

## Computational fluid dynamics simulation of thermodynamic behaviour of tubular digester

Vaz N. Patrícia\*, Oliveira Filho Delly\*\*, Martins A. Márcio\*\*, Carlo C. Joyce\*\*\*, Rosa P. André\*\*, Mendes M. A. M. Eduardo\*

\* Postgraduate Program in Electrical Engineering, Federal University of Minas Gerais Minas Gerais, Brazil (e-mail: [patricia.vaz@ufv.br](mailto:patricia.vaz@ufv.br); [emmendes@ufmg.br](mailto:emmendes@ufmg.br))

\*\* Department of Agricultural Engineering, Federal University of Viçosa, Minas Gerais, Brazil (e-mail: [delly@ufv.br](mailto:delly@ufv.br); [aredesufv@gmail.com](mailto:aredesufv@gmail.com); [andrerosa@ufv.br](mailto:andrerosa@ufv.br))

\*\*\* Department of Architecture and Urbanism, Federal University of Viçosa, Minas Gerais, Brazil (e-mail: [joycecarlo@ufv.br](mailto:joycecarlo@ufv.br))

**Abstract:** The anaerobic digesters have been widely used worldwide and followed by the environmental treatment, biogas (energy source) and biofertilizers can be produced at the same process. The plug flow digester is the most common digester system in Brazil, but it still faces great difficulties of implementation because of the low efficiency. In this context, this work proposes ways of improving the energy efficiency of such a digester. To this end, simulations were performed for this type of digester in order to analyze the thermodynamic behavior. It was possible to verify that the velocity gradient was acceptable for the studied reactor characteristics, that is, 0.054, and the average temperature reached with the heating system was 33°C, which is considered an optimal temperature for biogas production. The simulation proved to be an important tool in scenarios using the digester model and can be of help when designing new units and in different cases of agitation. However the model used here does not evaluate the thermal changes of the digester plastic blanket due to the simplification of the simulation.

Copyright © 2020 The Authors. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0>)

**Keywords:** CFD in agriculture; Modeling and control of agriculture, Bio-energetics, Recirculation and temperature control.

### 1. INTRODUCTION

In recent years, techniques that adopt anaerobic digestion (AD) processes have been widely used for waste treatment (López-jiménez et al., 2015). Through these techniques, complex organic matter such as agricultural waste is converted to simpler compounds such as methane and carbon dioxide (biogas compounds), phosphorus and nitrogen (biofertilizing elements) (Kinyua et al., 2016; Mohammadrezaei, Zareei and Khazaei, 2018; Sajjadi et al., 2016). According to Sajjadi (2016), more than half of the available fresh water in the world is polluted mainly due to the non-treatment of domestic and industrial waste.

Digesters have been considered as an advantageous option in waste treatment, arousing the interest of the academic community in researching ways to optimize anaerobic processes. This advantage is explained by the fact that digesters provide an appropriate destination for environmentally harmful waste and use them as a source of fertilizers and energy, whether electric or heating (Arif et al., 2018).

Among the approaches used to optimize the anaerobic digestion process are the studies of the thermodynamic behavior of digesters. The temperature is one of the most significant factors of AD (Khan and Martin, 2016). According to Cowley and Brorsen (2018) since the efficiency in biogas, production of the anaerobic digester usually increases with

increasing temperature. In some cases, biogas production may increase 100% for each 10°C increase between 15 and 35°C (Cowley and Brorsen, 2018). In the same way digestate, homogeneity is also a feature that has been gaining more and more importance among the research developed for AD technology because it influences the biodigestion rate, as well as biogas production (Hulle, Van et al., 2014).

The use of computational tools to simulate this behavior contributes to increase the speed of technological advance. The use of simulation facilitates the creation and comparison of different study scenarios and considerably reduces the costs related to validation and experimentation steps, which depend in part on operations to be performed directly at the plant (Leonzio, 2018).

The CFD - Computational Fluid Dynamics simulation technique has been presented as an efficient tool to study and evaluate the different phenomena that occur inside digesters (Meister et al. 2018; Hreiz et al. 2017; Liu et al. 2017; Hassanein et al. 2015 and Wu, 2013).

The most widely used type of digester in Brazil, with its largest application in swine farms, is the plastic blanket tubular flow model, also known as the Canadian model (Barros, 2008). The present work shows a study of the thermal behavior of a covered lagoon biodigester with few antecedents. The study has an unprecedented character because it differentiates the thermal behavior of the substrate and the soil, points neglected by other authors. This is a semi-buried model where 100% of

the substrate is separated from the soil and ambient air by plastic cover. In Brazil, there are few cases of automation and control of this biodigester model, which compromises its efficient production of biogas and biofertilizer. As previously stated, substrate temperature and homogenization are essential characteristics for efficient anaerobic digestion inside reactors. Thus, the objective of this study is to analyze the influence of heating and recirculation automated systems on the thermodynamic behavior of the tubular flow biodigester by modeling the digester and taking into account the boundary conditions involved.

## 2. METHODOLOGY

The software ANSYS CFX academic version 19.1 was used in this work in order to perform the computational study of bioreactors. The simulated Canadian biodigester was adopted because it is the most used model in Brazil, due in large part to pig farming (Cervi, Esperancini and Bueno, 2010).

The dimensions used in the modelling of the 250 m<sup>3</sup> biodigester were those of the swine waste treatment plant in the Production and Breeding and Genetics Farm of the Federal University of Viçosa, Viçosa, Minas Gerais State, Brazil (Leandro and Maradini, 2018). This University reactor was adopted to perform the simulations, as it is an operating model that deals with swine waste and because of the availability of having access to the operational data needed for modelling.

Brazilian swine reactors are usually similar in shape to an inverted pyramid trunk, as is the case with the research model. The width of the largest base is 10.0 m and the smallest base below ground level only 5.0 m, longitudinal length 15.0 m and 2.5 m deep. The height of the cover where the generated biogas is stored is about 2.5 m above ground level, as shown in Fig.1. For this study, the 1.0 mm thick plastic cover was modelled with HDPE (High Density Polyethylene) properties.

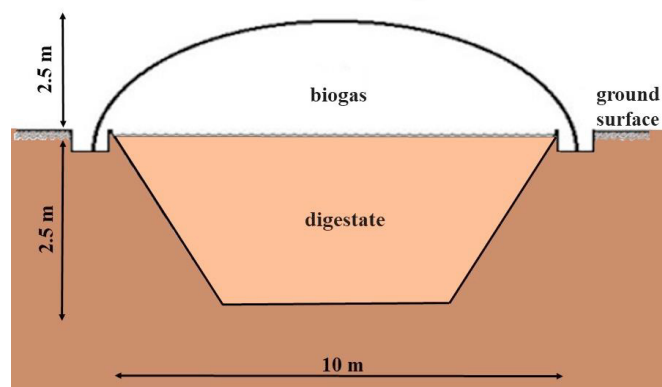


Fig. 1. Model of the Canadian biodigester.

The first governing equation used in the simulation was the continuity equation, ensuring that the velocity vectors are free of divergence at each point (equation 1):

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

where,  $\mathbf{v}$  is the absolute velocity vector of the fluid, remembering that the velocity vector has components in all three directions, that is,  $x$ ,  $y$  and  $z$ .

To analyze the behavior of the rate of change of  $\mathbf{v}$ , we used the conservation of motion quantity equation (equation 2):

$$\nabla(\rho\mathbf{v}) = -\nabla(\rho\mathbf{v}\mathbf{v}) - \nabla p - \nabla\tau + \mathbf{F} \quad (2)$$

where  $\rho$  is the specific mass, the fluid inlet pressure,  $\tau$  the viscous tension tensor and  $\mathbf{F}$  the forces acting on the body, and the last term of equation 2 was neglected for this study as in (Kariyama, Zhai and Wu, 2018; Lovato et al., 2018).

Substrate flow was modeled with a single phase with constant density and viscosity, as in Meister et al. (2018); Mohammadzadei, Zareei and Khazaei (2018). At this point in the work, the digester was considered as a pyramid trunk, disregarding the presence of biogas. Thus, the boundary conditions considered were that of the underground substrate with the soil, and surface substrate with ambient air. The substrate was isolated from the ambient air and the ground for only a HDPE cover. The thermodynamic behavior was rated in a single phase like Liu et al. (2017); Curry and Pillay, (2015) and Perrigault et al. (2012).

The differential heat conduction equation that describes the heat transfer process can be expressed in the cylindrical coordinate system as (equation 3):

$$\nabla \cdot \mathbf{k}\mathbf{T} + \rho c_v \nabla \cdot \mathbf{T} = 0 \quad (3)$$

where  $T$  is the temperature,  $\rho$  is the density,  $c$  is the specific heat,  $k$  is the thermal conductivity. Thus, the characteristics adopted for substrate modelling are Newtonian fluid properties at 23°C, such as specific heat at constant pressure ( $c_p$ ), thermal conductivity ( $k$ ), specific mass ( $\rho$ ) and dynamic viscosity ( $\mu$ ). For the properties of the HDPE plastic cover and for the soil, uniform properties were used (Table 1), according to the methodology of Perrigault et al. (2012).

Table 1. Thermophysical properties of substrate.

Material	Thermophysical properties of substrate			
	$\rho$	$c_p$	$k$	$\mu$
Units	kg/m <sup>3</sup>	J kg/K	W/m K	Pa s
Substrate	998	4189.8	0.58	0.001
Ground	2000	1550.0	1.58	-
Cover	950	1700.0	0.35	-

The simulations were performed under steady state conditions to analyse the thermal changes during the operation of the biodigester. It was adopted that the simulation solutions should converge when all residues are below 10<sup>-4</sup> and the final convergence is reached when the velocity, pressure and temperature fields remain constant.

In this study the finite volume method (FVM) was applied to discretize and solve the governing equations (Dapelo et al., 2019; Meister et al., 2018; Wang et al., 2018).

A study was performed for the refinement and convergence of the system mesh to ensure the stability of the numerical solution. The refinement consisted of two processes: (i) variation of controlled mesh parameters; and (ii) time stepping variation.

The Reynolds number (Re) was calculated to determine the type of flow, laminar or turbulent. The calculation of Re was made using equation 4:

$$Re = \rho v Dh / \mu \tag{4}$$

where  $\mu$  dynamic viscosity,  $Dh$  biodigester equivalent hydraulic diameter, which is calculated by means of the biodigester cross-section and perimeter, 4.4 m in this case.

For the substrate modelling in CFX software it was necessary, to enter the velocity and temperature that the fluid enters the biodigester in addition to the thermal properties. The velocity, 0.026 m/s, was calculated from the flow and cross-sectional area of the inlet pipe. The 250 m<sup>3</sup> biodigester flow from UFV was adopted. The inlet temperature of the fluid was considered equal to the average annual ambient temperature for Brazil, around 24°C.

A heating and recirculation systems have been proposed to be implemented in the biodigester (Fig. 2). The heating system consisted of a heat exchanger external to the reactor. The substrate was heated by means of a heat exchanger. The motor pump system was at the end of one of the inspection boxes (3) where the heated fluid returned to the reactor. The fluid is suctioned through the other two inspection boxes (2 and 1), keeping the volume of the biodigester constant. The temperature chosen was 40°C because it is the limit for the optimal substrate metabolization by the mesophilic arches, so as not to impair the digestion.

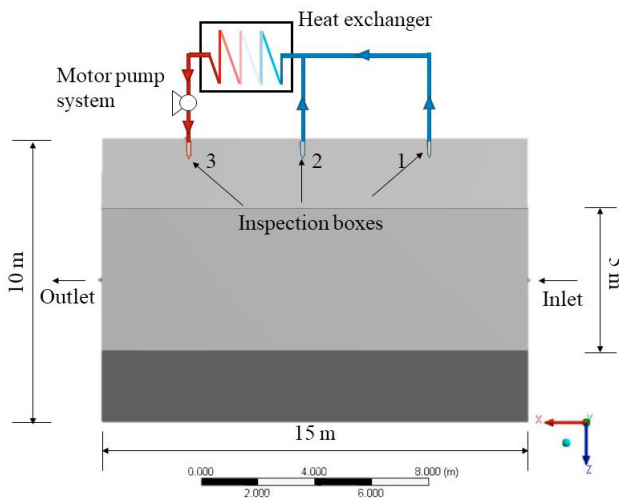


Fig. 2. Schematic representation of the biodigester recirculation and heating system.

The first simulated case was the one without recirculation and without heating, to evaluate standard system operation, called Case (0).

The next case included the insertion of the recirculation and heating system. Therefore, the Case (i) fluid is suctioned through two inspection boxes (1 e 2), then is heat up and then squeeze out of one inspection box (3).

To evaluate substrate homogenization, that is, the presence or absence of dead zones and region (s) with low flow, we used monitoring by  $G$  (s<sup>-1</sup>) absolute velocity gradients (equation 5). In other words, the velocity gradient was analyzed to determine the fluid mixing level (Bridgeman, 2012; Bridgeman, Jefferson and Parsons, 2010; Sindall, Bridgeman and Carliell-Marquet, 2013).

$$G = \sqrt{\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2} \tag{5}$$

According to (Bridgeman, Jefferson and Parsons, 2010) the velocity gradient can be considered as a measure of the angular strain rate of an elemental volume resulting from the application of forces on the tangential surface. Thus, it was defined in this study as the square root of the velocity gradient in a tank that contains a certain mixture.

### 3. RESULTS

The heating system consists of a heat exchanger external to the reactor, which can use biomass present in the farm as a source of energy as well as the burning part of biogas itself. The need to implement a heat exchanger external to the biodigester is due to the lack of access to the interior, since it would be impracticable to insert a stirrer inside for recirculation.

The first case to be analysed was the behaviour of the fluid inside the biodigester in the absence of recirculation and heating, Case (0).

By analysing the velocity field within the biodigester for Case (0) it can be observed that velocities range from zero to inlet and outlet velocities, about 0.028 m/s near the pipe inlet, as shown in Fig. 3.

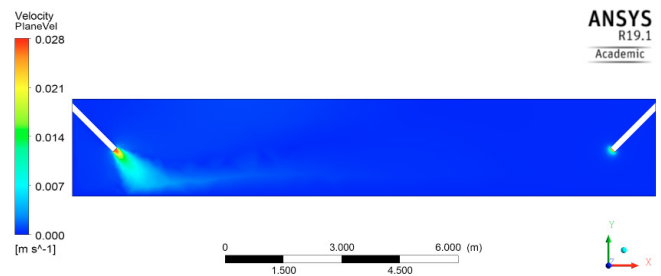


Fig. 3. Velocity behaviour inside the biodigester, from the inlet pipe (left) to the outlet pipe (right) for Case (0).

When fluid enters in the reactor, it decelerates due to biodigester substrate flow is practically inert, so that the fluid enters into dynamic equilibrium and flows at a next to zero constant velocity until it exits on the opposite side of the vessel.

The velocity difference between the fluid flow inside the inlet tube and the reactor generates a small-localized recirculation, but it is not enough to agitate the entire volume.

By analysing the current lines, it is possible to verify the behaviour of the fluid leaving the biodigester inlet tube to the outlet tube. Fig. 4 shows the plan and longitudinal sectional view of the fluid flow streamlines, respectively.

Recirculation can be assessed either by streamline analysis or by velocity gradient analysis. Fig. 4 shows the result of the current lines. Note that, in the absence of recirculation system, there are zones, such as the reactor ends, which are practically unmixed.

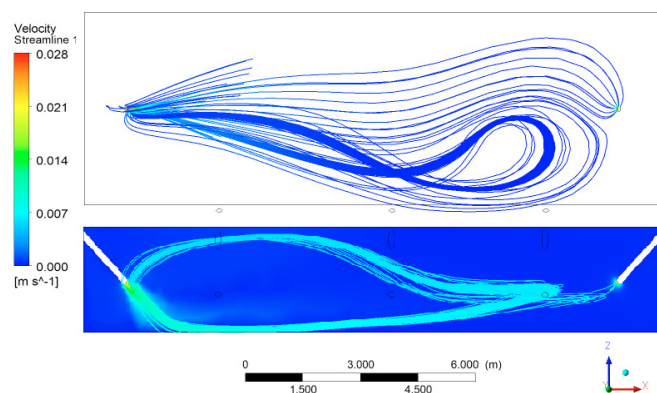


Fig. 4. Biodigester floor plan view and longitudinal section of the substrate flow streamlines for Case (0).

As for the velocity gradient analysis, it can be concluded for Case (0) that practically no fluid mixing occurred due to the low velocity gradient value found, i.e.  $0.210 \text{ s}^{-1}$ , as in the case of Meister et al. (2018) which achieved a velocity gradient of  $0.5 \text{ s}^{-1}$  for a system without recirculation and temperature around  $24^\circ\text{C}$ .

It is also important to note that the flow streamlines shown in Fig. 4 (plan view) cover only the middle of the biodigester, i.e. the central base of the biodigester (5.0 m) and the entire length (15.0 m) in the floor plan view. Recall that the full dimensions of the biodigester seen in the floor plan are 15 m long and 10 m wide.

There is a consensus among researchers that correct fluid agitation optimizes substrate degradation by microorganisms, and higher generation of biogas and biofertilizers is possible, in other words, substrate recirculation or agitation can make biodigesters more efficient (Leonzio, 2018; López-Jiménez et al., 2015; Rasouli et al., 2018; Wu, 2011).

Case (i) was then analysed with the objective of evaluating which one obtains the best level of mixture and the uniform distribution of temperature.

Table 2 presents the minimum, average and maximum temperatures, the standard deviation of simulated temperatures and the temperature gradient of the mixture. It can be observed that for Case (0) the minimum, average and maximum

temperatures were the same, all around  $24^\circ\text{C}$ , as expected due to the absence of heating and recirculation systems.

**Table 2. Temperature distribution, velocity gradient and standard deviation of temperature.**

	Minimum temperature ( $^\circ\text{C}$ )	Average temperature ( $^\circ\text{C}$ )	Maximum temperature ( $^\circ\text{C}$ )	Velocity gradient $\text{s}^{-1}$
Case (0)	24.15	24.15	24.15	0.210
Case (i)	24.15	33.26	40.15	1.747

With the recirculation system the velocity gradient increased by 700%, comparing Case (0) with Case (i), implying that in Case (i) the fluid has a better mixture and also has better homogeneity in temperature, and as a consequence can produce biogas in greater quantity and quality (Hulle, Van et al., 2014).

It can also be observed that in Case (i) two flow vortices are formed (Fig. 5). These vortices are the meeting of the flow of the biodigester input with the recirculation from the inspection box 01 (input 2). The fluid recirculation system has more zones being revolved compared to the results from Case (0), i.e., without recirculation, Fig. 4, as well as significant increase in the speed gradient.

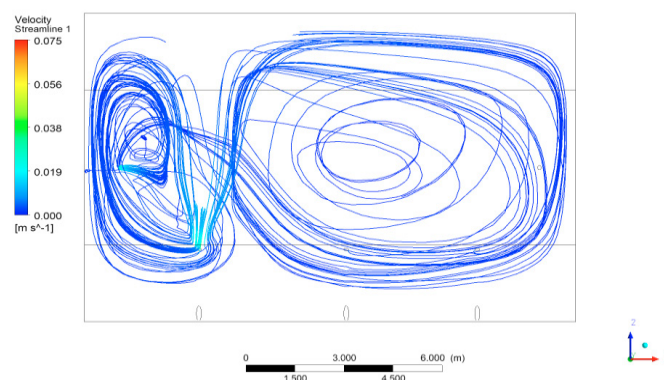


Fig. 5. Bottom view of the behavior of the flow current lines for Case (i).

In addition to the better recirculation performance Case (i) when compared to Case (0) proved that heating the part of the fluid that passes through the recirculation / heating system to a temperature of  $40^\circ\text{C}$  is sufficient for virtually all fluid to reach a homogeneous temperature, about  $33^\circ\text{C}$  in this case.

Fig. 6 shows the behaviour of the temperature inside the biodigester from the cross-sectional view along the x-axis at 3.0 m and longitudinal section at the center of the z-axis 5.0 m respectively for Case (i). Fig. 6(a) shows a plan with the temperature distribution at the centrum of the digester, it can be observed that the temperature is predominantly uniform. The distribution of fluid temperature within the biodigester at different depths for Case (i) in Fig. 6(b).

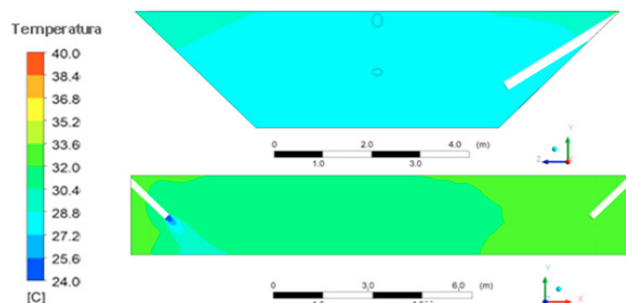


Fig. 6. Digester bottom view of the behaviour of the flow current lines for Case (i).

It can be seen from the cross-sectional view of Fig. 6 that this zone does not receive a significant amount of heat from the heating system at temperatures between about 28 and 32°C. As seen in Fig. 4 this part of the biodigester receives great influence from the biodigester inlet flow and it can be seen that the recirculation system cannot homogenize all temperatures. However, there are few zones with temperature differences along the biodigester, with temperatures between 28 and 37°C.

A larger vortex was formed near the reactor inlet, where there is greater recirculation, as shown in Fig. 5; on the other hand, the second vortex shape at the reactor outlet did not reach all biodigester zones thus resulting in less mixing. Moreover, in the presence of dead zones at the ends of the digester. The presence of dead zones is of great concern, because it can cause substrate sedimentation leading as well as a lower volume of microorganisms that, in some cases, can halt the process.

In addition to the best revolving performance, Case (i) also demonstrated better behaviour regarding temperature homogeneity. With the analysis of the automation system it can be proved that heating only part of the substrate to a temperature of 40°C was enough for practically all the reactor digester volume to reach homogeneous temperatures, 33°C. Reaching a temperature of 33°C could mean that the biodigester may have optimized its production of biogas and fertilizer material.

The biodigester design parameters comparison were the absolute velocity gradient and the velocity / length ratio. Calculating the ratio between the speed and the length of the simulated biodigester and the oval model digester, with and without recirculation (Meister et al., 2018) found 7.2. Likewise, the ratio between the absolute velocity gradient ratio for the simulated model and the one described by Meister et al. (2018) and a value of 7.1 was found.

Because velocity coefficients are observed in the simulations about 60% lower than those indicated in the literature, Meister et al. (2018). In addition, the existence of “dead zones”, i.e. substrate flow velocities close to zero, it is recommended that changes be made to design parameters such as increased fluid inlet velocities in the reservoir and / or suction and repression to meet the indications in the literature. Another possibility is to change the type of biodigester, i.e. the design itself.

#### 4. CONCLUSIONS

Computational fluid dynamics has proved to be an efficient and relatively fast tool for performing tests for thermodynamic behaviour analysis. Although some approximations were necessary, results followed closely the results available in the literature. It is emphasized here that the results presented in this analysis are in each of the layers or volumes considered, and can generate solutions in three dimensions, which better specifies the results in relation to other types of simulation.

The type of plastic blanket tubular biodigester is still poorly studied when compared to other types, which makes the study more interesting in terms of research for the area of swine manure treatment systems and the generation of energy from biomass. The inclusion of a recirculation and heating systems simultaneously with the heating system proposed for the tubular biodigester was efficient for heating, with average temperatures close to 33°C. The recirculation system should be simulated for other speeds to achieve recommended indexes proposed in the literature.

Therefore, it can be stated that the use of the computational fluid dynamics method proved to be efficient and effective to simulate the optimization of biodigesters with and without recirculation and heating systems.

#### ACKNOWLEDGEMENTS

The authors would like to thank the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support to develop this research

#### REFERENCES

- Arif, S., Liaquat, R. and Adil, M. (2018) ‘Applications of materials as additives in anaerobic digestion technology’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 97(January 2017), pp. 354–366. doi: [10.1016/j.rser.2018.08.039](https://doi.org/10.1016/j.rser.2018.08.039).
- Barros, T. D. (2008) *Árvore do Conhecimento: Biodigestor Tubular*, Agência Embrapa de Informação Tecnológica. Available at: <http://www.embrapa/agroenergia> (Accessed: 24 January 2019).
- Bridgeman, J. (2012) ‘Computational fluid dynamics modelling of sewage sludge mixing in an anaerobic digester’, *Advances in Engineering Software*. Elsevier Ltd, 44(6), pp. 54–62. doi: [10.1016/j.advengsoft.2011.05.037](https://doi.org/10.1016/j.advengsoft.2011.05.037).
- Bridgeman, J., Jefferson, B. and Parsons, S. A. (2010) ‘The development and application of CFD models for water treatment flocculators’, *Advances in Engineering Software*. Elsevier Ltd, 41(1), pp. 99–109. doi: [10.1016/j.advengsoft.2008.12.007](https://doi.org/10.1016/j.advengsoft.2008.12.007).
- Cervi, R. G., Esperancini, M. S. T. and Bueno, O. de C. (2010) ‘Viabilidade econômica da utilização do biogás produzido em granja suínica para geração de energia elétrica’, *Engenharia Agrícola*, 30(5), pp. 831–844. doi: [10.1590/S0100-69162010000500006](https://doi.org/10.1590/S0100-69162010000500006).

- Cowley, C. and Brorsen, B. W. (2018) ‘Anaerobic Digester Production and Cost Functions’, *Ecological Economics*. Elsevier, 152(June), pp. 347–357. doi: [10.1016/j.ecolecon.2018.06.013](https://doi.org/10.1016/j.ecolecon.2018.06.013).
- Curry, N. and Pillay, P. (2015) ‘Integrating solar energy into an urban small-scale anaerobic digester for improved performance’, *Renewable Energy*. Elsevier Ltd, 83, pp. 280–293. doi: [10.1016/j.renene.2015.03.073](https://doi.org/10.1016/j.renene.2015.03.073).
- Dapelo, D. et al. (2019) ‘Towards Lattice-Boltzmann modelling of unconfined gas mixing in anaerobic digestion’, *Computers and Fluids*. Elsevier Ltd, 180, pp. 11–21. doi: [10.1016/j.compfluid.2018.12.008](https://doi.org/10.1016/j.compfluid.2018.12.008).
- Hassanein, A. A. M. et al. (2015) ‘Simulation and validation of a model for heating underground biogas digesters by solar energy’, *Ecological Engineering*. Elsevier B.V., 82, pp. 336–344. doi: [10.1016/j.ecoleng.2015.05.010](https://doi.org/10.1016/j.ecoleng.2015.05.010).
- Hreiz, R. et al. (2017) ‘Modeling and simulation of heat transfer phenomena in a semi-buried anaerobic digester’, *Chemical Engineering Research and Design*. Institution of Chemical Engineers, 119, pp. 101–116. doi: [10.1016/j.cherd.2017.01.007](https://doi.org/10.1016/j.cherd.2017.01.007).
- Van Hulle, S. W. H. et al. (2014) ‘Importance of scale and hydrodynamics for modeling anaerobic digester performance’, *Chemical Engineering Journal*. Elsevier B.V., 255, pp. 71–77. doi: [10.1016/j.ccej.2014.06.041](https://doi.org/10.1016/j.ccej.2014.06.041).
- Kariyama, I. D., Zhai, X. and Wu, B. (2018) ‘Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: A review’, *Water Research*. Elsevier Ltd, 143, pp. 503–517. doi: [10.1016/j.watres.2018.06.065](https://doi.org/10.1016/j.watres.2018.06.065).
- Khan, E. U. and Martin, A. R. (2016) ‘Review of biogas digester technology in rural Bangladesh’, *Renewable and Sustainable Energy Reviews*. Elsevier, 62, pp. 247–259. doi: [10.1016/j.rser.2016.04.044](https://doi.org/10.1016/j.rser.2016.04.044).
- Kinyua, M. N. et al. (2016) ‘Use of physical and biological process models to understand the performance of tubular anaerobic digesters’, *Biochemical Engineering Journal*. Elsevier B.V., 107, pp. 35–44. doi: [10.1016/j.bej.2015.11.017](https://doi.org/10.1016/j.bej.2015.11.017).
- Leandro, M. T. R. and Maradini, P. da S. (2018) Proposta para regularização ambiental e avaliação do sistema de tratamento de efluentes de suinocultura: um estudo de caso de duas granjas no campus da Universidade Federal de Viçosa. Undergraduate Thesis, Federal University of Vicosa, Agricultural Engineering Department.
- Leonzio, G. (2018) ‘Study of mixing systems and geometric configurations for anaerobic digesters using CFD analysis’, *Renewable Energy*, 123, pp. 578–589. doi: [10.1016/j.renene.2018.02.071](https://doi.org/10.1016/j.renene.2018.02.071).
- Liu, Y. et al. (2017) ‘Investigation on the heat loss characteristic of underground household biogas digester using dynamic simulations and experiments’, *Biosystems Engineering*. Elsevier Ltd, 163, pp. 116–133. doi: [10.1016/j.biosystemseng.2017.09.002](https://doi.org/10.1016/j.biosystemseng.2017.09.002).
- López-jiménez, P. A. et al. (2015) ‘Application of CFD methods to an anaerobic digester: The case of Ontinyent WWTP, Valencia, Spain’, *Journal of Water Process Engineering*, 7, pp. 131–140. doi: [10.1016/j.jwpe.2015.05.006](https://doi.org/10.1016/j.jwpe.2015.05.006).
- Lovato, G. et al. (2018) ‘Hydrogen production by co-digesting cheese whey and glycerin in an AnSBBR: Temperature effect’, *Biochemical Engineering Journal*. Elsevier B.V., 138, pp. 81–90. doi: [10.1016/j.bej.2018.07.007](https://doi.org/10.1016/j.bej.2018.07.007).
- Meister, M. et al. (2018) ‘Mixing non-Newtonian flows in anaerobic digesters by impellers and pumped recirculation’, *Advances in Engineering Software*. Elsevier, 115(October 2017), pp. 194–203. doi: [10.1016/j.advengsoft.2017.09.015](https://doi.org/10.1016/j.advengsoft.2017.09.015).
- Mohammadrezaei, R., Zareei, S. and Khazaei, N. B.- (2018) ‘Optimum mixing rate in biogas reactors : Energy balance calculations and computational fluid dynamics simulation’, *Energy*. Elsevier Ltd, 159, pp. 54–60. doi: [10.1016/j.energy.2018.06.132](https://doi.org/10.1016/j.energy.2018.06.132).
- Perrigault, T. et al. (2012) ‘Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model’, *Bioresource Technology*. Elsevier Ltd, 124, pp. 259–268. doi: [10.1016/j.biortech.2012.08.019](https://doi.org/10.1016/j.biortech.2012.08.019).
- Rasouli, M. et al. (2018) ‘CFD simulation of fluid flow in a novel prototype radial mixed plug-flow reactor’, *Journal of Industrial and Engineering Chemistry*. The Korean Society of Industrial and Engineering Chemistry, 64, pp. 124–133. doi: [10.1016/j.jiec.2018.03.008](https://doi.org/10.1016/j.jiec.2018.03.008).
- Sajjadi, B. et al. (2016) ‘Fluid dynamic analysis of non-Newtonian flow behavior of municipal sludge simulant in anaerobic digesters using submerged, recirculating jets’, *Chemical Engineering Journal*. Elsevier B.V., 298, pp. 259–270. doi: [10.1016/j.ccej.2016.03.069](https://doi.org/10.1016/j.ccej.2016.03.069).
- Sindall, R., Bridgeman, J. and Carliell-Marquet, C. (2013) ‘Velocity gradient as a tool to characterise the link between mixing and biogas production in anaerobic waste digesters’, *Water Science and Technology*, 67(12), pp. 2800–2806. doi: [10.2166/wst.2013.206](https://doi.org/10.2166/wst.2013.206).
- Wang, J. et al. (2018) ‘A review on CFD simulating method for biogas fermentation material fluid’, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 97(August), pp. 64–73. doi: [10.1016/j.rser.2018.08.029](https://doi.org/10.1016/j.rser.2018.08.029).
- Wu, B. (2011) ‘CFD investigation of turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters’, *Water Research*. Elsevier Ltd, 45(5), pp. 2082–2094. doi: [10.1016/j.watres.2010.12.020](https://doi.org/10.1016/j.watres.2010.12.020).
- Wu, B. (2013) ‘Advances in the use of CFD to characterize, design and optimize bioenergy systems’, *Computers and Electronics in Agriculture*. Elsevier B.V., 93, pp. 195–208. doi: [10.1016/j.compag.2012.05.008](https://doi.org/10.1016/j.compag.2012.05.008).