Design and CFD Numerical model of biogas digestion plant of Biomass Blending

Engr. Nnadikwe Johnson[1], Engr. Ewelike Asterius[2], Dr. Ume Cyril Sunday[3], Okereke Godson[4]

1. H.O.D in Department of Petroleum and Gas Engineering, Imo State University, Nigeria
2. H.O.D in Agricultural Engineering, Imo State University, Nigeria
3. H.O.D in Chemical Engineering Department, Alex Ekwueme Federal University, Ebonyi State, Nigeria
4. Lecturer in department of Building, Federal University of Technology Owerri, Imo State, Nigeria

ABSTRACT

The three main goals for future energy systems are reduced greenhouse gas emissions, more renewable energy, and enhanced energy efficiency. Biogas production via biodegradation and anaerobic digestion is a popular bioenergy method for producing biofuels and managing industrial and home organic waste. Proper mixing of the organic mass is required in biogas production to generate high biogas outputs by bacteria and enzymes. According to assessments of biogas plant electric power consumption, the electrical energy need of the stirrer system accounts for a considerable portion of the whole electricity consumption of a biogas plant. As a result, laboratory prototypes and computational simulations may be beneficial for analyzing and improving the efficiency of mixing systems. This research demonstrates how a computational fluid dynamics (CFD) model can be used to commercial stirring devices. Two propeller stirrers in diametrically opposed orientations are detailed in a tank filled with approximately 1400 m3 of substrate. The fluid rheology is altered to a biomass with a dry matter concentration of 12 wt% and a non-Newtonian generalized Ostwald-de Waele power law for the simulation. The suggested modeling approach takes into account the rotation angle and height of each propeller. The technological benefit of 441 mixing setups is computed and evaluated. The findings reveal that rotor positions far from the bottom, as well as significant rotational angles, provide beneficial fluid dynamics.

Keywords: *Biogas plant, Biomass, organic waste, energy*

Nomenclature		
v_m	Flow velocity in the digester	m/s
v_i	Flow velocity in the *i*-component	m/s
α	Side angle, horizontal, (x-y) plane, anticlockwise	degree
h	Height of the mixer in the digester	m
τ	Technical benefit parameter	%
φ	Degree of fulfilment	–
W	Weight of each criterion	–

1. INTRODUCTION

Optimizing the mixing system is one of the most promising technological options for increasing the efficiency of biogas production via anaerobic digestion [1]. According to cost-benefit assessments [2–4], mixing is the largest contributor to overall energy demand in biogas facilities. To improve total biogas plant efficiency, this parasitic contribution must be decreased, and innovative mixing regimes (i.e. spatial and operational arrangements of agitators) must be researched [5]. To examine mixing in fluid dynamics, laboratory scale experiments and computational simulations appear to be helpful and successful methodologies [6], [7].

Computational fluid dynamics (CFD) can be used to model the mixing processes in anaerobic digesters [8]. A plethora of simulation models have been presented in recent years. [9–13] provide an up-to-date overview of the use of CFD for bioreactor analysis. Valid specifications of the digester tank, stirrers, and initial and boundary initial conditions are necessary to provide reliable model generation. An experimental validation is required, as is the case with any mathematical model [14].

The current research is being carried out in collaboration with UTS products GmbH, a leading German manufacturer of biogas plant components such as mixing systems and pumps. The collaboration will enable the creation of a CFD-based digester model that takes into consideration the geometry of commercial mixing systems often used in the biogas industry, allowing simulation results to be compared to the performance of commercial facilities.

In this paper, a mathematical model with numerous geometric configurations and mixing systems is developed in order to determine the ideal conditions for improving mixing quality efficiency. Using the CD-Adapco Siemens StarCCM+ application, the Ostwald-De Waele technique is utilized to construct three-dimensional geometries, produce meshes, and solve fluid dynamics. To validate the model, it was first used to mimic mixing in small experimental digesters [7], [15]. The laboratory digester was built out of acryl glass and filled with an aqueous cellulose mixture that matched the rheology of the substrate [16]. The mixing was assessed using the fluid velocity as a characteristic parameter [17–19].

The methodological approach is briefly outlined in the opening section of this work. The findings for one mixing system in 441 potential configurations are then discussed using the newly constructed full-scale digester model. For real-world structures, CFD simulations provide another tool to the planning toolbox. They do, in fact, decrease the requirement for costly post-construction field tests [20–23].

2. METHOD AND PROCEDURE IN A SCALED-DOWN LABORATORY DIGESTER

2.1. Methods of Mixing in Scaled-Down Laboratory Digester

To take use of the material's transparent thermoplastic features, the mixing behavior was investigated in a cylindrical tank made of polyethylene (methylmethacrylate). The tank had a diameter of 1.5 meters, a height of 0.7 meters, and a wall thickness of 15 millimeters. To acquire roughly 800 l of liquid, the tank was filled to a liquid depth of 46 cm. The three varieties of agitators tested in the lab were RW-L, a propeller with three rounded blades and a diameter of 7.5 cm; PW-L, a propeller with three pointed blades and a diameter of 12.5 cm; and RP-L, a paddle with four rectangular plates of 4.57 cm dimension.

The letter L is still used to differentiate the current scale-down agitators from the real-scale agitators described in the following paragraphs.

(a) (b) (c)

Fig. 1. Typology of the agitators: (a) propeller with three rounded blades and Ø = 7.5 cm, called RW-L; (b) propeller with three pointed blades and Ø = 12.5 cm, called PW-L; (c) paddle with four rectangular plates of 4.5·7 cm dimension, called RP-L.

The experimental tank was used to replicate the digesters of full-scale biogas plants. It's a prototype for studying the mixing process on a smaller scale in order to make commercial digester investigations easier.

In the laboratory digester, three example mixing configurations consisting of two agitators situated diametrically opposite each other are examined. As seen in Fig. 2, the layouts exhibit the following characteristics:

- − M-1 includes a pointed blade propeller (PW) and a rounded blade propeller (RW) (Fig. 2(a));
- − M-2 includes two pointed blades propellers (PW) (Fig. 2(b));
- − M-3 includes a pointed blade propeller (PW) and a paddle system (RP) (Fig. 2(c)). A detailed description of the mixing configurations is presented in [19].

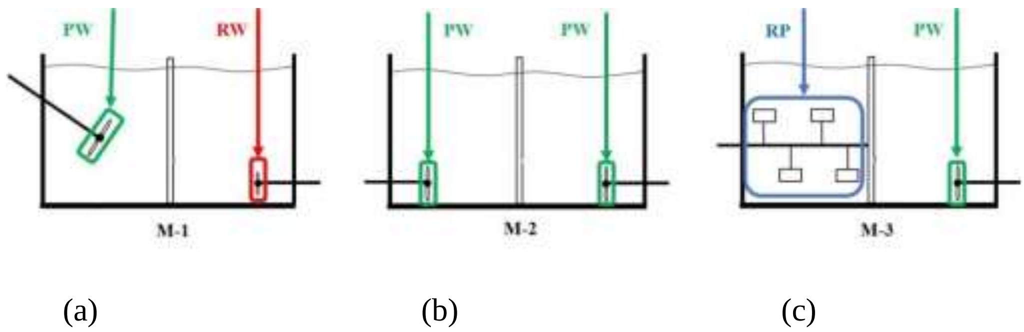


Fig. 2. Mixing configurations investigated in the laboratory digester: (a) M-1 includes a pointed blade propeller (PW) and a rounded blade propeller (RW); (b) M-2 includes two pointed blades propellers (PW); (c) M-3 includes a pointed blades propeller (PW) and a paddle system (RP).

In the laboratory digester, the biomass substrate was replaced with a water-cellulose solution to ensure clarity and ease of handling. A sodium carboxymethyl cellulose concentration of 0.3 wt percent was chosen to attain rheological characteristics comparable to genuine biomass [16]. The chosen 0.3 wt% water-cellulose solution has representative flow characteristics at room temperature, including an Ostwald-de Waele power-law behavior, non-Newtonian characteristics, a consistency factor of 0.05 Pasm–1, a flow index of 0.35, and a dynamic viscosity of 14 mPas at a shear rate of 7 s–1.
The fluid velocity in different regions of the laboratory tank was measured and evaluated to explore the mixing process. An acoustic velocimeter based on the Doppler Effect and a particle image velocimetry (PIV) spectrometer based on the photoexcitation of seeding particles were used to map the fluid velocity throughout the entire volume. More information on the velocity readings can be found in [19], [24].

As a result, fluid dynamics are exceedingly complicated, with turbulent flows characterized by some fluid motion patterns and laminar flow regimes characterized by others, as well as the creation of vortexes and dead zones [25], [26]. xyz is a made-up character. In the Cartesian coordinate system, the x-y plane was formed coincident with the tank's base, the x- and y-axes were defined crossing in the center position of the tank's circular base, and the z-axis was selected pointing up. [19] provides an explanation of the measurement data. In a nutshell, the averaged velocities of the three components' maximum absolute values are: | vx |max| vy |max| vz |max. The absolute readings ranged from 4 to 13 cm/s. The data from acoustic velocimetry and PIV spectroscopy were used to validate a computer model that was recently developed to mimic the fluid dynamics in a laboratory digester using CFD simulations [15].

2.2. CFD Modelling of Fluid Mixing in Scaled-Down Laboratory Digester

A static mechanical simulation model was used to analyze the mixing mechanism in the cylindrical tank. The simulation approach used by the generated model involves the following steps:

1. The geometrical design of the cylindrical tank was developed.;
2. The stirrers' geometrical design was produced;
3. Generation of the grid;
4. Selection of the physical model;
5. Selection of the solvers;
6. Evaluation of the data;
7. Optimization of the model.

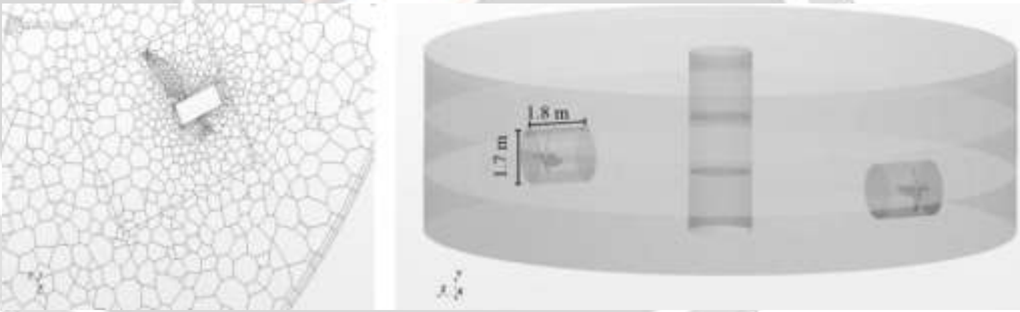
The experimental method for determining the mixing process is briefly detailed in Section 2.1. In the experimental digester, the flow velocity of the water-cellulose combination is used as a substrate substitute. Data from acoustic Doppler effects and optical particle image spectroscopy investigations are used to evaluate the CFD model. The two propeller mixers and the paddle system were used to construct three alternative mixing configurations that were comparable to the laboratory trials. The geometrical parametrization of the three stirrers was created using 3D-CAD. The developed stirrer geometries are shown in Figures 3(a) and 3(b) (b). As shown in Fig. 4, the stirrer geometries are included within the cylindrical volume of the mixing fluid (b). The meshes were then built, as shown in Figures 3(c) and 4(a) (a).

The Star-CCM+ application was used to create the meshes. There are two meshing methodologies to choose from, depending on the system to mesh: surface or volume. The four meshers mentioned below were carefully chosen [15]: for the surface mesh, the Surface Remesher and the Automatic Surface Repair were chosen. The latter was used to identify and resolve issues. The Polyhedral Mesher and the Advancing Layer Mesher were used to generate the volume mesh. The usual k-model was used to account for wall boundary effects. No-slide requirements were developed on the tank's wall and bottom since they were more accurate, whereas slip conditions were established on the fluid surface on top (transition to gas). [15] contains additional information.
A basic cell size of 1.5 cm in diameter was chosen, yielding a total of 250,000 cells.

(a) (b) (c)

Fig. 3. Geometry imported in the CFD model for: (a) propeller RB with rounded blades; (b) paddle system RP with rectangular plates; (c) propeller PB with pointed blades. In (c) the meshes of the regions and sub-regions inside the cylindrical volume of the laboratory digester are shown.

The model is based on the assumption that the fluid's homogeneity is the most essential component in influencing the mixing operation's quality. Use the flow velocity vector and its components in the axis system's x, y, and z directions to measure homogeneity. As a result of CFD computations, the velocity fields are thoroughly characterized. The digester's flow velocity vector and its three spatial components are the output parameters of the CFD simulations. If the dispersion is nearly uniform in all three directions, the substrate is homogeneous.



(a) (b)

Fig. 4. Geometry of regions and sub-regions imported in the CFD model: (a) mesh around propeller RW; (b) whole digester with the presence of two propeller mixers placed in diametrically opposite positions and in M-2 configuration.

The flow velocity for the three mixing setups is shown in Figure 5. The results of the simulations and the experimental values obtained by PIV spectroscopy and acoustic velocimetry investigations [15], [19] show a high degree of consistency. Based on successful experimental validation, the CFD model is upscaled to recreate the mixing process in full-scale anaerobic digesters.
As a result, in the following paragraph, the characteristics of mixers used in biogas plants are provided and explored.

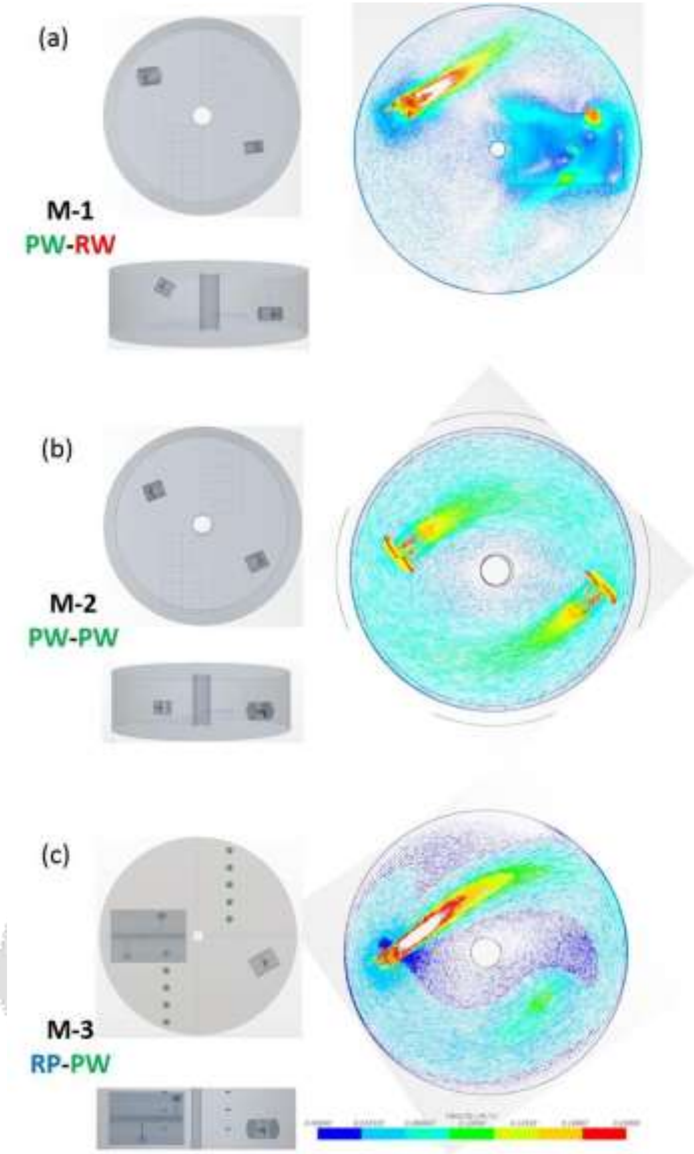


Fig. 5. Simulations results from CFD calculations: CAD models and visualization of the flow velocity in the three mixing configurations: (a) M-1, with a pointed blade propeller (PW) and a rounded blade propeller (RW); (b) M-2, with two pointed blade propellers (PW); (c) M-3 with a paddle system (RP) and a pointed blade propeller (PW) [15].

3. METHOD AND PROCEDURE IN A FULL-SCALE ANAEROBIC DIGESTER

3.1. Methods of Mixing in Full-Scaled Laboratory Digester

The program is being run in conjunction with UTS Products GmbH in Germany, as well as some UTS-affiliated biogas facilities. As a result, the investigation will concentrate on the UTS mixer typologies. They are seen in Figure 6. Genuine (R) mixers are distinguished from laboratory (L) mixers, which are depicted in Fig. 1 and designated "L."

(a) (b) (c)

Fig. 6. Typology of the agitators used in the anaerobic digesters of biogas plants: (a) propeller with three rounded blades and Ø = 0.9 m, called RW-R; (b) propeller with three pointed blades and Ø = 1.5 m, called PW-R; (c) paddle with four rectangular plates of 54·84 cm dimension, called RP-R.

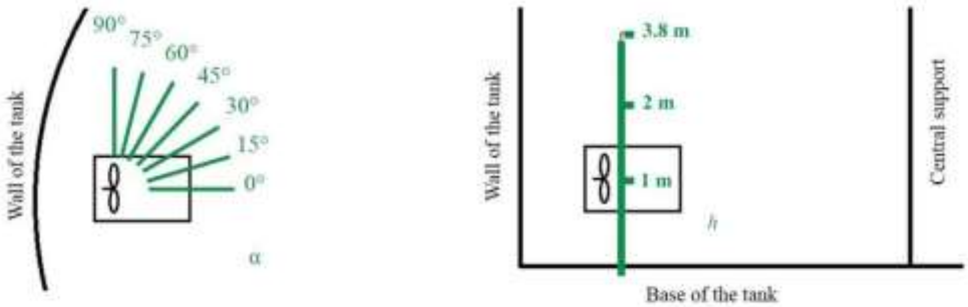
Table 1 lists the basic properties of laboratory and real mixers. The real mixers have the same geometrical dimensions (diameter) as the UTS partners' mixers. The data from the laboratory mixer are scaled down by a factor of 12.

TABLE 1. Types and Characteristics of the Investigated Mixers

Name of mixer	Description	Diameter in reality, cm	Diameter in laboratory, cm	Rotation speed in reality, rpm	Rotation speed in laboratory, rpm
RW	Propeller with 3 rounded blades	150	12.5	80–50	140
PW	Propeller with 3 pointed blades	94	7.8	120–170	238
RP	System with 4 rectangular paddles	422	35.2	Confident	15

3.2. CFD Modelling of Fluid Mixing in Full-scale Anaerobic Digesters

This study used the following configuration to test the mixing process CFD model: two mixers in diametrically opposite positions, each with a rounded blades propeller and a pointed blades propeller. The developed simulation approach takes into account the following variables: Angles and heights of the two propellers, h. The variation range yields a total of 441 mixing alternatives, as illustrated in Fig. 7.



(a) (b)

Fig. 7. Geometrical parameters of the mixers and corresponding values used in the CFD simulations: (a) angle of axis of the mixer; (b) height of the axis of the mixer.

The fluid's rheology was adjusted to a genuine substrate combination with a dry matter content of 12 wt percent for the model-based sensitivity analysis, and the consistency factor and flow index of the power law conditions were changed to 16.77 Pasn and 0.35, respectively.
The k- model was employed to address the wall boundary effects as an appropriate simplification already used in the CFD model for scaled-down experimental digester [15]. No-slip criteria were applied to the tank's wall and bottom, while slip boundary conditions were applied to the fluid surface on top.

4. RESULTS AND DISCUSSION

The CFD model results are taken into account in the sixteen locations illustrated in Fig. 8. The digester's bottom and top components are separated. Each segment is divided into eight sections. Due to the mechanical support found in practically all biogas facilities, the regions have cylindrical geometries with an empty internal component.
The flow velocity is calculated in three axial components and as a magnitude of the velocity vector by the model. The magnitude and z-component of velocity in the 16 sites as a function of the second mixer's angle are plotted in Fig. 9. The velocity profile in the lower areas reaches a massive maximum, but the profiles in the top parts are very faint. The maximum value of the velocity increases as the angle of the mixer increases, indicating that mixing is more efficient at high angles. The velocity is frequently lower during the peak.
Because of the influence of gravitational attraction, the z-component of velocity is fascinating to investigate. Because the profiles do not reflect any particular patterns, the portrayal in Fig. 9(b) emphasizes the varied vertical flow behavior. As a result of the dynamics, turbulent and laminar flow regimes can define various patterns of fluid motion with the creation of vortexes [25], [26].
The results of the CFD simulations were analyzed in order to discover which propeller position options were the most advantageous (angle and location). Six measures were chosen as the criteria for this goal. Five variables influence the fluid's flow velocity. The torque required to rotate the mixers is the sixth measure used as a criterion. The torque is examined in order to determine the required energy.

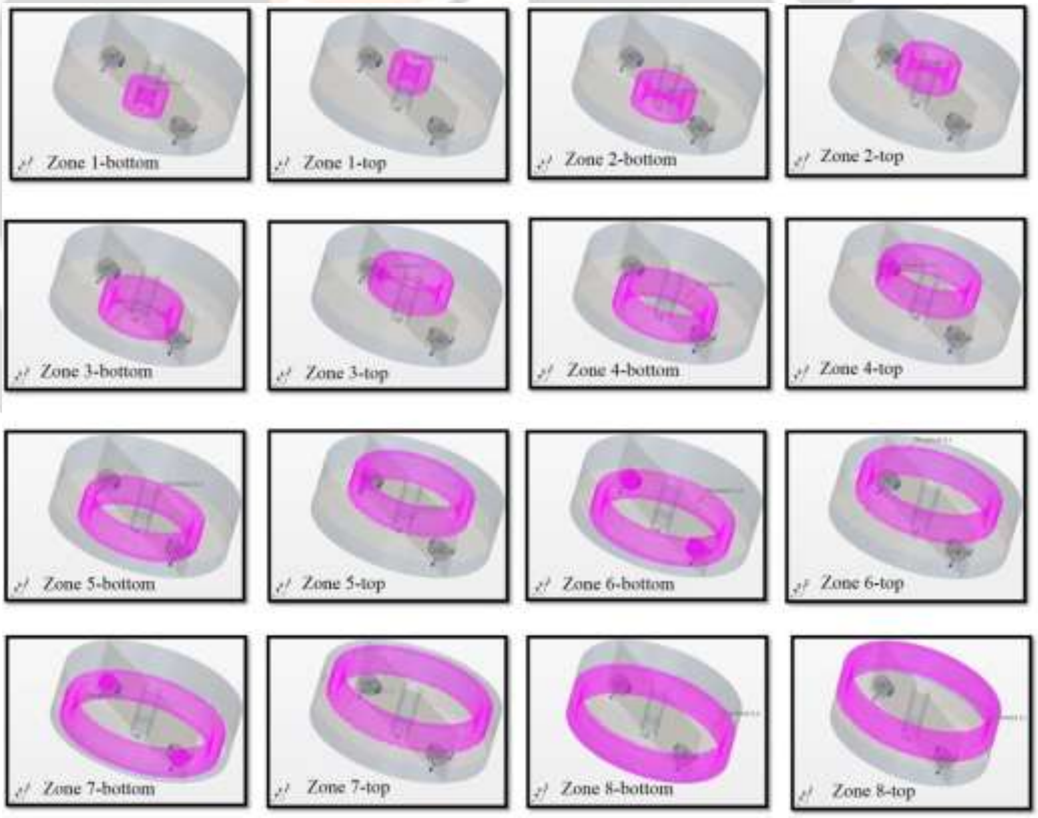
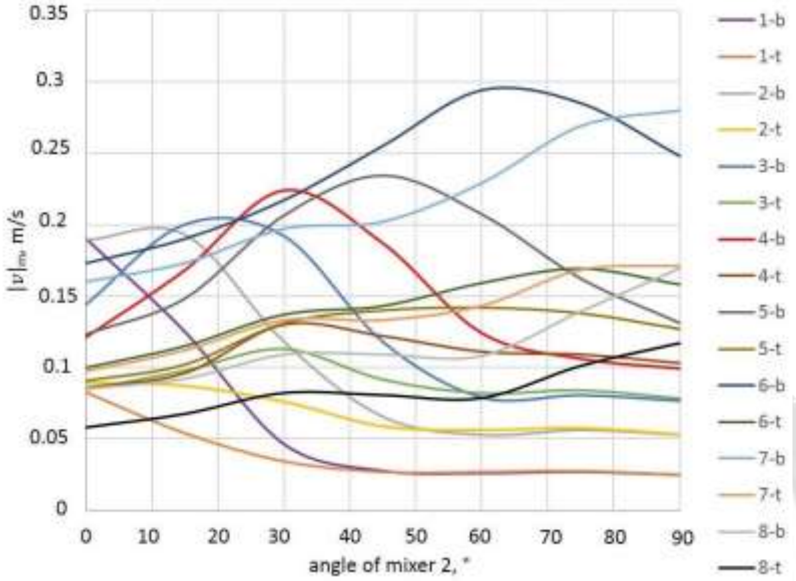


Fig. 8. Shape of partitions for the 8 bottom and 8 top areas in 3D environmental obtained by CFD simulation.

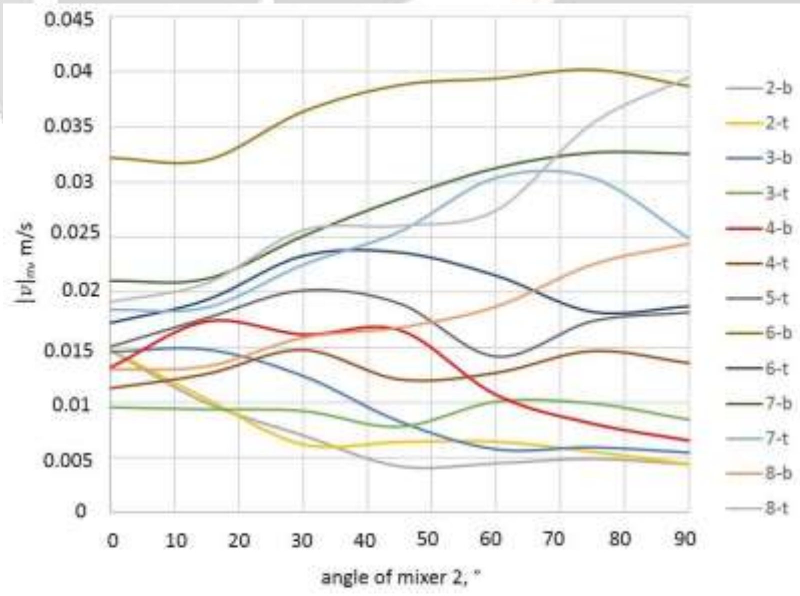
Table 2 lists the six parameters that will be utilized as criteria. Each criterion was assigned a weight (W) ranging from 4 to 2. Only the first four criteria have recently been used to test the CFD model in the 1:12 scaled-down laboratory digester described in sections 2.1 and 2.2. [15] The weights were 4, 3, 2, and 1 respectively. For the current investigation on a full-scale digester, two additional criteria are introduced, and the values for the first four are 4, 3, 2, and 2, as indicated in the last column of Table 2. In comparison to the previous study [15], the weight value for vertical movement

has been increased from 1 to 2. Along the Z-axis, solid portions can float at the surface or descend at the bottom of a poorly mixed volume. If a good blend has to be established, both of these scenarios must be avoided. As a result, the original weighting of one exaggerated the complexity of the operation. In addition, for each criterion, five value intervals were established. A satisfaction rating was assigned to each interval (). The following values were chosen: 0, 1, 3, 5, and 9. Table 3 shows the degree of completion for the various criterion parameter ranges.
The benefit of each mixing configuration was quantified using the technical benefit measure, which is expressed in % and calculated using the following equation:

$$\tau = \frac{\sum_{i=1}^{6} \varphi_i \cdot w_i}{144} \cdot 100 \quad (1)$$



(a)



(b)

Fig. 9. Velocity profiles of the bottom and top zones depicted in Fig. 8 as function of the angle of mixer 2: (a) averaged value of flow velocity; (b) Z-component of the flow velocity.

TABLE 2. CRITERIA AND EVALUATION WEIGHTS USED FOR BENEFIT ANALYSIS

Parameter	Criterion	Description	Criterion's weight W
v_m [15]	Flow velocity digester	Indication of flow intensity	4
v_x, v_y, v_z [15]	Uniform distribution of flow velocity vector components (1/3 each, 33 %)	Indication of homogeneous mixing	3
Z % [15]	Total amount of vertical up/down flow velocity	Horizontal (circular) movement dominates in cylindrical digesters, vertical up/down amount of z-component indicates better mixing	2
$Z+$%, $z-$% [15]	Uniform amount of positive (up) and negative (down) of z vertical component (1/2 each, 50 %)	Avoidance of an up- or down-ward movement tendency	2
Z_{GI}	Zone specific uniformity index	Describe the ratio between average velocity of the zone (v_n) and the whole digester (v_m), $Z_{GI} = v_n/v_m$	2
T	Torque	Parameter to determine the required performance in term of energy	3

The relationship between criterion weight and degree of completion is seen in Eq. (1). The term 144 in the denominator denotes the best scoring scenario, in which all six conditions are met. It was used to evaluate each of the 441 mixing configurations for its technological merit. Setups with rotors at high angles have bigger values of, as expected from the previous investigation of the patterns of the velocity profiles observed in Fig. 9. On the other hand, configurations with low values of have a poor benefit.

TABLE 3. DEGREE OF FULFILMENT (φ) FOR DIFFERENT RANGES OF CRITERION PARAMETERS

Criterion	φ = 0	φ = 1	φ = 3	φ = 5	φ = 9
v_m, m/s	<0.10	<0.11	<0.12	<0.13	>0.13
v_i, %	>30	>25	>20	>15	<15
Z %, %	<21	<24	<27	<30	>30
$Z+$%, %	>16	<16	<12	<8	<4

The two mixers are also arranged in a predictable sequence. In comparison to the top, the location near the bottom is inefficient. Eight of the 441 possible layouts are depicted in Table 4. The determining factor In the last column, the technical benefit is expressed as a percentage. Table 4 displays the best five and worst three combinations, with figures ranging from 72.01 to 24.50, based on the technical benefit value. The parameter is crucial for calculating the needs for the construction of anaerobic digester mixing systems.

TABLE 4. Technical benefit (τ) of simulation at different angles (α) And height (h) of the two mixers placed in diagonal opposite positions

No.	α of RW, °	α of PW, °	h of RW, m	h of PW, m	τ, %
1	75	75	3.8	3.8	72.01
2	90	75	2	3.8	71.26
3	90	60	3.8	3.8	70.98
4	90	60	2	3.8	70.94
5	90	90	2	1	70.78
439	15	15	1	2	26.77

440	30	15	2	1	26.63
441	15	15	1	1	24.50

The parameter velocity dominates the current study's debate. Greater fluid homogeneity and, as a result, increased methane generation were associated to high velocity. The model does not take into account the biological component of biomass. There is, in fact, a sophisticated microbial consortium of bacteria present, which is responsible for the fermentation's efficacy [27–29]. High shear rates come from breaking up the microbial flocculation structure and limiting the operation of methanogenic bacteria and enzymes.

5. CONCLUSIONS

The mixing system in anaerobic digesters in biogas plants consumes a lot of energy, lowering overall plant efficiency. Mixing has the most negative impact on the plant's overall energy management and budget, according to a cost-benefit analysis. Operational circumstances and geometrical factors must be changed to reduce the parasitic influence. The current research introduces a new CFD-based method for analyzing alternate designs. In the setup shown, two propeller rotors are oriented in opposite directions. Within the digester, the position of the rotors was studied. The researchers discovered that rotor placements that are far from the bottom and have large rotation angles result in favorable fluid dynamics and high velocity values. Paddle systems, for instance, are being developed as alternatives.

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REFERENCES

[1] Lebranchu A., et al. Impact of shear stress and impeller design on the production of biogas in anaerobic digesters. *Bioresource Technology* 2017:245(A):1139–1147. doi:10.1016/j.biortech.2017.07.113

[2] Naegele H. J., et al. Electric energy consumption of the full scale research biogas plant ‘unterer lindenhof’: results of longterm and full detail measurements. *Energies* 2012:5(12):5198–5214. doi:10.3390/en5125198

[3] Sonnleitner M. Ecological and economic optimization of biogas plants. MPhil Thesis. Leicester: De Montfort University, 2012.

[4] Singh B., Szamosi Z., Simenfalvi Z. State of the art on mixing in an anaerobic digester: a review. *Renewable Energy* 2019:141:922–936. doi:10.1016/j.renene.2019.04.072

[5] Kowalczyk A., et al. Different mixing modes for biogas plants using energy crops. *Applied Energy* 2013:112:465–472. doi:10.1016/j.apenergy.2013.03.065

[6] Wiedemann L., et al. Mixing in Biogas Digesters and Development of an Artificial Substrate for Laboratory-Scale Mixing Optimization. *Chemical Engineering & Technology* 2017:40:238–247. doi:10.1002/ceat.201600194

[7] Conti F., et al. Mixing of a Model Substrate in a Scale-down Laboratory Digester and Processing with a Computational Fluid Dynamics Model. *Proc. of 26th EUBCE-European Biomass Conference and Exhibition*, Copenhagen 2018:811–815. doi:10.5071/26thEUBCE2018-2CV.5.34

[8] Leonzio G. Study of mixing systems and geometric configurations for anaerobic digesters using CFD analysis. *Renewable Energy* 2018:123:578–589. doi:10.1016/j.renene.2018.02.071

[9] Bridgeman J. Computational fluid dynamics modeling of sewage sludge moxing in an anaerobic digester. *Advances in Engineering Software* 2012:44(1):54–62. doi:10.1016/j.advengsoft.2011.05.037

[10] Dapelo D., Alberini F., Bridgeman J. Euler-Lagrange CFD modelling of unconfined gas mixing in anaerobic digestion. *Water Res.* 2015:85:497–511. doi:10.1016/j.watres.2015.08.042

[11] Ding J., et al. CFD optimization of continuous stirred-tank (CSTR) reactor for biohydrogen production. *Bioresource Technology* 2010:101:7005–7013. doi:10.1016/j.biortech.2010.03.146

[12] Keshtkar A., et al. Mathematical modeling of nonideal mixing continuous flow reactors for anaerobic digestion of cattle manure. *Bioresource Technology* 2003:87(1):113–124. doi:10.1016/S0960-8524(02)00104-9

[13] Vesvikar M. S., Al-Dahhan M. Flow pattern visualization in a mimic anaerobic digester using CFD. *Biotechnology in Bioengineering* 2005:89(6):719–732. doi:10.1002/bit.20388

[14] Lopez-Jimenez P. A., et al. Application of CFD methods to an anaerobic digester: the case of Ontinyent WWPT, Valencia, Spain. *Journal of Water Process Engineering* 2015:7:131–140. doi:10.1016/j.jwpe.2015.05.006

[15] Wiedemann L., et al. Modeling Mixing in Anaerobic Digesters with Computational Fluid Dynamics Validated by Experiments. *Chemical Engineering & Technology* 2018:41:2101–2110. doi:10.1002/ceat.201800083

[16] Conti F., et al. Thermal behaviour of viscosity of aqueous cellulose solutions to emulate biomass in anaerobic digesters. *New Journal of Chemistry* 2018:42:1099–1104. doi:10.1039/c7nj03199h

[17] Wiedemann L., et al. Investigation and optimization of the mixing in a biogas digester with a laboratory experiment and an artificial model substrate. *Proceeding of 25th EUBCE-European Biomass Conference and Exibition*, Stockholm 2017:889–892. doi:10.5071/25thEUBCE2017-2CV.4.14
[18] Sindall R. C., Bridgeman J., Carliell-marquet C. Velocity gradient as a tool to characterrize the link between mixing and biogas production in anaerobic waste digesters. *Water Sci. Technol*. 2013:67:2800–2806.
[19] Conti F., et al. Monitoring the mixing of an artificial model substrate in a scale-down laboratory digester. *Renewable Energy* 2019:132:351–362. doi:10.1016/j.renene.2018.08.013
[20] Shen F., et al. Improving the mixing performances of rice straw anaerobic digestion for higher biogas production by computational fluid dynamics (CFD) simulation. *Applied Biochem. Biotechnol.* 2013:171626–642.
[21] Gerogiorgis D. I., Ydstie B. E. Multiphysics CFD modeling for design and simulation of a multiphase chemical reactor. *Chemical Engineering Research and Design* 2005:83(6):603–610. doi:10.1205/cherd.04364
[22] Atta A., Roy S., Nigam K. D. P. A two-phase Eulerian approach using relative permeability concept for modeling of hydrodynamics in trickle-bed reactors at elevated pressure. *Chemical Engineering Research and Design* 2010:88(3):369–378. doi:10.1016/j.cherd.2009.06.011
[23] Celik I. B., et al. Procedure for estimation and reporting of uncertainty due to discretization in CFD applications. *Journal of Fluid Engineering* 2008:130(7):0780011–0780014. doi:10.1115/1.2960953
[24] Conti F., et al. Effect of mixing of waste biomass in anaerobic digesters for production of biogas. *IOP Conf. Series: Materials Sci. Eng*. 2018:446:012011. doi:10.1088/1757-899X/446/1/012011
[25] Wu B. CFD investigation of turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters. *Water Research* 2011:45(5):2082–2094. doi:10.1016/j.watres.2010.12.020
[26] Alexopoulos A. H., Maggioris D., Kiparissides C. CFD analysis of turbulence non-homogeneity in mixing vessels: a two compartment model. *Chemical Engineering Science* 2002:57(10):1735–1752. doi:10.1016/S00092509(02)00053-2
[27] Trentini M., Lorenzon M., Conti F. Biotechnology to investigate the microbial community responsible of biogas production from biomass. *Proceeding of 26th EUBCE-European Biomass Conference and Exhibition*, Copenhagen, 2018:816–820. doi:10.5071/26thEUBCE2018-2CV.5.35
[28] Castellan N., Conti F. Molecular biotechnology to improve biofuel production from biomass. *Proceeding of 27th EUBCE-European Biomass Conf. and Exhibition*, Lisbon, 2019:951–957. doi:10.5071/27thEUBCE2019-2CV.6.24
[29] Djossou A., Conti F. Mesophilic and thermophilic bacteria in anaerobic digestion process. *Proceeding of 27th EUBCE-European Biomass Conf. and Exhibition*, Lisbon, 2019:942–945. doi:10.5071/27thEUBCE2019-2CV.6.9