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► **To cite this version:**

Hélène Caillet, Alain Bastide, Graziella Chuppa-Tostain, Thomas Petit, Laetitia Adelard. Anaerobic digestion of vinasse and cfd modelling approach. WasteEng 2018 - 7th International conference on Engineering for Waste and Biomass Valorisation, Jul 2018, Prague, Czech Republic. hal-01857234

**HAL Id: hal-01857234**

**<https://hal.science/hal-01857234v1>**

Submitted on 14 Aug 2018

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# ANAEROBIC DIGESTION OF VINASSE AND CFD MODELLING APPROACH

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**Keywords:** anaerobic digestion, computational fluid dynamics (CFD), Newtonian, non-Newtonian, large-eddy simulation, mechanical mixing

## Abstract

The study's ultimate goal consists of modelling and optimising the co-digestion of particulate substrates like sewage sludge, biowaste and vinasse from sugar cane. Given these substrates, the medium is highly heterogeneous and has particular physical characteristics and behaviour. Moreover, anaerobic digestion could be lead in wet-mode or in dry-mode, thus we want to develop a model valid for both configurations. In this context, the fluid flow modelling is of interest. Indeed, the contact between substrates and microorganisms has a significant influence on the anaerobic digestion process. It is directly correlated to the flow inside the digester. The research question is therefore the following: Is it possible to predict the spread of microorganisms inside the digester for both liquid and solid digestion? In this paper, we present the context of the work and the mathematical model based on Navier-Stokes equations with the Boussinesq approximation. Large-eddy simulation (LES) is used for the turbulence modelling. The sliding mesh method is used to characterise the impeller rotation. In further work, we will present the simulation results validated with the literature data. The differential equations will be solved on OpenFOAM software using the finite volume method. The flow will be simulated for both Newtonian (vinasse) and non-Newtonian fluids (manure) and at different total solid (TS) rates for non-Newtonian fluids. The obtained results will be the velocity and temperature profiles within the digester. It will hence be possible to optimise the process through both the medium physical properties (TS rate and viscosity) and the digester configuration. We will also consider the multiphase flow. Alongside numerical simulations, experiments are carried out on the substrates studied in order to estimate the methane production. In this article, we present the results of experiments on the vinasse and the development of the CFD model.

## 1- INTRODUCTION

The development of renewable energies is generally growing in relation to the current context, particularly, due to the depletion of fossil fuels and the need to limit the negative effects on the environment. Anaerobic digestion is a widely used process in waste treatment (agro-industrial waste, biowaste, manure, sewage sludge, vinasse...). The interest of anaerobic digestion is twofold, it allows organic waste to be treated with energy recovery. Thus, this process meets the particular needs of Reunion Island, which by its insular character, must call for sustainable solutions in terms of waste treatment. In fact, the household waste produced in Reunion Island is currently buried while the landfills are reaching their saturation point. It is therefore urgent to find durable solutions for waste management. It is in this perspective that studies are funded by the Region to examine the methanogenic potential of waste produced in Reunion Island (biowaste, sewage sludge, and vinasse) as well as to optimise the process on an industrial scale. In addition, local renewable energy production is a real asset for insular territories.

In methanisation industrial plants, the main process parameters are the temperature, the hydraulic retention time, the biomass and the mixing conditions. These parameters are directly correlated to the efficiency of the process. The mixing conditions are of utmost importance because mixing allows the temperature homogenisation and fosters the contact between the substrate and the micro-organisms. The substrate is naturally crucial in the methane yield because the yield will depend on the nature of the substrate. In addition, mono-digestion and co-digestion are two means of carrying out anaerobic digestion. Co-digestion is subject to many studies, in a review published in 2014, the authors stated that anaerobic co-digestion is a feasible option to overcome the drawbacks of mono-digestion and to improve the economic feasibility of industrial plants [1].

## 1- CONTEXT OF THE STUDYWORK CARRIED OUT

### 1-1- INHIBITION AND FAILURE RISKS IN ANAEROBIC DIGESTION

Various phenomena can destabilise the process of anaerobic digestion lowering it to complete failure of the biogas production. Anaerobic digestion is subjected to inhibition or failure risks due to the following reasons:

1. While the hydrolysis phase is largely considered as the rate-limiting phase for complex organic, intermediate product concentrations like free ammonia, volatile fatty acids and sulphide/sulphate can lead to inhibitions. Methanogenesis can also be considered like a rate-limiting phase [2] for easily biodegradable substrates such as wastewater sludge. Total nitrogen concentration measured on the vinasse is approximately  $2000 \text{ mg.L}^{-1}$ , which is relatively high for anaerobic digestion. Although this concentration is relatively high, anaerobic digestion is possible if the micro-organisms are acclimatised to the substrate [3].
2. For liquid anaerobic digestion ( $\text{TS} < 15\%$ ), inhibitions can occur because of an uneven distribution of biomass and substrates, the intensity and duration of the mixing as well as the retention time, must therefore be precisely studied to optimise the hydrodynamic behaviour of the process. Unsuitable mixing conditions can break the flocs of micro-organisms, disturbing the synergetic effects. Proper mixing conditions also have to be established to control the volume of dead zones and turbulence.
3. For solid anaerobic digestion, where dry processes are concerned, i.e. if the dry solid content reaches 15% or for cases of codigestion, high viscosity leads to limited mass and heat transfer among enzymes, bacteria and substrates in the digester. Mechanical mixing is in this case, considered to be the most efficient way to optimise the diffusion processes [4]. However, few studies have been carried out on the hydrodynamics of media.

4. Anaerobic co-digestion is often recommended to optimise biogas yield. However, co-digestion can lead to solid digestion and inhibitions due to the accumulation of volatile fatty acids. In that case, the development of biofilms among the substrate can disrupt the liquid flows [5].

## 1-2- ANAEROBIC DIGESTER MODELLING

We have seen a rise in numerical models, especially CFD models in recent years. Regarding the process modelling, the biochemical and physicochemical processes are taken into account in the ADM1 model [6]. To meet the needs related to the industrialisation of the methanisation, the development of models taking the flows into account in a precise way, is necessary. There is experimental evidence that mixing schemes and intensities have an impact on biogas production [7]. Indeed, all the chemical reactions leading to the complete digestion of the substrates can only occur when they are in contact with the microorganisms involved in each reaction. To do this, the digestion medium must be stirred. The agitation mode and type thus influences the quality of the digestion of the substrates. In fact, vigorous mixing suppresses growth and the propagation of methanogenic centres if methanogenesis is the rate-limiting step, but also may enhance methane production and degradation if hydrolysis is the rate-limiting step [8].

In addition, anaerobic digestion can also be carried out by the dry route (TS > 15%). In this case, the medium agitation is even more significant than in the wet digestion, since the homogenisation of the medium becomes more difficult. Moreover, the waste treated by this process also has particular rheological properties which influence the flow and therefore have a role in the optimisation of the mechanical agitation. Indeed, these fluids can be viscous, Newtonian or non-Newtonian. The rheology of waste including sewage sludge, manure and biowaste, has been studied in order to model the flow of these fluids which have a Newtonian or non-Newtonian behaviour according to the rate of total solid [9]–[15]. It has been shown that the fluid dynamics in the digester can be affected by the TS [16]. CFD provides accurate results on the flow and is therefore of great interest for anaerobic digestion modelling and optimisation. The major interest of the CFD is to characterise the flows within the digester in order to study configurations (digester, impeller) that allow optimal contact between the substrates and the microorganisms. Ultimately, in our study, we wish to model the displacement of microorganisms within the digester for both Newtonian and non-Newtonian fluids, in order to propose stirring optimisation. Indeed, to ensure that all substrates will be digested, it is necessary to ensure the spread of micro-organisms at any point in the digester. With this in mind, we conducted a literature review of CFD models applied to anaerobic digesters to identify studies that have already been carried out using this technique. These models are implemented to optimise the industrial process. The following table outlines the literature review of the aims of CFD in digesters.

References	Objectives	Phase model	Fluid property
[17]	Study the impact of the design of the digester (diameter of the draft tube) on the flows by studying the position and the volume of the dead zones.	Liquid-gas	N
[18], [19]	Compute the flow with LES techniques.	Liquid	N
[12]	Optimise the power supply and reduce the volume of dead zones or weakly stirred area.	Liquid	N-N
[9], [20], [21]	Study the liquid homogenisation in stirred tanks and the required time for homogenisation (RANS and LES).	Liquid	N ; N-N

[22]	Reduce the percentage of poorly mixing zones in gas-lift digesters by testing configurations of the bottom of the digesters.	Liquid	N-N
[23]	Simulate the characteristics of digesters: the rates of mixing and the slug injection of tracers from the digester volume turnover time, the mixture diffusion time, and the hydraulic retention time.	Liquid	N
[24]	Study different mechanical stirring configurations.	Liquid	N ; N-N
[25]	Investigate the flow fields, power and mixing time in a fully baffled stirred vessel with mechanical agitation (LES).	Liquid	N
[26], [27]	Investigate turbulence models.	Liquid	N-N
[16]	Simulate mechanical agitation in high solid anaerobic digester.	Liquid	N-N
[28]	Model the flows with mechanical agitation.	Liquid	N-N
[29]	Describe the settling and suspension in anaerobic digester and evaluate the biomass retention physical process.	Three phases	N
[30]	Model the flows for fluids with variable rheology to study the impact on the performance of the digester.	Liquid	N-N
[31]	Study the stirring performance of gas recirculation agitation configurations, and the impact of agitation intensity on biological processes.	Liquid-gas	N
[10]	Study the hydraulic performance of an existing digester (percentage of dead zones, recirculation volume).	Liquid	N
[32]	Study the impact of the agitator on suspended particles in order to optimise the digester.	Liquid-solid	N
[33]	Study the effect of impeller rotational speed and velocity field in the mixing tank.	Liquid	N
[34]	Study the influence of the behaviour of the sludge on the flow and the consequences on the quality of the agitation.	Liquid-gas	N-N

N = Newtonian, N-N = non-Newtonian.

*Table 1: Objectives of CFD models.*

### 1-3- TURBULENCE MODELLING

A point of attention is the modelling of turbulence phenomena. The interest comes from the fact that the mass transfer during the process is dependent on the turbulence phenomena in digesters [28], and the contact between micro-organisms and substrate is correlated to turbulence [35]. Moreover, studies show that flow predictions are particularly sensitive to the turbulence model implemented [36]. Thereby, the choice of the turbulence model is important in the simulations. Mainly Reynolds-average Navier-Stokes (RANS) simulations were conducted on digesters [10], [12], [13], [16], [17], [24], [26], [29]–[31], [36]–[38]. The SST k-omega model [30], [31], [36]–[38], the standard k-epsilon model [10], [12], [16], [23], [27], [37] and the realisable k-epsilon model [13], [21], [24], [27], [29] are recommended by many authors among the RANS models. Furthermore, other authors claim that the Reynold stress model (RSM) is the most suitable model to predict the behaviour of this bioreactor [35], [36].

However other studies have been conducted using the large-eddy simulations (LES) to model turbulence phenomena in anaerobic digesters and stirred tanks [18], [18]–[20], [25], [28], [39]. In these studies, the outcomes show that LES provide a better flow description than RANS simulations

[18], [18]–[20], [25], [28], [39]. In the study conducted by Wu in 2012, the free subgrid scale (SGS) models investigated are the Smagorinsky-Lilly (LES-SL) model, the wall-adapting local eddy-viscosity (LES-WALE) model and the kinetic energy transport (KET) model [28]. The three models give very similar results for flow fields [28]. The comparison between simulated and measured axial velocities shows that the LES shapes are in general agreement with the experimental data but they differ clearly in velocity magnitudes [28]. Concerning the impeller power and flow numbers, the SGS models give excellent predictions and the KET model provides the best results [28]. The author also compares the results with Reynolds-averaged Navier-Stokes turbulence models (realisable k- $\epsilon$  model, standard k- $\omega$  model, Reynolds stress model) [28]. The disadvantage of the LES approach is the computing cost, but a hybrid simulation approach can overcome this problem on industrial applications [28]. Given the ultimate goal, which is to predict the displacement of microorganisms within the digester, the modelling of these flows requires precision, thus we chose the LES turbulence model which offers the most accurate results. In this work, we use the dynamic Lagrangian SGS model of turbulence developed by Meneveau et al. (1996) [40]. This approach allows us to optimise the SGS model coefficients [40]. The Lagrangian model is derived by minimising the error incurred by inserting the Smagorinsky model into the Germano identity along fluid-particle trajectories [40]. This method is applicable to complex-geometry and unsteady flows [40].

## 2- MATERIALS AND METHODS

### 2-1- THE CHARACTERISATION OF SUBSTRATES

The study examines the biochemical potential (BMP) of the vinasse. The vinasse and the sewage sludge for the BMP tests come from the active mesophilic biogas plant of the sugar-cane distillery Rivière du Mât (Saint-Benoit, Reunion Island). The inoculum was sieved through a 900-1000  $\mu\text{m}$  mesh screen in order to remove coarser materials. No pre-treatment was done on the substrates. The inoculum is stored at ambient temperature and then incubated at 37°C which is the test temperature before the BMP tests. The vinasse is stored at 4°C for few days until the tests.

The substrates are characterised with TS, volatile solids (VS) and pH triplicate measurements. The TS content is obtained after drying 20g of the samples for 24h at 105°C and the VS content after burning the dried samples for 4h at 550°C. The pH value is determined with a pH metre. The measured characteristics are the TS, the VS, the pH, the chemical oxygen demand (COD), the total organic carbon (TOC), the ammonium, the alkalinity and the Kjeldahl azote. The vinasse is autoclaved for sterilisation. The samples were then homogenised with the Ultra turrax IKA T25 digital at 12,000 rpm for 10 min. The chemical tests were conducted on the Hach Lange DR5000 Spectrophotometer, using the Hach Lange tests LCK 914 (COD), LCK 381 (TOC), LCK 303 (Ammonium), LCK 362 (Alkalinity) and LCK 338 (Kjeldahl nitrogen). The values are reported in Table 2. According to the results, the C/N ratio of the vinasse is 15.23.

Substrates	TS %	VS %	pH	COD $\text{gO}_2\cdot\text{L}^{-1}$	TOC $\text{mg}\cdot\text{L}^{-1}$	Ammonium $\text{mg}\cdot\text{L}^{-1}$	Alkalinity $\text{mg}\cdot\text{L}\cdot\text{CaCO}_3^{-1}$	Kjeldahl nitrogen $\text{mg}\cdot\text{L}^{-1}$
Sewage sludge	2.2480	0.9700	4.84	9.93	-	517.67	-	-
Vinasse	6.6391	4.0378	7.57	79.67	27646.11	239.00	3651.25	1815.00

Table 2: Physico-chemical characteristics of vinasse and sewage sludge.

## 2-2- THE BIOCHEMICAL POTENTIAL TESTS AND THE PILOT TEST

The BMP tests are done using the Automatic Methane Potential Test System II (AMPTS II - Bioprocess Control). The BMP tests were performed according to the latest recommendations [41]. The system includes 15 digesters of 500mL. The substrate quantity is calculated with the ratio of VS from the inoculum to VS from the substrate (I/S ratio). The recommended ratio is between two and four [41]. In these BMP tests, the ratio used is two. All the tests are carried out in triplicate. Two controls must also be made, the blank assay and the positive control. The blank assay allows us to estimate the endogenous methane production. The positive assay enables the inoculum activity to be validated [41]. The digesters are supplemented with distilled water to obtain identical test volumes. The BMP tests were carried out under mesophilic conditions at 37°C.

The pilot (10L) test is also carried out with the vinasse in mesophilic conditions for 41 days. The working volume is 7L and 1.6L are added during the period test because of analysis. The initial pH of the digestion medium is 7.29. The produced biogas is analysed daily in order to measure the percentage of methane.

## 3- CFD MODELLING

### 3-1- MODEL ASSUMPTIONS

At the beginning, we consider the following hypotheses for the development of the mathematical 3D single-phase model: digestion is carried out in a mesophilic regime (37°C); vinasse is a Newtonian fluid; sewage sludge is a non-Newtonian fluid; the digestion medium is isothermal and incompressible; the digester is heated at its walls; the impeller initial rotation speed  $N$  is 500 rpm.

### 3-2- CONSERVATION EQUATIONS

The conservation of mass and momentum equations with the Boussinesq approximation are used. The momentum equation and the heat transfer equation are coupled by the Boussinesq term. The space-filtered equations of an incompressible Newtonian fluid can be written as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial(\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial(\sigma_{ij})}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + g \beta \bar{\theta} e_z \quad (2)$$

Where  $t$  is the time,  $\rho$  is the fluid density,  $\bar{u}_i$  is the filtered velocity component in the  $x_i$  direction,  $\nu$  is the kinematic viscosity,  $\bar{P}$  is the filtered pressure,  $\bar{\theta}$  is the filtered temperature,  $g$  is the gravity force,  $\beta$  is the thermal expansion coefficient and  $\tau_{ij}$  is the subgrid scale (SGS) stress tensor.

The filtered heat transfer equation in convection-diffusion is:

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{u}_i \frac{\partial \bar{\theta}}{\partial x_i} - \frac{\partial^2 D_T \bar{\theta}}{\partial x_j \partial x_j} = 0 \quad (3)$$

Where  $D_T = \lambda / \rho C_p$  is the thermal diffusion coefficient,  $C_p$  is the specific heat and  $\lambda$  thermal conductivity .

The stress tensor for Newtonian incompressible fluid is:

$$\sigma_{ij} = \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (4)$$

The SGS stress tensor for incompressible flow is expressed as:

$$\tau_{ij} = -2\mu_t \bar{S}_{ij} \quad (5)$$

$$\bar{S}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (6)$$

$$|\bar{S}_{ij}| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \quad (7)$$

Where  $\mu_t^{SGS} = \rho L_s^2 |\bar{S}|$  is the SGS turbulent viscosity,  $\bar{S}_{ij}$  is the rate of strain,  $L_s = \min(\kappa d, C_s \Delta)$  is the mixing length,  $\kappa$  is the Von Karman constant,  $d$  is the distance to the closest wall,  $C_s$  is the Smagorinsky constant, and  $\Delta = \sqrt[3]{V}$  in which  $V$  is the volume of the computational cell.

We use the dynamic Lagrangian model. In this model, the fluid particle trajectory for earlier time  $t' < t$  is [40]:

$$z(t') = x - \int_{t'}^t \bar{u} [z(t''), t''] dt'' \quad (8)$$

### 3-3- RHEOLOGICAL EXPRESSIONS

The non-Newtonian viscosity for power-law fluids is expressed as:

$$\eta = k \dot{\gamma}^{n-1} \quad (9)$$

Where  $k$  is the consistency coefficient,  $\dot{\gamma}$  is the shear rate and  $n$  is the power-law index.

The consistency coefficient and the power-law index for liquid manure are defined as [42]:

$$k = \left[ 8.722 e^{(4830/T + 0.58319 \times TS)} \right] \times 10^{-10} \quad (10)$$

$$n = 0.6894 + 0.0046831 \times (T - 273) - 0.042813 \times TS \quad (11)$$

Where  $T$  is the temperature.

The density  $\rho$ , the specific heat  $C_p$  and thermal conductivity  $\lambda$  are expressed [12], [43], [44]:

$$C_p = 4187.5 - 28.9 \times TS \quad (12)$$

$$\lambda = 0.6173 - 0.0069 \times TS \quad (13)$$

$$\rho = 0.0367 \times TS^3 - 2.38 \times TS^2 + 14.6 \times TS + 1000 \quad (14)$$

### 3-4- DIMENSIONLESS NUMBERS

The two dimensionless numbers typically used in a stirred vessel are the power and flow numbers expressed as [45]:



$$N_p = \frac{P}{\rho N^3 d^5} \quad (15)$$

$$N_Q = \frac{Q}{Nd^3} \quad (16)$$

Where  $P$  is the power input,  $N$  is the impeller rotation speed,  $d$  is the impeller diameter and  $Q$  is the flow rate through the moving zone.

The power and flow numbers are two good indicators for model validation. We will compare their values, as Wu [28], to measured values in literature data [46]:  $N_p=0.3$  and  $N_Q=0.56$ .

### 3-5- THE PHYSICAL DESCRIPTION OF SUBSTRATES

Our study is about mesophilic anaerobic digestion whose optimum temperature is 37°C. This is an important parameter because the physical parameters depend on it. Rheological experimental measurements at different temperatures (10°C, 25°C, 40°C and 60°C) showed that the viscosity and the yield stress decrease as the temperature increases [11]. Moreover, this study showed that the rheological behaviour is irreversibly altered by the thermal history [11].

Firstly, we consider the vinasse. The vinasse has a pseudoplastic behaviour for temperatures between 10 and 20°C [47]. Indeed, when the temperature is superior to 30°C, the power-law index is close to 1, indicating an approach to the Newtonian model [47]. In another study, the vinasse is considered as Newtonian fluid [48]. The sludge treated in a Wastewater treatment plant anaerobic digester is also considered as Newtonian fluids [10]. The total dissolved solids (TDS) contents sludge of this plant were 2.5, 5.4 and 9.1% [10]. We will thus perform simulations on the flow of vinasse and sludge, which are Newtonian. The corresponding physical parameters are given in Table 3.

Fluid	Density (kg.m <sup>-3</sup> )	Dynamic viscosity (Pa.s)
Vinasse	1044.69	0.001 009 7
Sludge	999.66	0.065

Table 3: Physical parameter values of vinasse at 35°C (Newtonian model) [10], [48].

Secondly, we study the flow of sewage sludge which is a non-Newtonian fluid. We can use the liquid manure rheological properties to characterise sewage sludge [10]. In order to compare our results, we use the same properties as Wu [12], [13], [28] (Table 2). The manure slurry exhibits pseudo-plastic fluid behaviour when TS is superior to 2.5% [13]. The manure is modelled with a pseudoplastic model in studies [10], [12], [13], [16], [28], [42], [43]. Moreover, viscosity and shear stress increase exponentially as TS increases [12]. The lower and upper limits of viscosities are calculated from the equation (11) [12]. The physical properties for different values of TS are given in Table 4.

TS %	T °C	k Pa.s <sup>n</sup>	n	Density kg.m <sup>-3</sup>	$\eta_{\min}$ Pa.s	$\eta_{\max}$ Pa.s	$\dot{\gamma}$ s <sup>-1</sup>	$C_p$ J.kg <sup>-1</sup> .°C <sup>-1</sup>	$\lambda$ W.m <sup>-1</sup> .°C <sup>-1</sup>
2.5	35	0.042	0.710	1000.36	0.006	0.008	4186.78	4186.78	0.6171
5.4	35	0.103	0.639	1000.72	0.009	0.025	50-702	4185.94	0.6169
7.5	35	0.525	0.533	1001.00	0.03	0.17	11-399	4185.33	0.6168
9.1	35	1.052	0.467	1001.31	0.07	0.29	11-156	4184.87	0.6167
12.1	35	5.885	0.367	1001.73	0.25	2.93	3-149	4184.00	0.6165
15	17-24	31.3	0.30	973.0	3.35	44.24	0.61-24.37	4183.17	0.6163
20	17-24	35.4	0.29	1091.8	3.69	48.6	0.64-24.14	4181.72	0.6159

Table 4: Physical parameter values of manure (power law model) [12], [15], [28], [42].

### 3-6- GEOMETRY AND MESHING

In order to compare our results with simulations conducted by Wu [28], we used the same geometry. This consists of a cylindrical tank with 0.152m diameter (with a 25° slope on the hopper bottom) and 0.26m liquid height. The agitation is performed by a Lightnin A313 impeller (0.062m diameter). The digester geometry is given in Figure 1.

Concerning the meshing approach, two main strategies are used for modelling stirred tanks: the reference frame (RF) (known as the “frozen rotor approach”) and the sliding mesh (SM) [49]. The RF convergences fast, but it is suitable only for steady-state flows [49]. In contrast, SM is suitable also for unsteady flows, for which it provides a time-dependent solution, but at the expense of significant computational effort and time [49]. A comparison between the multiple reference frame (MRF) and SM techniques showed that the SM technique is more accurate, but it is also much more time-consuming than the MRF [20]. In recent studies, the MRF is widely used for its simplicity and the quality of the results [32], [33], [50]–[52]. However, transient simulations require the SM method, some authors used MRF method for a first approximation and then SM method [25], [53]; whereas others used SM method directly [19], [39].

In our study, our choice will be based on the SM method to characterise the impeller rotation. The cylindrical moving zone contains the impeller with 0.098m diameter, and the rest of the digester is the stationary zone. The cylindrical moving zone is 0.234m height and 0.152m diameter. The two zones are schematised in Figure 1. The mesh will be then refined at the digester edges, at the interface between the stationary zone and the moving zone, and at the agitator edges.

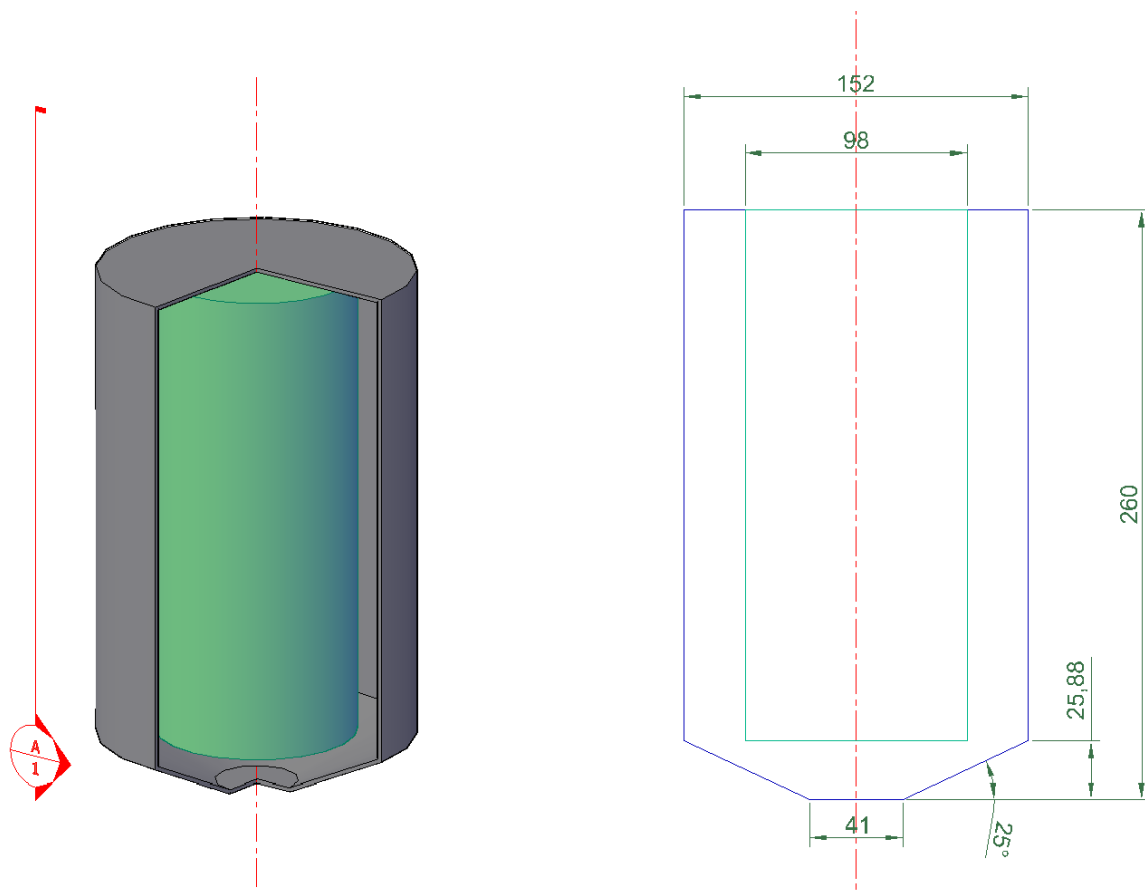


Figure 1: Digester geometry (mm).

## 4- RESULTS AND DISCUSSION

The cumulated BMP curves (Figure 2) shows that vinasse is a complex substrate which can be difficult to treat in anaerobic digestion. The maximum production of methane is not reached beyond 45 days. The maximum methane production is 284.29  $L_{CH_4} \cdot kg_{COD}$  in the BMP test and 114.64  $L_{CH_4}$  in the pilot test. The biogas production of the pilot is 270.22 L. The vinasse is composed of complex molecules like proteins. The COD is also quite difficult to treat, and these curves show why in most digesters using sugar cane vinasse, only half of the COD is treated by anaerobic digestion.

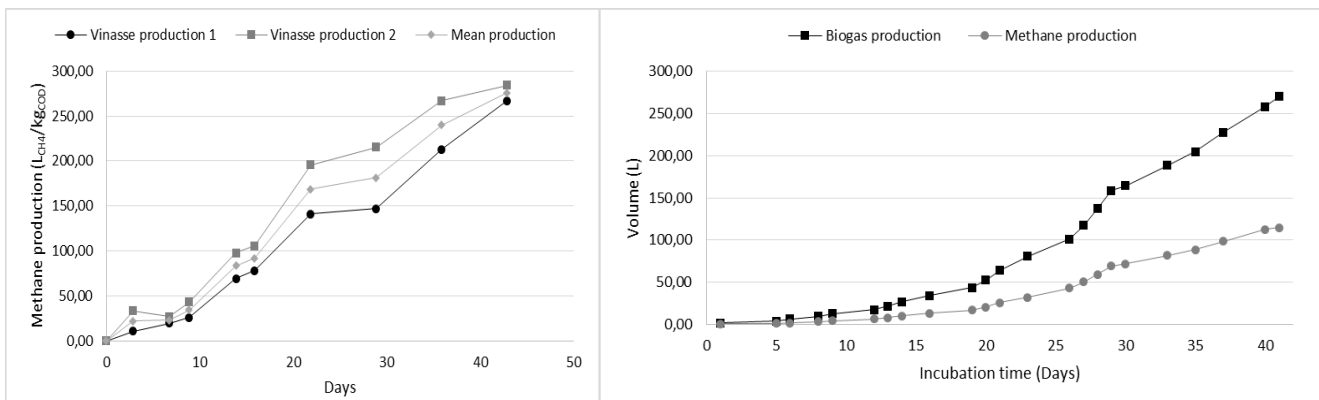


Figure 2: Cumulative methane production average as a function of time of vinasse in BMP (left) and pilot (right) tests.

The results from CFD simulations of Newtonian and non-Newtonian fluids flow will be presented in further studies. The simulations will allow us to choose the frequency and the intensity of mechanical stirring of the pilot digester. Furthermore, the fluid movement allows contact between the microorganisms and the substrate. Thus, the flow is linked to the substrate composition and the digestion rate, which are part of ADM1 parameters. The fluid rheological properties depend on the substrate composition, but also on the digestion rate. In other words, some ADM1 results, the digestion rate and the composition, are useful in CFD simulations, and CFD simulations bring results, the velocities profiles, which are not considered in ADM1 model.

## 5- CONCLUSION

This article presents the reasons justifying the importance of setting up a CFD model of industrial digesters. The main purposes being the strong link between the flows and the biogas yield as well as the physical characteristics of the substrates treated in anaerobic digestion. In conclusion, the CFD model is naturally based on the Navier-Stokes equations. This model is also coupled with the heat transfer equation given the impact of temperature on the process. In addition, we use the LES approach to model turbulence with the Lagrangian dynamic model, to predict turbulent flow accurately. The modelling of the digester will be carried out for Newtonian fluids and non-Newtonian fluids, and for different dry matter rates (both wet and dry digestion).

Currently, we develop a single-phase model. Then, we will realise the multiphase model (liquid, gas, solid), the liquid phase will be the digestion medium, the gaseous phase will be the biogas and the solid phase will be the microorganisms. It will thus be possible to study the propagation of microorganisms within the digester. Subsequently, we want to couple the CFD model with the ADM1 model in order to study the impact of flows (influenced by mechanical agitation) on the biogas production and on the inhibition phenomena. The CFD model is an additional tool for digester configuration choices. The emphasised inhibition phenomenon will be the detachment of the biofilm, which is a recurring problem in mechanically stirred anaerobic digesters.

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