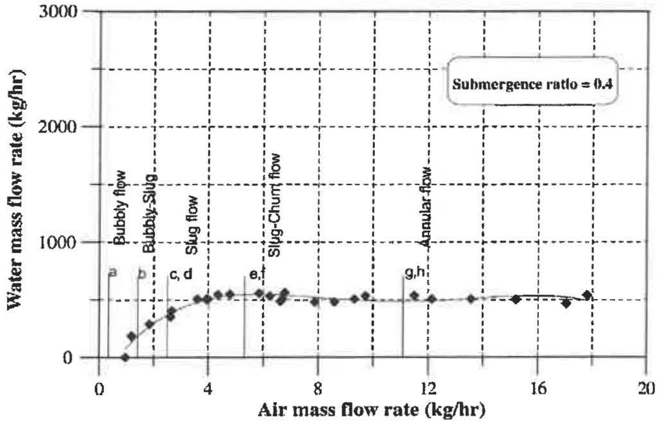


Figure 2: Airlift pump-phase transitions with water mass flow rate as a function of air flow rate (from Kassab *et al.* 2009)

In 2010, Karim *et al.* looked at improving the performance of an airlift pump even further using an increasing step geometry in draft tube. The study was based on a 3D eulerian–eulerian mass momentum balance model, assuming isothermal expansion. The results of the study were as follows: the maximum efficiency was found to be in the plug-flow regime, step geometry led to an increase in the efficiency but optimum step height needs to be determined.

In the case studies reviewed, it was found that the most effective mixing method was mechanical draft tube mixing in an upward direction. The problems with this method have been pointed out in terms of maintenance and the hazardous working environment due to biogas. The second most effective method, according to the comparative studies reviewed, was the gas recirculation bubble column, with a 29 % increase in UP to achieve the same DVTT. However from a review on airlift pumps it was found that the plug flow two-phase flow regime was more effective at conveying liquids, therefore, this method was selected.

3. Mixing Concept and Numerical model

The main design criteria set for the development of the mixing system for a CSTR in this study was: there should be no moving parts inside the digester, it should be able to operate at TS contents up to 10 %, the mixing rate must be adjustable and must be able to be unblocked without opening the digester.

A concept was drawn up using the confined gas recirculation in a plug flow regime mixing method. It consisted out of a gas accumulator referred to as a plug-flow generator, working on a series of chambers based on the U-tube principle at the bottom of the draft tube. The plug-flow generator was supplied with pressurised gas and which then releases the accumulated gas into the draft tube in a plug form and was also equipped with n pressurised water line with a set nozzle in the in the chambers to flush when it gets blocked. The flow diagram of the concept is illustrated in Figure 3 as well as an illustration of the plug-flow generator a) front and b) side section view.

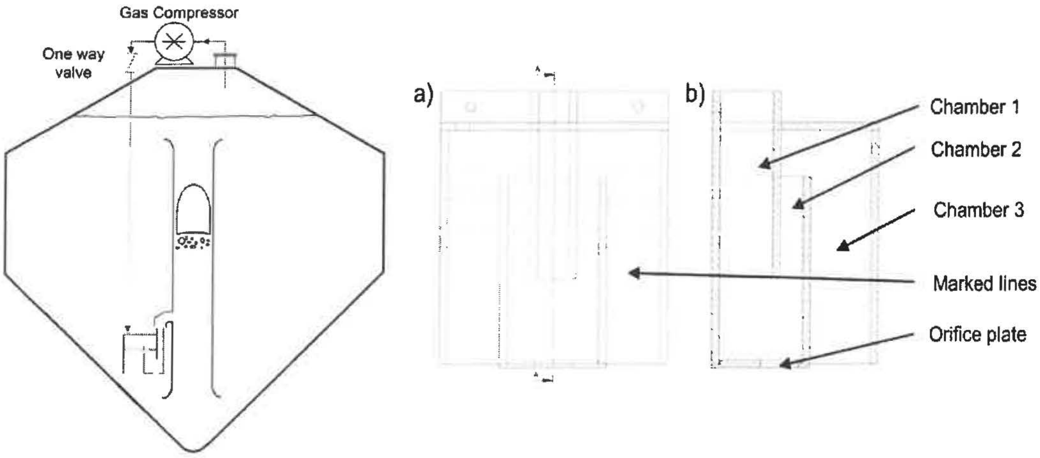


Figure 3: Confined gas recirculation plug-flow generator mixing system

Based on the selected mixing concept a numerical model was derived to capture the full cycle of the plug until motion in draft tube returns to rest. To capture this phenomenon a transient model is needed.

A review was conducted to look for a transient numerical model that could capture the cycle of the plug in the draft tube. The numerical models that were found that could possibly predict this phenomenon were, the transient 1D slug flow model on a Eularian grid base with a mass and momentum balance (De Henau & Raithby, 1994) and a transient 1D plug flow model on a Lagrangian grid base with a mass and momentum balance assuming incompressible flow (Kjeldbly, 2013).

From reviewing these models it became clear that most plug flow models are 1D mass momentum balance models with the following uncertainties; the liquid film thickness that surrounds the rising plug, the downward velocity of the liquid film and the interface shear stress between gas and liquid. A decision was made to construct a new model that would capture where the shear forces acting on the plug would be determined by experimental work in terms of a friction multiplier (FM). The model was limited to a 1D transient explicit mass and momentum balance model based on a Lagrangian grid with three control volumes to simplify the complexity of the two-phase flow. The assumptions made while constructing the numerical model were:

- Isothermal expansion of plug was assumed using the ideal gas law using the properties of air
- The instantaneous velocity of the liquid above the plug, the velocity of the plug and the velocity of the liquid below the plug were assumed to be the same
- A friction multiplier was used for the plug and the liquid below the plug
- The plug's initial velocity was taken as zero

With the assumptions made, the geometry of the draft tube was discretised into the three controlled volumes (namely L1 = liquid 1, P = plug and L2 = liquid 2 above plug) where the mass balance for the i'th controlled volume in the discretisation diagram was derived using equations 2 and 3 below: (2)

$$\frac{d}{dt}\int_{i}^{i+1} \rho \, dV = \int_{i}^{i+1} \rho v dA_x$$

$$\frac{d}{dt}\rho A_{x_i}\Delta z = \sum \rho v A_{x_i} - \sum \rho v A_{x_i} \tag{3}$$

where

$$A_{x_{L1,L2}} = 0.25\pi D^2 \tag{4}$$

$$A_{x_P} = 0.25\pi {D_{eq}}^2 \tag{5}$$

and the equivalent plug diameter D_{eq} is

$$D_{eq} = D - \%\delta \, D \tag{6}$$

The momentum balance for the i'th controlled volume was derived in equations 7 and 8 below:

$$\frac{d}{dt}\int_{i}^{i+1} \rho v \, dV = \int_{i}^{i+1} \rho v \, v \, dA_x - \int_{i}^{i+1} P \, dA_x - \int_{i}^{i+1} \rho g \, dV - \int_{i}^{i+1} \tau_w \, dA_z \tag{7}$$

$$\frac{d}{dt}\rho A_x \Delta z v = \sum \rho v v A_x + \sum \rho g h A_x - \rho g A_x \Delta z - \tau_w \pi d \Delta z \tag{8}$$

where the shear force, τ_i, for each i'th controlled volume is calculated by

$$\tau_i = \frac{1}{2}\lambda_i \rho v^2 \tag{9}$$

The friction factor, λ_i, for the i'th controlled volume is

$$\lambda_i = FM_i\, C_{f_i} \tag{10}$$

where the friction multiplayer, FM for control volume L1, was taken as

$$FM_{L1} = 1 \tag{11}$$

and the FM for control volume P and L2 as

$$FM_{P,L2} = e\hat{}(-0.18393(ln\, P_e)^8 + 4.93657) \tag{12}$$

The friction coefficient, C_f , for the plug in turbulent flow

$$C_{f_p} = 0.316{R_e}^{-0.25} \quad if \quad R_e > 2300 \tag{13}$$

The friction coefficient, C_f, for the controlled volume L1 and L2 in turbulent flow:

$$C_{f_{L1,2}} = 0.079{R_e}^{-0.25} \quad if \quad R_e > 2300 \tag{14}$$

The friction coefficient, C_f, for the i'th controlled volume in laminar flow:

$$C_{f_i} = \frac{64}{R_e} \qquad if \quad 1 > R_e < 2300 \tag{15}$$

$$C_{f_i} = 16 \qquad if \quad R_e < 1 \tag{16}$$

The plug ratio, P_e used was defined as height over diameter of plug;

$$P_e = \frac{z_p}{D_p} \tag{17}$$

Equations 2, 3, 7, 8 and 13 to 16 were obtained from White (2011) with the %δ in equation 6 taken as 5 %. Equations 9 to 11 were obtained from Kjeldbly *et al.* (2013) and equation 12 was obtained from the experimental work conducted that will be covered in the next section.

The full-scale base case mixing system for the numerical simulations geometrical construction consisted of a 13 m long draft tube with an internal diameter of 364 mm. The top clearance between the draft tube outlet and the liquid level was taken as 600 mm and the bottom clearance as 1.2 m both fitted with a Bell mouth, with an entrance and exit loss coefficient of 0.25 and 0.3 respectively. The plug inlet was placed 1.2 m above the inlet of the draft tube, with a plug ratio of 1.2P_e.

The base case numerical model was used to determine the effect of the plug frequency on the mass and mass flow rate displaced. The plug frequency in the simulations was varied between 0.019 Hz to 0.054 Hz for five consecutive cycles. A sample of the results obtained at a plug frequency of 0.048 Hz and a plug ratio of 1.2P_e is illustrated in Figure 4 below. The results of the rest of the plug frequencies were averaged and are plotted in Figure 5.

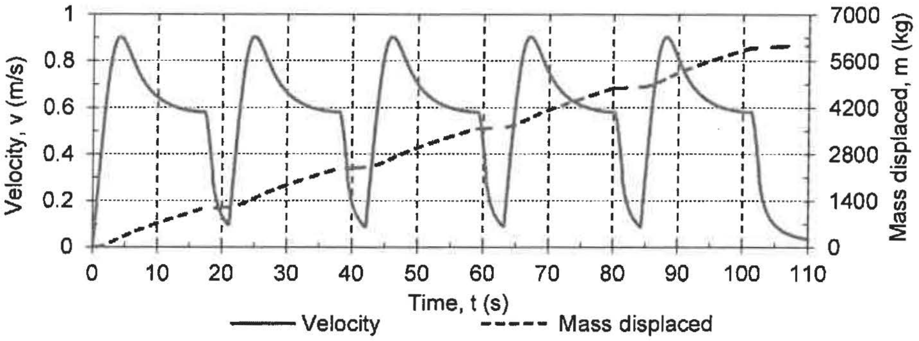


Figure 4: Velocity profile and the mass displaced over time of five cycles with a plug frequency of 0.048 Hz

The first cycle within the results illustrated in Figure 4 show that the velocity profile increased sharply from rest to 0.9 m/s after 4.2 s, and then started to decline at 0.33 m/s when the plug exited the draft tube at 17.28 s. From this point onwards, a sharp decrease in the velocity can be seen, with a long tail until the cycle ends and the next starts at 21.2. s. The results of the mass displaced on the secondary axis of Figure 4 show a steady increase in the mass displaced until the plug exits the draft tube. This is followed by a plateau in the trend for 1.32 s as the plug exits the draft tube, followed by the tail before the next plug is introduced.

The averaged results presented in Figure 5 indicate that an increase in plug frequency led to an increase in the averaged mass flow rate. The result of the mass displaced on the secondary axis shows a trend line that follows a parabolic shape, peaking at 0.025 Hz. At this frequency a plug was introduced just after the motion of the draft tube returned to rest.

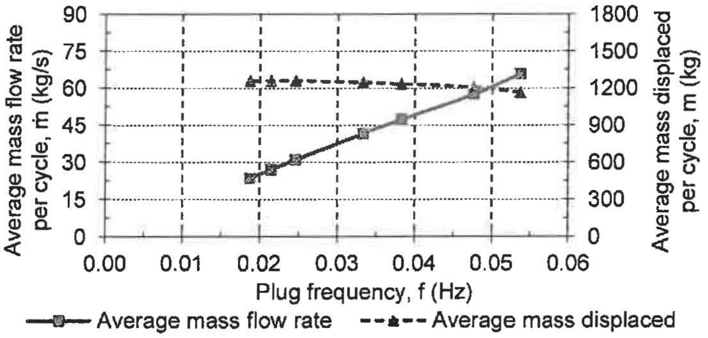


Figure 5: Effect of plug frequency on the average mass flow rate and average mass displaced per cycle

In the third set of simulations, a sensitivity analysis of the geometrical construction of the mixing system was conducted. The internal diameter of the draft tube was varied from 176 to 516 mm, the top clearance from 0.2 to 1.2 m, the bottom clearance from 0.6 to 2.2 m and the plug ratio from 0.7 to 1.4P_e. The results were normalised against the base case draft tube and given in Figure 6.

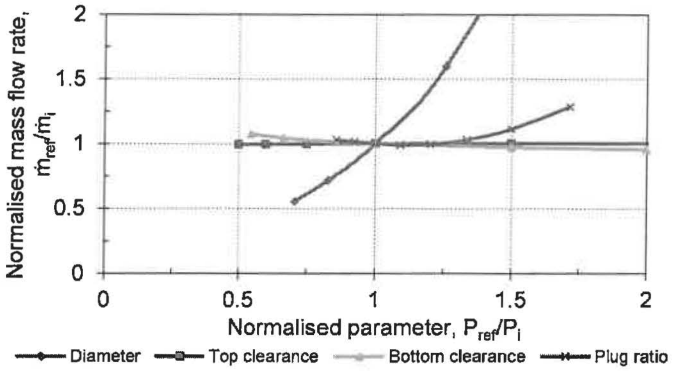


Figure 6: Sensitivity analysis of averaged mass flow rate of mixing system based on geometrical construction

Figure 6 illustrates that the diameter is the only parameter that has a major effect on the mixing system. The results also indicated that the plug ratio follows a parabolic trend and therefore an optimum plug size could be determined for a geometrical configuration to increase the mass flow rate of the mixing system.

4. Experimental work and Verification

The experimental work was broken into two different sections. In the first section, the focus was on the ability of the plug-flow generator to generate plug by varying the geometry, gas supply flow rate and hydrostatic pressure. In the second section, the focus was on obtaining the liquid mass displaced for a selected plug-flow generator at different gas supply flow rates and hydrostatic pressures. These results were also used to gather data to construct an explicit equation for the FM for the two-phase numerical model and to verify the numerical model.

For the first section, seven different geometrical variations of the plug-flow generators were built using Perspex sheets. The experimental setup used (illustrated in Figure 7) comprised out of a pressure regulator, a pressure vessel (10 L capacity) an air service unit, a rotameter from National Instrument's with a gas flow range of 0.05 to 2.5 Nm^3/h, a 1 500 L testing tank with inspection windows and a GoPro 3 Hero edition at a video setting of 100 frames per second.

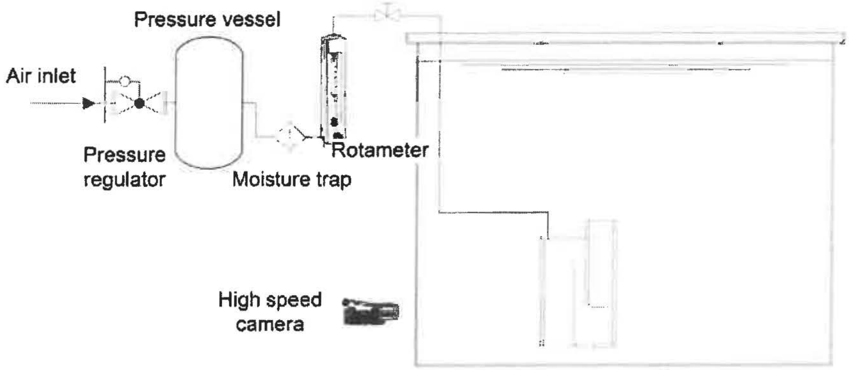


Figure 7: Experimental setup for effect of geometry, pressure and calibration

In the experimental work the air supply volume flow rate was recorded on the rotameter, the volume of the plug generated was determined from the video captured by the camera as well as the time interval between plugs. The volume of the plug generated was determine by etching 5 mm spaced lines on the plug flow generator and recoding the volume of accumulated air inside the known volume of the plug-flow generator and also after the plug was released.

A total of 252 data points were obtained on the volume, frequency and hydrostatic pressure of the different geometrical plug-flow generators. These data points were inserted in a multi-linear variable regression model using the Microsoft Excel ANOVA model to obtain a mathematical relationship. The multi-linear variable regression model indicated that a change in hydrostatic pressure has a negligibly small effect and was eliminated. The empirical equations obtained for the mass of the plug generated and the plug frequency based on the geometry are presented in equation 18 and 19 below.

$$m_p = 232.974 \times 10^{-6}\dot{m}_{air} - 1.089A_{or} + 84.318V_2 + 821.712 \times 10^{-3}V_3$$
$$-3.2A_1 - 8.308A_2 - 1.943 \times 10^{-3} \qquad \mathrm{R}^2 = 0.9085 \qquad (18)$$
$$f = e\hat{}(1.107\, ln\, \dot{m}_{air} - 892.263 \times 10^{-3}\, ln\, m_p - 7.653) \qquad \mathrm{R}^2 = 0.9894 \qquad (19)$$

where $\dot{m}_{air}$ is the mass flow rate of the air supply rate in kg/h, A_{or} is the area of the orifice in m^2, V_2 is the active volume of chamber 2 in m^3, V_3 is the active volume of chamber 3 in m^3, A_1 is the area of chamber 1 and A_2 the area of chamber 2 in m^2.

The accuracy of empirical equation 18 and 19 were determined by plotting the predicted and measured data points against each other and includes a percentage deviation envelope on the figures. A percentage uncertainty of ± 20 % where obtained for equation 18 with an R^2 of 0.9098 and an uncertainty of ± 15 % with an R^2 of 0.9894 for equation 19 were obtained.

In the second set of experiments the liquid mass displaced for a selected plug-flow generator at different gas supply flow rates and hydrostatic pressures where investigated. The experimental setup used was the same as used previously, only this time the following were added: a draft tube, a container to capture liquid displaced, a liquid outlet line, a beaker and an electronic scale which can be seen in Figure 8.

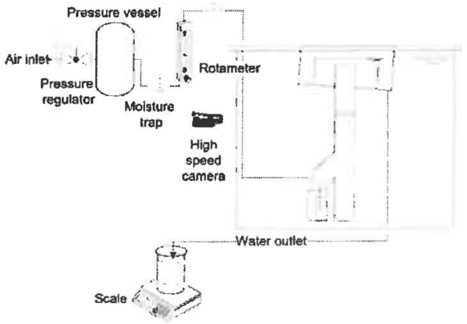


Figure 8: Experimental setup used to measure liquid mass displaced

The draft tube made of 100 mm (internal diameter) Perspex tubing was installed vertically with its outlet 1D from the surface of the water level and its bottom inlet 1D from the floor tank. A plug inlet was added to the draft tube 210 mm from the bottom inlet and the plug-flow generator was installed 10 mm below the plug inlet of the draft tube. The container separated the air from the liquid displaces out of the top of the daft tube and conveyed it in to a beaker on electronic scale with an accuracy up to 1 x10^{-3} kg.

For the test work, only a single plug generator was used, but the liquid level was varied from 0.7 m, 0.85 m and then to 1 m above the plug-flow generator, with the draft tube ending each time1D below the liquid level.

The experimental results illustrated in Figure 10 indicated that the increase in hydrostatic pressure on the mixing system leads to an increase in the amount of water displaced. The averaged mass flow rates per cycle calculated from the results are displayed in Figure below and illustrates that an increase in hydrostatic pressure on the mixing system leads to an increase in mass flow rate displaced from the top of the draft tube.

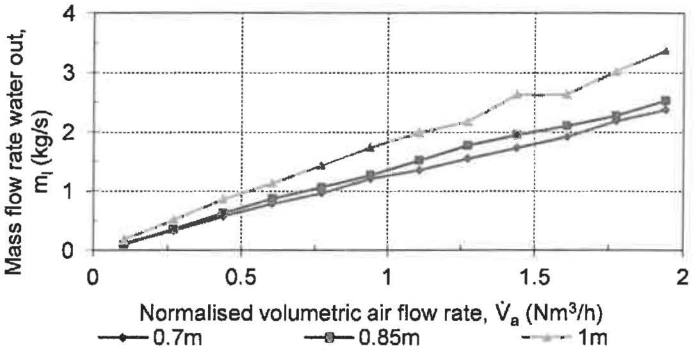


Figure 9: Liquid mass flow rate displaced at different hydrostatic pressures as a function of air flow rate using plug-flow generator 1.1.1 with an orifice area of 415 x10^{-6} m^2

The results show that a 21 % increase in hydrostatic pressure leads to an average of 7 % increase in mass flow, where a 43 % increase in hydrostatic pressure leads to an average 45 % increase in mass flow.

The data obtained from the second set of experimental work was used to determine the friction multiplier (FM) for the 1D numerical two-phase flow model and also to validate it. In Kjeldbly *et al.* (2013) work the FM was set at 100, but was not related to a parameter. In this study, an investigation was conducted to relate the FM to a parameter that will enable one to sale the experimental work to a full-scale prototype. A relationship between plug size and mass displaced by the draft tube was found and a multi-linear regression model was used again to determine the mathematical relationship. The empirical equation obtained are presented below and its accuracy was determined by plotting calculated FM against the predicted FM data points and all fell well with in a ± 15 % accuracy envelope and a R^2 of 0.943 was obtained.

$$FM = e\text{^}(-0.18393(ln\, P_e)^8 + 4.93657) \qquad R^2 = 0.943 \qquad (20)$$

The numerical model with the FM was then used to predict the measured liquid displaced by the mixing system to validate the model. The numerical results as well as the experimental results were plotted on the same axis in Figure 10 below where numerical results were plotted as a hashed line series and experimental results as a solid line series.

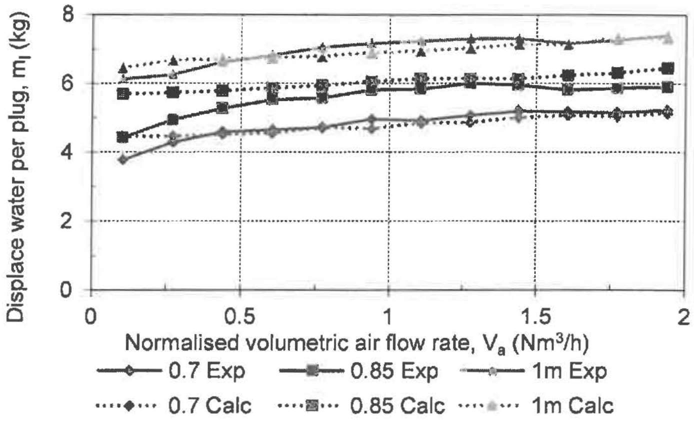


Figure 10: Measured and calculated liquid displaced as a function of normalised volumetric flow rate at different liquid depths

The results in the figure illustrate that the only points that the numerical model were not capable of capturing were the initial points at an air flow rate from 0.104 up to 0.438 Nm^3/h. Volumetric air flow rates greater than 0.438 Nm^3/h were predicted within the ± 5 % accuracy envelope if the FM was smaller than 123.7.

5. Analysis and Proposed Design

To quantify the required amount of mixing needed to keep the different types of microorganisms in the digester healthy and to eliminate the formation of dead zones, the mixing parameters were used. For this work, the DVTT was used to calculate the volume flow rate required to mix the digester and the UP and G were calculated from the DVTT. The DVTT was taken as one hour and the volume of the digester as 1 600 m^3, the required volume flow rate required was 1 600 m^3/h. This is quite a large flow rate compared to the results obtained from the base case simulated.

5.1. Draft tube

From the raw data of the sensitivity analysis it can be calculated that the averaged mass flow rate by a 518 mm draft tube is 55.7 kg/s at 0.021 Hz and a plug ratio of $1.2P_e$. With this mass flow rate, a total of eight draft tubes are needed operating at a plug frequency of 0.021 Hz for the mixing system to comply with the DVTT. The number of draft tubes can be decreased by increasing the plug frequency and selecting the correct plug size for the draft tube.

To determine the number of draft tubes needed for the mixing system, the geometry of each of the draft tubes first needed to be selected followed by the plug size and the plug frequency. The top clearance of the selected draft tubes was taken as 1D below the liquid level in the 1 600 m^3 digester. The bottom clearance for the middle draft tube was selected to be 2D and the side dart tune to be 1D from the bottom of the digester as it is located on an incline. This resulted in a 12.7 m middle and a 10.38 m side draft tubes.

These selected dimensions of each draft tube were used in the numerical model to simulate the effect of the different plug sizes on both of the selected draft tube arrangements for a single plug cycle and the summarised results are illustrated in Figure 11 below.

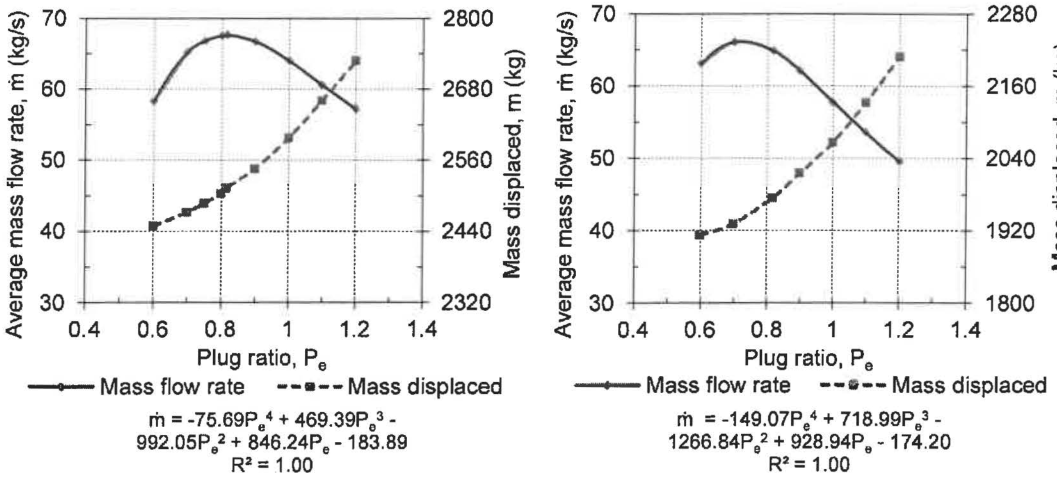


Figure 11: Effect of plug size on the average mass flow rate and mass displaced per cycle by the a) middle draft tube and b) side draft tube proposed

The results above illustrate that an optimum plug size can be determined to increase the mass flow rate. Parabolic trend lines were placed through each of the results in the figures and the calculated plug size for the middle draft tube came to 0.818P_e and 0.724P_e for the side. With these plug sizes for the selective draft tubes known, the numerical model was used to determine the average mass flow rate per cycle at increased plug frequencies and are summarised in Figure

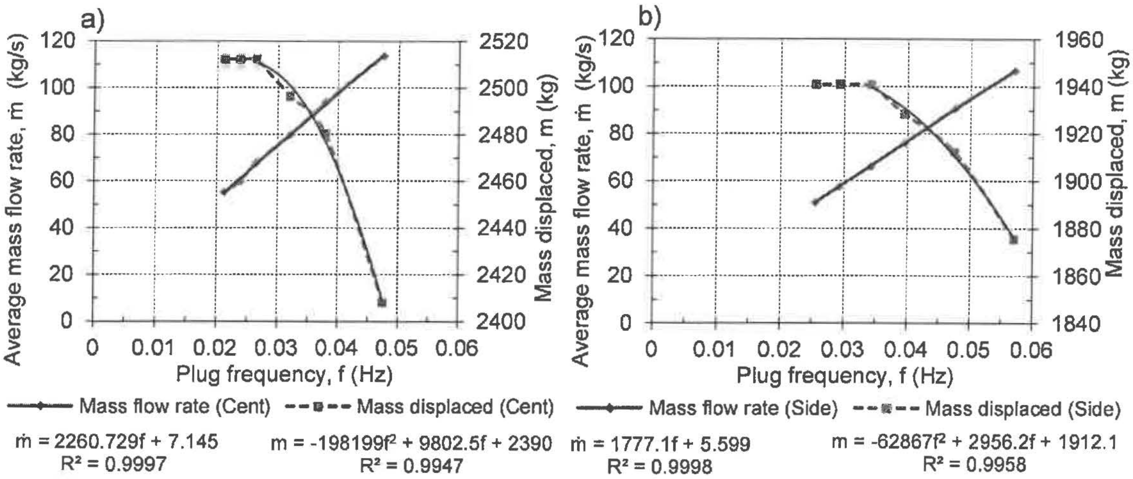


Figure 12: Effect of plug frequency on average mass flow rate and mass displaced for the a) middle draft tube with a plug size of $0.818P_e$ and b) side draft tube a plug size of $0.724P_e$

From the results at increased plug frequencies for the selected draft tubes the highest operating point for the draft tubes were selected to be as the initial plug exits at the top the next is injected. Thus, for the middle daft tube, the highest and lowest operating point was at 0.0264 Hz and 0.047 Hz and for the side draft tube was selected to be between 0.034 Hz 0.057 Hz. It should be noted that the draft tube could be operated outside these selected operating rages, but the numerical model was only validated to predict a single plug rising in the draft tube.

With these selected operating ranges for the selective draft tubes known, the number of draft tubes were calculated. With four draft tubes it was possible to achieve a DVTT of one hour but with all four of the draft tubes running at full capacity. With five draft tubes it is possible to achieve a DVTT as low as 0.82 h when running it at full capacity, but five draft tubes can achieve a DVTT of one hour running only at 50 % capacity. The decision on the number of draft tubes for the proposed design will be based on a difference in volumetric gas flow rate which will ultimately relate to power consumption of the mixing system.

The volumetric gas flow rate required for the draft tubes to operate in the selected operating range was determined with Equation 19. The calculated difference between four and five draft tubes at a DVTT of one hour was only 1.12 % increase in volumetric gas flow rate where five draft tubes required 64.852 Nm^3/h. Based on this results a decision was made to select five draft tubes for the proposed mixing system.

To determine the power consumption of the mixing system an Elmo Rietschle 2BV2 071 liquid ring compressor was selected and from its respective pump curves it was calculated that 3.86 kW was required to compress 65.708 Nm^3/h (additional 5 % for leakage) to a delivery pressure of 1.77 bar gauge pressure. With the DVTT and power consumption known the UP and G of the proposed mixing system was calculated and plotted as a function of DVTT Figure below.

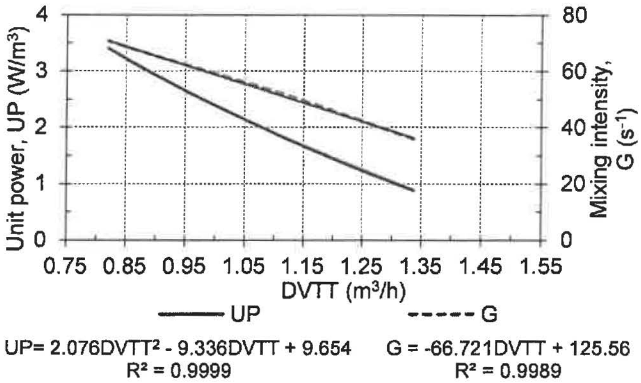


Figure 13: Unit power and mixing intensity of the proposed mixing system as a function of DVTT

When the proposed design was compared to mechanical draft tube simulated by Binix (2010a) with both mixing systems operating in egg-shaped digesters and in water; the mechanical draft tube archived effective mixing at a DVTT, UP and G of 0.85 h 2.97 W/m^3 and 65.5 s^{-1} respectively, where the proposed design obtains a UP and G of 3.22 W/m^3 and 68.84 s^{-1} respectively, at the same DVTT of 0.85 h. This shows that the proposed design requires only a 7 % increases in terms of power consumption per unit volume compared to the mechanical draft tube to achieve the same DVTT at almost the same G at 0 % TS contents.

5.2. Plug-flow generator

To develop the plug generators for the two selected draft tubes in the proposed design, the operating depth, plug size and mass flow rate of the gas supplied to the selective plug-flow generator had to be known. As all of the above-mentioned parameters for the plug-flow generators were calculated the geometrical construction of the two plug generators could be calculated with Equation 18.

By using this equation to determine the geometrical construction of the two plug-flow generators a number of solutions could be found, some of which might not necessarily work. To avoid this situation, the dimensions of an experimental plug-flow generator were used as a reference case and converted into geometrical ratios. The geometrical ratios were inserted as constraints to a GRG nonlinear solver in Microsoft Excel to calculate the dimensions of the plug-flow generators for the proposed design. The dimensions are tabulated in Table 1.

Table 1: Proposed plug generators dimentions

Dimensions	Units	Middle	Side
Length of camber 1	mm	54.69	50.34
Length of camber 2	mm	118.38	108.96
Length of camber 3	mm	287.77	287.77
Width of camber 1	mm	54.69	50.34
Width of camber 2	mm	118.38	108.96
Width of camber 3	mm	400.00	400.00
Height of camber 1	mm	271.33	253.36
Height of camber 2	mm	271.33	253.36
Height of camber 3	mm	431.65	431.65
Diameter of Orifice	mm	48.21	44.38

6. Discussion and Conclusion

Anaerobic digestion is a complex multi-biological degrading process that is also influenced by different environmental and process operating factors and can either enhance the deration or inhibit process and gas production.

Mixing is one of the important process-operating factors, noted by several researchers, which enhance the digesters performance on the biological and effective digester volume side have investigated its effects.

The main design criteria set for the development of the mixing system for a CSTR in this study was, that there should be no moving parts inside the digester, should be able to operate in TS contents up to 10 % and mixing rate must be adjustable. Based on the design criteria and limitations set for the mixing system a concept was drawn up using the confined gas recirculation in a plug flow regime mixing method.

With the mixing system selected, the next objective was to develop a one-dimensional, transient two-phase flow numerical model that was able to predict the liquid mass displaced by the draft tube for a defined plug size. The numerical model was used to predict the effect of plug frequency and to conduct a sensitivity study on the geometry of construction of the mixing system on mass displaced and averaged mass flow rate of the plug cycle. The results indicated that the only major parameter of the geometrical construction affecting the performance was the draft tube diameter and that the plug size can be optimized for a draft tube diameter to increase the mass flow rate of liquid displaced.

An experimental study followed where a scale model was constructed with the objective to capture the effect geometrical construction of the plug-flow generator has on the formation of the plug volume released. Two empirical correlations were obtained using multi-linear regression that capture the mass of plug released as well as the plug frequency at which the plug is released based on the geometrical construction of the plug-flow and gas supply flow rate. The experimental results were also used to define an empirical correlation for the friction multiplier for the numerical model and to validate the numerical model against the experimental results and indicated that the numerical model could predict the experimental results within ± 5 % accuracy if the FM is smaller than 123.7.

The validated numerical model, sensitivity study and the experimental work were used to develop a mixing system for a continuous stirred digester. With the diameter of the mixing system limited to 518 mm operating at 0.021 Hz and a plug ratio of $1.2P_e$ a total of eight draft tubes were needed to achieve a DVTT of 1 hour. To reduce the number of draft tubes the plug frequency can be increased the optimum plug size can be calculated to increase the mass flow rate of draft tubes.

The optimum plug size, operating frequency of the draft tubes and volumetric gas flow rate of four and five draft tubes where determined. Based on these results a gas recirculation mixing system consisting out of five draft tubes were selected as it only requires a 1.12 % increase in volumetric gas flow rate compared to four draft tubes, but it was able to achieve a DVTT as low as 0.82 h when running it at full capacity.

When the proposed design was compared to the mechanical draft tube at the same digester volume turn over time, the proposed design required 7 % more power per unit volume at 0 % total solid content. The proposed design however provides additional advantages over the mechanical draft tube, as all the mechanical equipment of the systems is located outside the digester and the proposed mixing system can be flushed with pressurised water if it gets blocked. Using the proposed design also eliminates the reduction in biogas production rate when the digester is opened for maintenance and exposed to air.

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