Multiphase modeling to evaluate and to improve mixing in the Chinese dome digester

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Abstract

Household or domestic biogas plants constitute a growing sub-sector of the anaerobic digestion industry worldwide, but had received low research attention for improvements. The Chinese dome digester (CDD), a major type of domestic biogas plant, is a naturally mixed, unheated and low tech system that is mainly used in rural areas.
In this study, a multiphase computational fluid dynamics (CFD) model was applied to evaluate and subsequently improve mixing in a lab scale Chinese dome digester. The normal Chinese dome digester (CDD1) and two baffle configurations were investigated to improve the hydraulic mixing in the digester (CDD2 and CDD3 respectively) . 2-D time dependent numerical simulations were done with the three-phase, phase field model in COMSOL Multiphysics in a CDD geometry.
Residence time distribution (RTD) curves were derived for all the configurations to evaluate and compare performances. In addition, three hydraulic indicators were also studied to evaluate mixing improvement. The Anaerobic digestion model No. 1 (ADM1) was used to evaluate biogas production. The effects of the addition of baffles to the CDDs did not significantly improve mixing, however about 16 % of dead zones was reduced in the two-baffle configuration.

Keywords
Mixing, Chinese dome digester (CDD), computational fluid dynamics (CFD), residence time distribution (RTD),

INTRODUCTION

Sufficient research effort has been made on substrates and large scale systems in the anaerobic digestion industry, but little effort has been put into studying household digesters especially the Chinese dome digester (CDD). Household digesters are non-mechanically (naturally) mixed and non-heated systems used mainly in the rural areas (Qi et al., 2013). Millions of these systems have been built around the world but lack proper evaluation for optimization and standardization especially with respect to mixing. Mixing is an important process in AD for i.e. establishing contact between micro-organisms and feed and for homogenization of temperature throughout the digester (Deubien and Steinhanuser, 2008)

Computational fluid dynamics (CFD) is an important tool to study velocity contours, particle trajectories and dead zones in anaerobic digesters which are all important parameters in studying mixing. CFD tools focus on fluid dynamics and is not connected to the biochemical process in anaerobic digestion. A major advantage of CFD modelling of anaerobic systems is the presentation of visual results which aids system analysis. Flow fields can be seen as well as the flow direction and velocities (Lindmark et al., 2014). To the best of our knowledge no study exists till date on evaluating mixing in Chinese dome digesters using CFD. In this study, therefore CFD was used to study the hydraulic characteristics of Chinese dome digester viz. feeding, biogas production and gas use. Biogas production was estimated using anaerobic digestion model (ADM)1 and later coupled with the CFD models.

Process description

A three phase 2-D multiphase model was developed for the Chinese dome digester. The three phases are solids, liquid and gas representing solid manure, liquid manure and biogas. The physical characteristics of the phases are given in Table 1. The Chinese dome digester is a hydraulic mixed reactor without any mechanical or internal mixer. The reactor is mixed when new feed is added, during biogas production and biogas use. The three processes are modelled and simulated separately in this study. Apart from the original geometry, two proposed designs were simulated for mixing optimization viz. the addition of two and four baffles as seen in Figures 1.a, b & c.

MATERIALS AND METHODS

Multiphase simulations were done using COMSOL Multiphysics software for the normal (CDD1) and two optimized baffled Chinese dome digesters (CDD 2 and CDD3). These CFD models are based on the mass conservation equation and the Naivier-Stokes equations of motion and the flow in the reactors is laminar. The simulations were done in two stages. First, the three-phase field model was used to solve for the velocity and pressure profile, then the transport of diluted species was modelled to determine the residence time distribution (RTD) viz. solute concentrations at the reactors outlets.

The F curve of the tracer concentration was estimated using equation 1.

$$F(t) = \frac{C_{out}(t)}{\sum_{i=1}^{n} C_{out-i}} \qquad (1)$$

The residence time distribution (RTD) function and the mean residence time were estimated using equations 2 and 3.

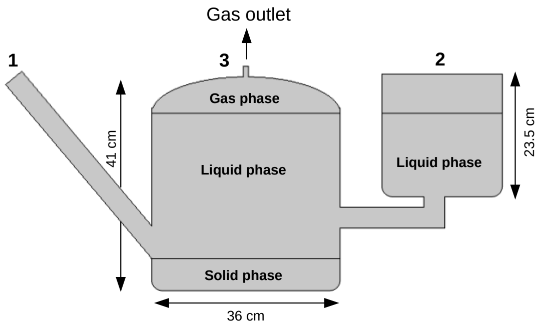
$$E(t) = \frac{dF(t)}{dt} \qquad (2)$$

$$Tres = \int_0^{\infty} t\, E(t)dt \qquad (3)$$

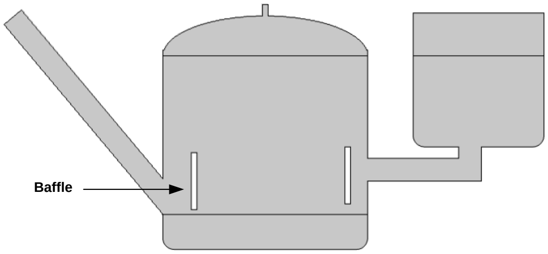
Table 1. Characteristics of phases

Phase	Density(kg/m3)	Viscosity (kg/m s)
Solid	1500	0.99
Liquid	1000	0.001002
Gas	1.139	0.000019

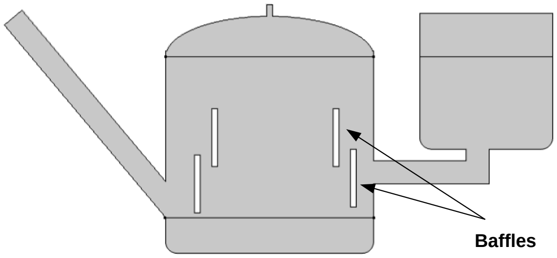
Furthermore, the hydraulic indicators Θ_{10}, Θ_{90} and Morill index (MI = Θ_{90}/Θ_{10}) were determined for each of the reactors, representing the dimensionless time for 10% and 90% of the tracer to reach the outlet and the spread between the two. Figure 1a shows the original geometry of the lab reactor with dimensions. The geometry was modified by changing the number of baffles and positions to compare their flow and concentration fields. Figures 1b and 1c show the proposed optimized 1 and 2 models. Three simulations were performed for each geometry. The three simulation schemes are feeding, biogas production and gas use. The runs and boundary conditions for the performed simulations are given in Table2. The inlet and outlet boundary conditions for the feeding simulations are points 1 and 2. A mean residence time of 23 days, obtained from a laboratory experiment (Jegede et al., in preparation), was applied in the model.



1a. Normal Design



1b. Optimized design 1



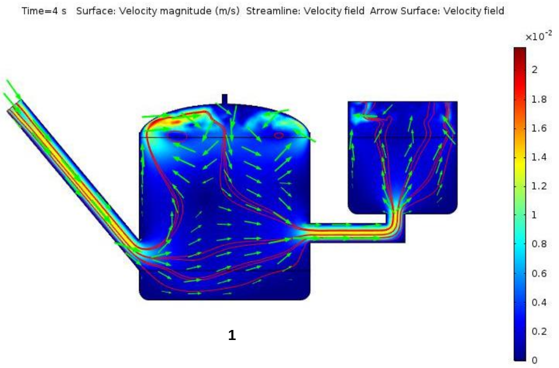
1c. Optimized design 2

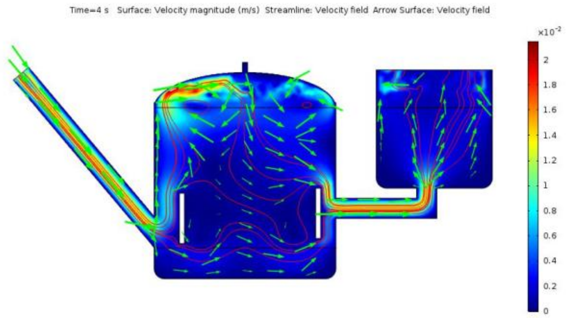
Table 2: Boundary conditions

Boundary conditions	Feeding	biogas production	Biogas use
inlet	point 1, inlet velocity, 0.01 m/s	point 3, Pressure 101660	points 1 & 2, pressure 500 & 1000 Pa
outlet	point 2, Pressure 0 Pa	points 1 &2, pressure 1013250	point 3, 0 Pa

RESULTS AND DISCUSSION

Experimental residence time was estimated as 507s viz by converting 23 days to dimensionless time from laboratory RTD experiments. Hydraulic efficiency indicators obtained are shown in Table 3 and all indicators are within the range of acceptable and compromising performances.





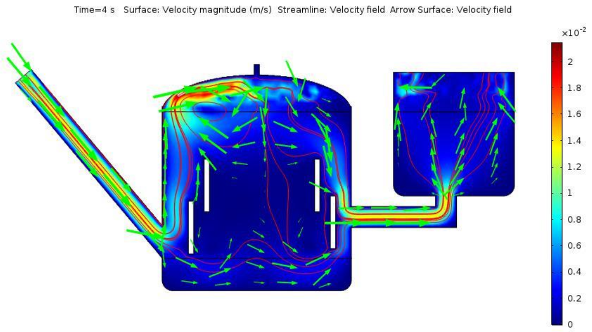


Figure 2. Velocity magnitude and vectors direction for all the geometries during the feeding regime simulations

Figures 2 show the velocity profiles and direction of all the geometries for the feeding regime simulations. The

Table 3. Hydraulic efficiency indicators

indicator	Normal	Optimized 1	Optimized 2
ϴ10	0.59	0.61	0.55
ϴ90	3.54	2.62	2.70
MI	6.03	4.32	4.88

Figure 3 shows the distribution over time of the tracer concentration at the outlets of the reactors. The peak values of tracer concentration were achieved at 302, 368 and 354 s for the normal, optimized 1 and optimized 2 reactors. The T_{res} are 800, 695 and 558s for normal (CDD1), optimized 1 (CDD2) and optimized 2 (CDD3) reactors respectively. The mean residence time from the simulations are larger than the applied theoretical residence time for normal and optimized 1 reactors, but much closer to optimized reactor 2. These implies that the normal reactor has a much higher dead volume compared to the other two. The mean residence time (507s) obtained in the laboratory experiment is not comparable to the simulation results (800 s) in the original geometry. Therefore, the tracer simulation studies will not be sufficient for evaluating the hydraulic characteristics of the Chinese and optimized reactors. In fact, in real life application, the feeding of the reactor is not continuous and the reactor is not mixed via feeding only but also, through biogas production and gas use (change of pressure).

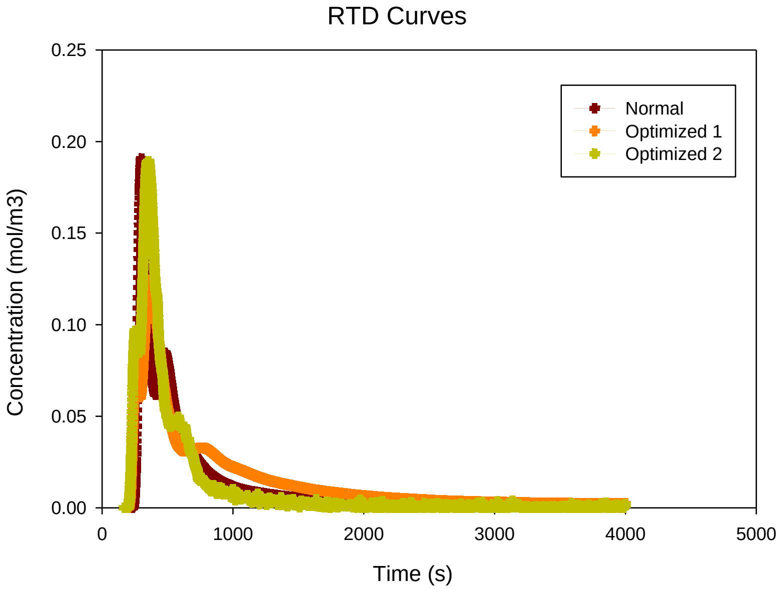


Figure 3. RTD curves of simulated geometries

Table 4 shows the estimated dead zones for regions of low velocities for all simulations. The region with low velocities were determined as 25% of the maximum velocities recorded for each case. Optimized 1 geometry has the lowest dead zone and more active volume compared to others. There are no additional benefits of increasing the number of baffles in the reactor as seen in the optimized 2 design. The percentage of dead volume in the laboratory experiment was shown to be 22 % (Jegede et al , in preparation) and much lower than the simulated results of 69% in the original geometry. In addition, despite the addition of baffles for optimization the percent of dead volume is still considerably high, almost 50 %.

Table 4. Estimated dead zones using simulated velocity profiles

Geometry	Feeding (%)	Biogas production (%)	Biogas use (%)	Total (%)
Normal	67	70	69	69
Optimized 1	50	55	53	53
Optimized 2	55	48	51	51

CONCLUSION

The optimization of the Chinese dome digester viz. the inclusion of baffles improved mixing slightly in the reactor because the percent of dead zone still remains significantly high.

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