Analysis of anaerobic digester mixing: comparison of long shafted paddle mixing vs gas mixing

U. Bergamo, G. Viccione, S. Coppola, A. Landi, A. Meda and C. Gualtieri

ABSTRACT

The anaerobic digestion (AD) process is influenced by a variety of operation parameters, such as sludge rheology, mixing, temperature, solid retention time (SRT), hydraulic retention time (HRT) and solids concentration. The optimum in the mixing lies somewhere between no-mixing and continuous mixing, as the lack or excessive mixing can lead to poor AD performance instead. A three-dimensional computational fluid dynamics steady/unsteady model, incorporating the rheological properties of the sludge, was developed and applied to quantify mixing in a full-scale anaerobic digester. Mechanical and gas mixing solutions were taken into account, keeping constant the daily energy consumption. Results, consisting of velocity magnitude and patterns, dead zone formation and turbulence levels were discussed. Compared to the mechanical mixing, gas mixing had lower percentage of dead zones (about 5% against 50%), larger maximum velocity (about 3 m/s against 1 m/s) as well as larger turbulent kinetic energy levels (0.24 m^2/s^2 against 0.001 m^2/s^2).

Key words | anaerobic digester, biogas, CFD, gas mixing, mechanical mixing, sludge rheology

U. Bergamo
G. Viccione (corresponding author)
S. Coppola
Department of Civil Engineering,
University of Salerno,
via Giovanni Paolo II, 132, 84084 Fisciano,
Italy
E-mail: *gviccion@unisa.it*

A. Landi
MEA S.R.L.,
Foro Buonaparte, 70, 20121, Milano,
Italy

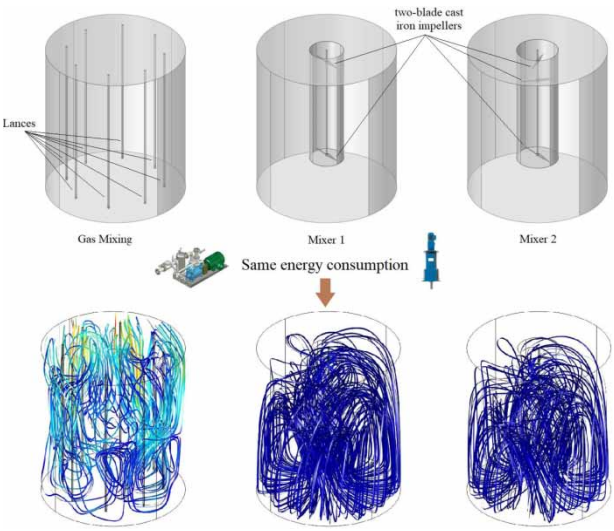
A. Meda
BHU Umwelttechnik GmbH,
Einsteinstrasse 57, 70229 Leonberg,
Germany

C. Gualtieri
Department of Civil, Architectural and Environmental Engineering,
University of Naples Federico II,
via Claudio, 21, 80125 Naples,
Italy

HIGHLIGHTS

- Mechanically stirred and gas-mixed anaerobic digestion solutions were compared.
- Daily energy consumption (E = 140.4 kWh) was kept constant.
- Detailed CFD modelling for non-Newtonian sludge in full-scale anaerobic digesters.
- Flow patterns, dead zones and turbulence levels were compared and discussed.
- Gas mixing yielded better results in terms of velocities, dead zones and turbulence levels.

GRAPHICAL ABSTRACT



doi: 10.2166/wst.2020.248

INTRODUCTION

Anaerobic digestion is one of the most long-established processes for the stabilization of sewage sludge (Tchobanoglous *et al.* 2014). It is widely used to convert waste into valuable end products such as biogas (Lisowyj & Wright 2020). A number of advantages can be ascribed to the use of anaerobic digestion. First of all, it is a source of renewable energy, replacing fossil fuels, such as gas petrol liquid for cooking included as well as allowing a reduction of gas emissions into the atmosphere from landfilling sites (Angelidaki *et al.* 2003). Anaerobic digestion can be employed to treat landfill leachate (Abuabdou *et al.* 2018, 2020), a highly contaminated wastewater which when accidentally released into the environment poses a severe threat for aquifers, aquatic ecosystems and human health (Stoppiello *et al.* 2020). Digesters in wastewater treatment plants to treat sewage sludge consist of insulated concrete or steel structures, usually cylindrical or egg-shaped, with a conical bottom from which the digested sludge is extracted. Recently, a renewed interest in anaerobic digesters has appeared (Kariyama *et al.* 2018; Sadino-Riquelme *et al.* 2018; Wang *et al.* 2018). Factors such as sewage sludge disposal and the pursuit of climate protection objectives gave reason to re-think the classical, long established approaches concerning wastewater and sludge treatment for sewage treatment plants, even in the case of small to medium size (approximately 5,000 to 50,000 population equivalent). In Germany, for instance, MULEWF (2014) and DWA (2015) reports proved that it is profitable to implement an anaerobic sludge digestion with biogas utilization in a co-generation unit for plant of small size against the common practice of aerobic simultaneous sludge stabilization. This new trend is giving a boost to the implementation of the anaerobic sludge digestion technology (Zare *et al.* 2019).

The anaerobic digestion process is sensitive to a large number of factors: temperature, retention time, nutrients concentration, pH and inhibitors concentration, mixing type and intensity (Dapelo 2016). Temperature is a main factor affecting the process. Appels *et al.* (2008) recommended temperature variation within 0.6 °C per day. Solid (SRT) and hydraulic (HRT) retention times are important parameters as well, depending on geometry, flow rate, and recirculation system. The former indicates the average time that solids, and the bacteria living on them, spend inside the digester, while the latter refers to the liquid fraction. Despite biomass retention being recognised among the most important parameters of anaerobic digestion providing SRT for the methanogens, poor biomass retention in the conventional anaerobic digesters is often found (Lin *et al.* 2013; Shi *et al.* 2017). The pH is a key parameter related to the efficient running of a digester. Most fermentative bacteria can thrive in a wide range of pH, between 4.0 and 8.5, but their by-products depend on pH (Dapelo 2016).

Effective anaerobic digestion is highly dependent on mixing system and frequency as well (Subramanian *et al.* 2015; Wang *et al.* 2019). As defined in the *Handbook of Industrial Mixing: Science and Practice* (Paul *et al.* 2004), mixing is 'the reduction of inhomogeneity in order to achieve a desired process result. The inhomogeneity can be one of concentration, phase, or temperature. Secondary effects, such as mass transfer, reaction, and product properties are usually the critical objectives'. Therefore, mixing promotes the establishment of a homogeneous environment for anaerobic digestion, by reducing temperature, concentration and other field gradients inside the reactor (Appels *et al.* 2008; Sindall *et al.* 2013). Meegoda *et al.* (2018) provided a comprehensive list of issues related to digester mixing.

Solid settling, short-circuiting, dead-zone, and scum formation arising from poor mixing are still major problems leading to less than optimal biogas production. Borole *et al.* (2006) proved that a pilot-scale digester with dairy manure yields continuous methane production with mixing, which soon deteriorates without agitation. On the other hand, the literature shows contributions where biogas production is sustained in unmixed conditions (Ghaly 1989; Wang *et al.* 2019). Similarly, intermittent mixing is sometimes recommended (Lindmark *et al.* 2014; Leite *et al.* 2017). In fact, resting times can result in higher methane yield compared to continuous mixing while avoiding floating layer formation. The reason behind higher gas production is related to a balance reaching among microorganisms involved in the anaerobic conversion of biomass to methane. In addition, intermittent mixing is preferred to save energy compared with continuous mixing solutions (Singh *et al.* 2020). In addition, intermittent mixing results in lower power consumption and maintenance costs related to mixing solutions where two or more digesters are installed in parallel. In this case, it is possible to use one single biogas compressor, shared by the digesters, feeding the units alternately with biogas. On the contrary, continuous mixing requires several compressor units

(usually one per digester) or a larger common compressor unit with a distribution and regulation system for biogas flow splitting. Comprehensive reviews of mixing in anaerobic digesters are given in Lindmark *et al.* 2014; Kariyama *et al.* 2018; and Singh *et al.* 2019.

There are three main mixing methods generally adopted in large-scale application of AD: mechanical mixing, gas mixing and pumped liquid recirculation through externally installed pumps or submerged jets (Qasim 1999).

Mechanical stirring (Manea & Robescu 2012) can be done using: (1) low-speed with large impellers (one to three levels) without draft tube, installed on the digester roof; (2) high speed, vertical mixers with one small impeller with draft tube, installed on the digester roof; (3) high speed, inclined mixers with one small impeller installed through the digester wall. In all cases, the rotating impellers displace the sludge, mixing the digester contents. Low-speed turbines usually have one cover-mounted motor with two turbine impellers located at different sludge depths. Biogas production is affected by impeller design, eccentricity, bottom and inter impeller clearance, baffles and position of draft tube. Incorrect choice of impellers and operating speed can lead to ineffective mixing. Singh *et al.* (2019) reported that the geometry of the impeller has a significant effect on digester performance. The impeller should be chosen considering sludge rheology and turbulence to achieve an optimum design (Wu 2010; Lindmark *et al.* 2014; Torotwa & Ji 2018).

In gas mixing systems (Chandran *et al.* 2017; Serna-Maza *et al.* 2017), gas recirculation inside the digester acts as mixer. They can be unconfined or confined: the former are designed to collect biogas at the top of the digesters, compress and then discharge it through a series of bottom diffusers or radially placed top-mounted lances. In the latter systems, biogas is collected at the top of the anaerobic digesters, compressed, and discharged through confined tubes where an airlift effect is induced. The design of gas mixing systems is currently based on empirical correlations using the power input per unit volume [W/m3], the gas flowrate per unit volume of sludge [$m^3/(h{\cdot}m^3)$], total solids (TS) [%], sludge rheology, and digester aspect ratio. Gas mixing systems have the advantage that they do not need moving parts installed inside the digester (Lindmark *et al.* 2014).

Pumping systems withdraw a portion of the biomass and reinject it tangentially through nozzles at the bottom of the tank (Sajjadi *et al.* 2016). This type of mixing, however, has been reported to be the least effective and has been rarely used alone for mixing (Tang 2009). Pumped recirculation does not increase the mixing, despite it having a strong influence on flow pattern (Meister *et al.* 2018).

Vesvikar & Al-Dahhn (2005) indicated that areas in which the speed was less than 5% of the maximum speed were considered as dead or inactive zones. Formation of dead zones depends on the viscosity of slurry which increases with the increasing of the TS content, as later shown in the sludge rheology sub-section. To quantify velocity fields, Wu (2010) defined three velocity ranges:

- areas with low velocity ($0 < v < 0.05$ m/s),
- areas with medium velocity ($0.05 < v < 1$ m/s),
- areas with high velocity ($v > 1$ m/s).

The turbulent kinetic energy (Sindall *et al.* 2013) and the shear rate at the bottom (Leonzio 2018) represent other parameters to characterize mixing in anaerobic digesters. Other mixing indicators are given in Teixeira & Do Nascimento Siqueira (2008), Gualtieri (2010), Angeloudis *et al.* (2016) and Ouro *et al.* (2018).

Although computational fluid dynamics (CFD) is widely applied to investigate environmental flows (Blocken & Gualtieri 2012; Amicarelli *et al.* 2020) as it enables the numerical simulation of flow patterns as well as various output parameters in anaerobic digesters, e.g. vorticity, turbulence levels, etc., the number of CFD studies on anaerobic digestion is still limited (Table 1). The main challenge arises in the attempt of successfully simulating a time varying process, solving the Navier-Stokes equations adapted to account for the presence of a non-Newtonian fluid flow. Investigations of digester mixing using CFD have been performed by many researchers, e.g. Wu & Chen (2008), Terashima *et al.* (2009), Martínez Mendoza *et al.* (2011), Wu (2011, 2012, 2014), Dapelo *et al.* (2015), López-Jiménez *et al.* (2015), Dapelo & Bridgeman (2018), Leonzio (2018), and Meister *et al.* (2018). Wu & Chen (2008) demonstrated that flow patterns for Newtonian and non-Newtonian fluids are completely different. Terashima *et al.* (2009) evaluated the performance of the laminar flow agitation numerically, introducing the uniformity index parameter. Martínez Mendoza *et al.* (2011) modelled the flow inside an anaerobic digester numerically, showing that the distribution of velocities and streamlines is vital for determining the occurrence of dead regions. Manea & Robescu (2012) developed three-dimensional numerical simulations, obtaining the optimum geometry and nominal shaft speed for the digester under study. Wu (2011) applied six turbulence models (see Table 1) to predict mixing flow pattern in a full-size digester. Later on, Wu (2012) simulated the mixing agitation using the large eddy simulation (LES) turbulence method, assuming the sludge as a pseudo-plastic. In this study, Wu (2012) used the sliding mesh method to characterize the impeller rotation.

Table 1 | Applied CFD methods, turbulence models and main results obtained in the surveyed literature

Reference	CFD method	Turbulence model	Main results
Vesvikar & Al-Dahhn (2005)	Finite difference	k-ε for liquid phase, zero equation model for gas phase	Dead zones, flow pattern, gas distribution
Wu & Chen (2008)	Finite volume	k-ε for sludge treated as single equivalent phase	Dead zones, flow pattern
Terashima *et al.* (2009)	Finite element	No turbulence, homogeneous single-phase treated as laminar	Sludge concentration in full-scale anaerobic digester
Wu (2010)	multiple reference frame (MRF) for propeller	k-ε for sludge treated as single equivalent phase	Dead zones, mixing energy level (Equation (2))
Wu (2011)	MRF for propeller	k–ε model, RNG k–ε, realizable k–ε (Shih *et al.* 1995), standard k–ω, SST k–ω, Reynolds stress model	Flow pattern, power and flow number (Paul *et al.* 2004)
Wu (2012)	MRF for propeller	Large eddy simulation or sludge treated as single equivalent phase	Flow pattern, power and flow number (Paul *et al.* 2004)
Manea & Robescu (2012)	MRF for propeller	No turbulence, homogeneous single-phase treated as laminar	Flow pattern, impeller geometry optimization
Wu (2014)	Eulerian multiphase flow model for gas mixing	SST k–ω model	Flow pattern, velocity gradient (Equation (1)), breakup number (Coufort *et al.* 2005)
Dapelo *et al.* (2015)	Euler-Lagrangian multiphase flow model for gas mixing	Reynolds stress model	Flow pattern, shear rate (Leonzio 2018)
López-Jiménez *et al.* (2015)	Finite volume method	k-ε for sludge treated as single equivalent phase	Dead zones, flow pattern, recirculation regions
Chandran *et al.* (2017)	Eulerian multiphase flow model for gas mixing	No turbulence	Velocity magnitude
Dapelo & Bridgeman (2018)	Euler-Lagrangian multiphase flow model for gas mixing	Reynolds stress model	Apparent viscosity (Equation (4)), flow pattern, shear rate (Leonzio 2018)
Leonzio (2018)	Euler-Euler/Euler-Lagrangian multiphase flow model for gas mixing	k–ε model	Flow pattern, dead zones, shear rate
Torotwa & Ji (2018)	Euler-Euler multiphase flow model for gas mixing	k–ε model	Sludge concentration in laboratory-scale anaerobic digester, flow pattern

Three subgrid scale (SGS) models are investigated, namely the Smagorinsky-Lilly model, the wall-adapting local eddy-viscosity model, and the kinetic energy transport (KET) model. Again, Wu (2014) simulated the gas mixture using a Eulerian multiphase flow model. The review paper of Lindmark *et al.* (2014) summarized a number of CFD studies evaluating different mixing methods, their modeling approaches and validation methods. López-Jiménez and co-workers (2015) studied the anaerobic digester applying the Reynolds Averaged Navier-Stokes (RANS) equations closed with the standard k-ε turbulence model. A single-phase model was applied considering both Newtonian and non-Newtonian rheology for the sludge simulations, allowing the identification of dead zones as well as possible shortcuts. Leonzio (2018) conducted research on the best mixing systems and geometric configuration for an anaerobic digester with CFD analysis. Meister *et al.* (2018) conducted a CFD analysis based on the finite volume method of the mixing of Newtonian and non-Newtonian sludge in anaerobic digesters to investigate the effects of operational variations on TS concentration. The study revealed that the operation with pumped recirculation and impeller rotating within a mechanical draft tube yielded the highest level of mixing. Dapelo & Bridgeman (2018) developed a hybrid Euler-Lagrange (EL) CFD model to simulate an anaerobic digester mixed with gas under pressure. The movement of the sludge is driven by the transfer of the moment from the bubbles to the fluid. Recent comprehensive reviews on CFD applied to anaerobic

digesters can be found in Sadino-Riquelme *et al.* (2018), Wang *et al.* (2018) and Singh *et al.* (2019). Table 1 summarizes applied CFD numerical methods for discretizing governing equations, turbulence models and main outcomes for the above discussed reports.

Few reports dealing with the analysis of full-scale anaerobic digesters are available (Monteith & Stephenson 1981; Kushkevych *et al.* 2020) because laboratory-scale digesters are typically adopted to evaluate a full-scale application of anaerobic digestion, see e.g. Wu & Chen (2008) and Bouallagui *et al.* (2010). However, scale effects could prevent a straightforward projection of operational data from laboratory-scale results to the full-scale designs.

In this study, full-scale gas mixing and mechanical mixing of a pseudo-plastic sludge of given rheology was compared at same operational conditions: input/treated sludge (75 m^3/day), TS (6%), temperature T (35 °C) and daily energy consumption E (140.4 kWh). For this purpose, a CFD analysis was carried out, an approach where literature studies are still limited. The comparative analysis was carried out in terms of the distribution of velocity magnitude and pattern, turbulent kinetic energy and the formation of dead zones. Consumed energy E, derived from the real case consisting of a gas mixing anaerobic digester, was kept constant for two hypothetical cases consisting of two mechanical mixings, as next described.

MATERIALS AND METHODS

Case study description

The present fluid-dynamic investigation is referred to one of the two gas mixed anaerobic digesters of the wastewater treatment plant (WWTP) connected to the municipality of Keszthely (Hungary). The WWTP is designed to serve 125,000 population equivalent (PE) as maximum during the tourist season (Figure 1(a)). Each digester is 11.30 m of inner diameter and 16 m high (14 m normal sludge filling level), for a sludge volume $\Omega = 1{,}404\ m^3$ per digester.

The sludge quantity and composition are given in Table 2.

In the actual configuration, eight vertical lances, 0.075 m of inner diameter and evenly spaced on a 4 m radius ring tube fed by a compressor, inject the biogas at a distance of 0.37 m from the bottom (Figure 1(b)). The gas mixing works discontinuously, according to the sequence of 120 min divided into six phases of 20 min each; see Table 3. During each phase, a group of four adjacent lances is activated and fed with the full biogas flow delivered by the compressor.

According to the operating conditions adopted for the digesters of the WWTP, the number of working hours in a day of the gas mixing system – considering one single digester – is therefore $n_h = 8$ overall. This modality was recently proved in Singh *et al.* (2019, 2020) as the best to maximize biogas production in intermittent mixing. The electric power absorbed by the compressor is calculated by means of the following equation:

$$P = \frac{Q_g\ dp\ p_s}{1000}\ [kW] \quad (1)$$

where $Q_g = 282\ Nm^3/h$ is the total biogas flow rate at normal conditions delivered by the compressor, $dp = 147.1$ kPa is the compressor discharge pressure, $p_s = 0.423\ Wh/(Nm^3\ kPa)$ is the compressor specific power consumption (Table 4). Daily averaged energy consumption for one digester is therefore given by $E = P\ n_h = 140.4$ kWh.

In the present study, we consider two long shafted paddle mixing impellers as possible alternatives to the

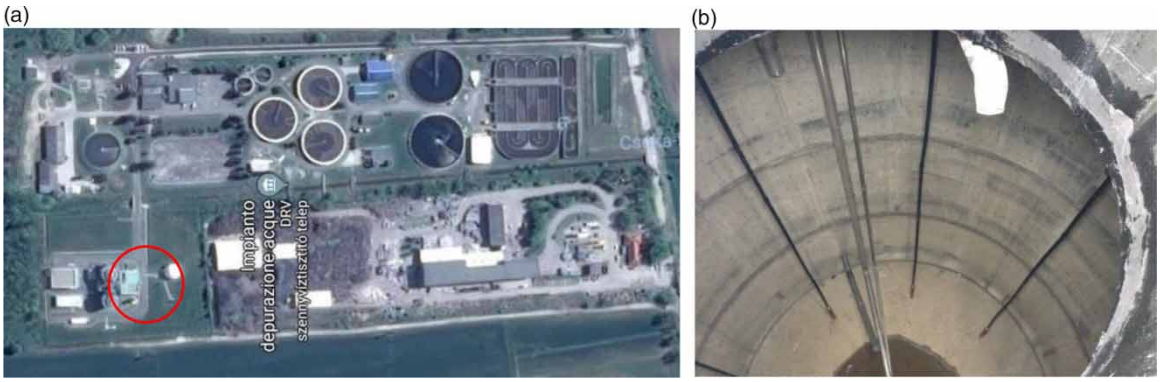


Figure 1 | (a) WWTP in Keszthely (Hungary). Red circle indicates the position of the digesters. (b) Inner side of one of the digesters with the gas recirculation lances. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2020.248.

Table 2 | Sludge quantity and composition (total for both digesters)

	Primary sludge	Biologic excess sludge
Volumetric flow [m^3/d]	83	68
Dry solids (DS) concentration [kg/m^3]	61	61
Organic dry solids (ODS) [%]	71	61

gas mixing system. The geometric specifications of the digester's shape and adopted mixers are summarized in Table 4.

The rpm of the mixer blades is derived on the basis of the P–rpm relationship given in Table S1, Supplementary material.

The linear regression yields for Mixer 1:

$$P_1 = 0.2109\text{rpm} - 0.4014 \quad R^2 = 0.9984 \tag{2}$$

whereas Mixer 2 is well described by a linear function crossing the origin (0,0):

$$P_2 = 0.27\,\text{rpm} \tag{3}$$

Power consumption for mechanical mixing (working continuously 24 h) was derived by keeping E constant. Since the daily averaged power consumption for one digester is $\bar{P} = E/24 = 5.87$ kW, the number of revolutions therefore adopted are $\text{rpm}_1 = 29.9\ \text{min}^{-1}$ (from Equation (2)) and $\text{rpm}_2 = 21.6\ \text{min}^{-1}$ (from Equation (3)) for Mixer 1 and Mixer 2 respectively.

Sludge rheology

Sludge in anaerobic digesters as wastewater, slurries from food processing plants and animal manure exhibit a non-Newtonian behaviour (Sajjadi *et al.* 2016). In particular, slurry flows with TS $\geq$ 2.5% can be described as non-Newtonian pseudo-plastic fluids (Meister *et al.* 2018). From a general point of view, the stress tensor τ [Pa] is defined in terms of the shear rate tensor γ' [s^{-1}] and the dynamic viscosity η [Pa s]:

$$\tau_{ij} = \eta\gamma'_{ij} \tag{4}$$

in which the shear rate components are given by

$$\gamma'_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i) \tag{5}$$

Table 3 | Sequence of lances operations for the biogas mixing on the digesters, referred to as 'A' and 'B', respectively, of the Keszthely WWTP

Phase nr.	1	2	3	4	5	6
Phase duration [min]	20	20	20	20	20	20
Cumulative time [min]	20	40	60	80	100	120
Action	digester A, lances 1 – 4	pause	digester B, lances 1 – 4	digester A, lances 5 – 8	pause	digester B, lances 5 – 8

Table 4 | Digester's geometry and adopted mixers

Digester inner diameter [m]	Digester total height [m]	Sludge filling level in digester [m]	Total sludge volume [m^3]	Daily treated sludge volume [m^3/d]
11.30	16	14	1,404	75
Gas mixing	**Lances' outlet from bottom [m]**	**Discharge pressure [kPa]**	**Total gas volume flow rate [Nm^3/h]**	**Specific power [Wh/(Nm^3 kPa)]**
8 lances ϕ75 mm half working at a time	0.37	147.1	282	0.423
Mixer 1	**Diameter [m]**	**Distance from the bottom [m]**	**Distance between impellers [m]**	
Propeller, 2 impellers, 2 blades per impeller	2.5	3.0	8.8	
Mixer 2	**Diameter [m]**	**Distance to the bottom [m]**	**Distance between impellers (not equally spaced) [m]**	
Propeller, 3 impellers, 2 blades per impeller	3.1	3.0	Upper spacing: 2.3 Lower spacing: 6.6	

where u_i is the scalar component of velocity field $\vec{v}$, along the x_i coordinate axis.

In this study, the viscosity appearing in Equation (4) is modelled as a function of the shear rate magnitude $|\gamma'|$ using a power–law relationship (Rendina *et al.* 2019):

$$\eta = K|\gamma'|^{n-1} \tag{6}$$

where K [Pa·s^n] is the consistency coefficient and n is the power–law index. The equation holds for the interval $\zeta = (|\gamma'|_{min}\ ;\ |\gamma'|_{max})$ depending on the content of TS (Wu & Chen 2008; Bridgeman 2012); see Table S2, Supplementary material. Beyond ζ limits, viscosity takes constant minimum η_{min} and maximum η_{max} values to prevent singularities when computing runs take place. Rheology parameters strongly depend on TS (Wu & Chen 2008) and temperature T as depicted in Table S2 (Achkari-Begdouri & Goodrich 1992).

From Table S2, the following regressions, either linear or exponential, are derived:

$$K = 0.0117\, e^{0.5078\,TS} \quad R^2 = 0.9983 \tag{7}$$

$$n = -0.034\,TS + 0.7793 \quad R^2 = 0.9777 \tag{8}$$

$$\rho = 0.1425\,TS + 999.99 \quad R^2 = 0.9956 \tag{9}$$

Parameters' values were derived from regressions, Equations (7)–(9), assuming the sludge isothermal and incompressible; see Table 5.

Numerical setup

The Level Set Two-Phase Flow method (Olsson & Kreiss 2005; Bovolin *et al.* 2017) is adopted to model fluid–gas interaction in the case of gas mixing. The Level Set method allows to simulate two immiscible fluids separated by moving interfaces making use of a level set function, that is a smooth continuous function $\varphi[\vec{x}(t)] \in [0,\ 1]$ whose value defines the phase locally:

$$\varphi \begin{cases} >0.5 & \text{fluid} \\ = 0.5 & \text{interface} \\ <0.5 & \text{air} \end{cases} \tag{10}$$

Table 5 | Derived parameters' values for the sludge at T = 35 °C with TS = 6%

TS [%]	K [Pa s^n]	n [–]	ρ [kg/m^3]
6	0.246	0.575	1,000.85

The evolution of φ is described by the following transport equation:

$$\vec{v}\cdot\vec{\nabla}\varphi = \gamma\vec{\nabla}\cdot(\varepsilon\vec{\nabla}\varphi - \varphi(1-\varphi)\vec{n}) \tag{11}$$

where ε and γ are the stabilization and reinitialization terms respectively, $\vec{n} = \dfrac{\vec{\nabla}\varphi}{|\vec{\nabla}\varphi|}$ is the unit normal vector. Sludge motion is modelled as incompressible, spatially integrating over a finite element grid the unsteady Reynolds-averaged Navier–Stokes (RANS) equations, modified for non-Newtonian rheology:

$$\vec{\nabla}\cdot\vec{v} = \vec{0} \tag{12}$$

$$\rho\left(\frac{\partial}{\partial t} + \vec{v}\vec{\nabla}\right)\vec{v} = -\vec{\nabla}p + \vec{\nabla}\cdot\tau + \rho\vec{g} + \sigma\kappa\delta\vec{n} \tag{13}$$

where the τ_{ij} components are given by Equation (4), $\vec{\nabla}$ is the symbolic operator of components ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$), $\vec{v}$ is the velocity field, $\vec{g}$ is the gravity acceleration, p is the pressure, '·' is the symbol of the scalar product:

$$\rho = \rho_a + (\rho_f - \rho_a)\,\varphi \tag{14}$$

$$\eta = \eta_f + (\eta_f - \eta_a)\,\varphi \tag{15}$$

are the local density and the dynamic viscosity obtained by linearly averaging between corresponding values for the fluid (f) and air (a). Last term on the right hand side of Equation (13) represents the surface specific tension force which arises over interfaces: $\sigma = 0.0705$ N/m is the tension coefficient, here assumed as for water–air, δ is the Dirac delta function and $\kappa = \vec{\nabla}\cdot\vec{n}$ is the local interface curvature field. Turbulence is modelled using the standard two-equation k-ε model (Launder & Spalding 1974), based on the transport equations for kinetic turbulent energy (k) and the dissipation rate (ε). The k-ε model has been successfully used by many researchers for related mixing problems in anaerobic digesters (Meroney & Colorado 2009; López-Jiménez *et al.* 2015).

Gas inlet is set at the lower end of four adjacent lances, each lance issuing a gas flow rate of 10.2 L/s. Gas outlet is set at the upper free surface of the sludge. Simulation domain corresponds to the inner space of digester with the presence of the eight lances, see Figure 2(a).

In the case of mechanical mixing (Figure 2(b) and 2(c)), the rotating domain is modelled using a homogeneous single-phase turbulent non-Newtonian flow. The steady Navier-Stokes equations formulated in the rotating

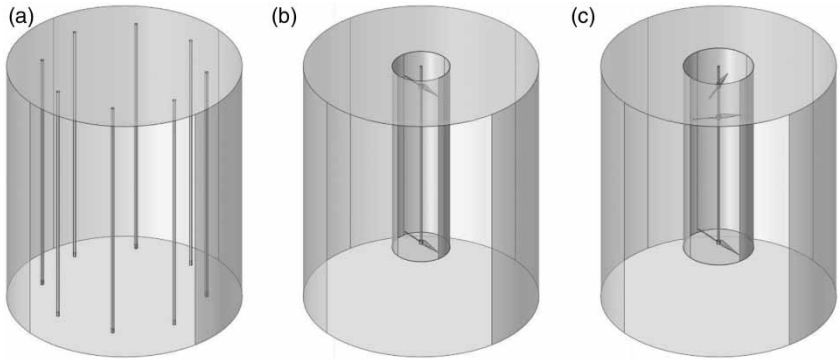


Figure 2 | Computational domain. (a) Gas mixing. (b) Mixer 1. (c) Mixer 2.

coordinate system:

$$\vec{\nabla} \cdot \vec{\mathbf{v}} = \vec{\mathbf{0}} \tag{16}$$

$$\rho \vec{\mathbf{w}} \vec{\nabla} \vec{\mathbf{w}} + 2\rho \vec{\Omega} \times \vec{\mathbf{w}} = -\vec{\nabla}\, \mathrm{p} + \vec{\nabla} \cdot \boldsymbol{\tau} + \rho \left[\vec{g} - \frac{\partial \vec{\Omega}}{\partial \mathrm{t}} \times \vec{\mathbf{r}} + \vec{\Omega} \times (\vec{\Omega} \times \vec{\mathbf{r}}) \right] \tag{17}$$

are solved with reference to the velocity vector $\vec{\mathbf{w}}$, referred to the rotating coordinate system. In the above Equations (16) and (17), $\vec{\mathbf{r}}$ is the position vector while $\vec{\Omega}$ is the angular velocity vector. In the global coordinate system, the velocity vector $\vec{\mathbf{v}}$ is related to the moving component $\vec{\mathbf{w}}$ by means of:

$$\vec{\mathbf{v}} = \vec{\mathbf{w}} + \frac{\partial \vec{\mathbf{r}}}{\partial \mathrm{t}} \tag{18}$$

Mesh generation

In the case of gas mixing, the lances are treated as void spaces. The mesh is finer where gas inlet is set, since the inlet gas flow velocity is the highest in this region. In the case of mechanical mixing, two regions with different mesh quality are introduced. The mesh of the rotating domain is finer than the mesh of the rest of the domain since the flow velocity is higher in this region.

The spatial decomposition is made by using unstructured meshes of tetrahedral elements. Finer boundary layer mesh elements are set at the walls to comply with the constraints imposed by the adopted k-ε turbulence model. Sharp corners are avoided because they may introduce singularities in the solution.

Mesh convergence study

Three levels of spatial discretization are tested, respectively indicated as meshes 1, 2 and 3 in Table 6 (gas mixing) and Table 7 (Mixer 1). The successive refined meshes yielded convergent solutions starting from mesh 2 for all cases, thus making the FSI computations reliable. Results next presented are obtained with such level of discretization.

Table 6 | Mesh properties in the case of gas mixing

Mesh parameters	Mesh 1	Mesh 2	Mesh 3
Max cell size [m]	1.980	1.650	1.254
Min cell size [m]	0.099	0.099	0.0099
Number of cells	36,323	62,566	123,931

RESULTS AND DISCUSSION

The evaluation of the mixing is done by computing the velocity magnitude and pattern, the turbulent kinetic energy and the formation of dead zones. Results are presented when nearly steady state conditions are reached as in Viccione *et al.* (2012) in the case of gas mixing. Dead zones refer to the regions of the digester where the velocity is smaller than 0.05 m/s according to Wu (2010). Computed quantities are all referred to the inner volume Ω of the digester. The analysis of the velocity pattern shows that a convective movement of the sludge is created inside the digester; see Figure 3. In the central section of the digester a large downward flow is created in the central part with vortexes located near the bottom of the digester. In the case of gas mixing (Figure 3(a)), higher velocity magnitudes are attained of the order of 1 m/s near the walls. This is basically due to the thrust exerted by air bubbles on the sludge when moving upwards to the free surface. In the case of mechanical mixing (Figure 3(b) and 3(c)), the velocity magnitudes were generally dramatically lower, with peaks of

Table 7 | Mesh properties in the case of Mixer 1

	Mesh 1		Mesh 2		Mesh 3	
Mesh parameters	**Rotating domain**	**Outer domain**	**Rotating domain**	**Outer domain**	**Rotating domain**	**Outer domain**
Max cell size [m]	0.0053	0.013	0.004	0.01	0.003	0.007
Min cell size [m]	0.01	0.006	0.001	0.005	0.001	0.004
Number of cells	26,696	204,432	41,094	334,752	66,766	672,912

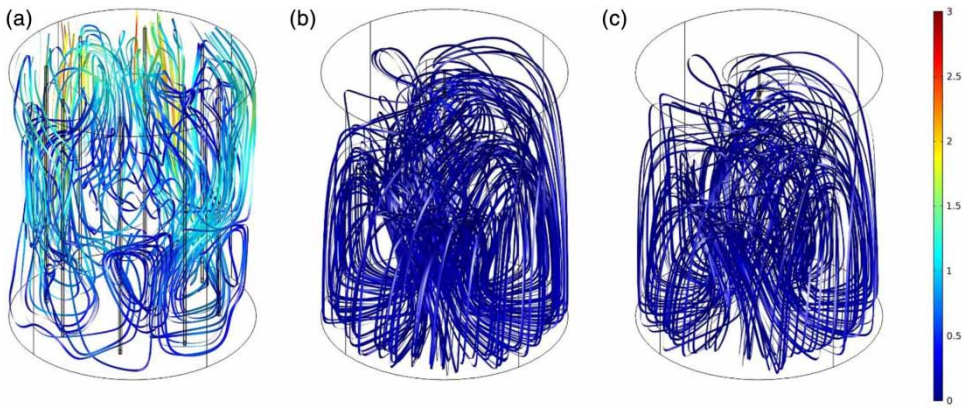


Figure 3 | 3D trajectory extraction. Colour is related to the velocity magnitude [m/s]. (a) Gas mixing. (b) Mixer 1. (c) Mixer 2. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2020.248.

1.33 m/s nearby the paddle blades for Mixer 1 (see Figure S1, Supplementary material).

The results concerning the turbulent kinetic energy [m^2/s^2] reveal a level of agitation at the upper part of the digester with a maximum value of 0.24 m^2/s^2 in the case of gas mixing (Figure 4(a)). This is an expected result as the gas bubbles finally break at the free surface, generating turbulence nearby. From an operational point of view, this aspect is very useful because it helps the digester function against the formation of crusts. In the case of mechanical mixing, turbulence levels are negligible as can be seen in Figure 4(b) and 4(c).

As concerning the formation of dead zones, half of the digester inner volume Ω participates actively in the mixing process, in the case of mechanical mixing (Figure 5(b) and 5(c)). Most of the stagnant regions are located near the vertical wall and at the free surface, whereas the inner regions near the paddle blades feature high levels of velocity.

In the case of gas mixing, dead zones are present far away from the gas inlet areas as depicted in Figure 5(a),

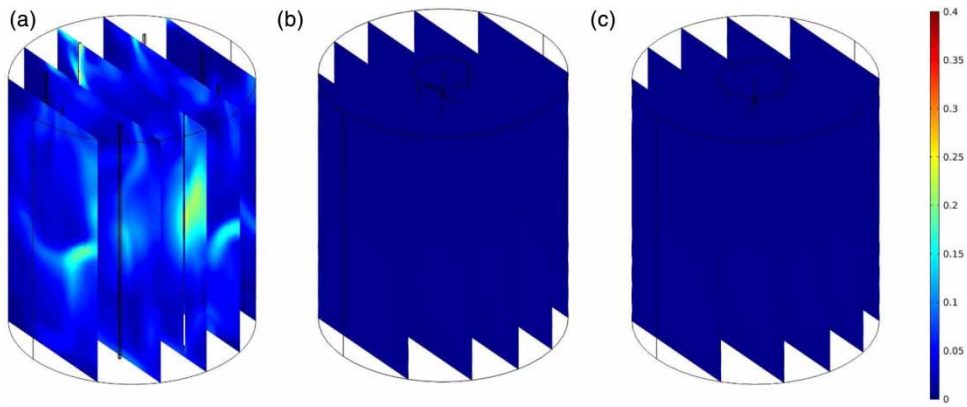


Figure 4 | Turbulent kinetic energy [m^2/s^2]. (a) Gas mixing. (b) Mixer 1. (c) Mixer 2.

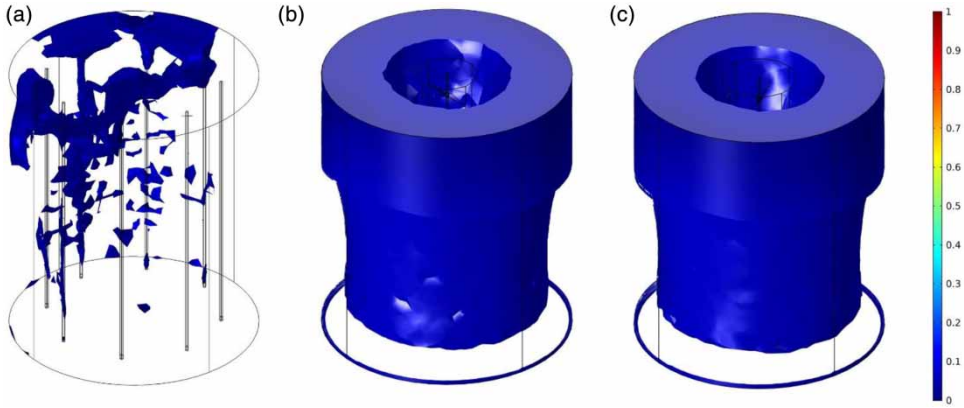


Figure 5 | Dead zones, defined on the basis of the condition v < 0.05 m/s. Colour contour is set with the upper value (unity) related to the threshold velocity. (a) Gas mixing. (b) Mixer 1. (c) Mixer 2. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2020.248.

attaining the mean value of about 4.8% (bold value in Table 8). Geometry optimization concerning the digester shape, length, distance to the bottom and diameter of lances would certainly allow a further decrease (Singh *et al.* 2019). In the following Table 8, a summary of the obtained numerical results is presented. The 'intermediate velocity zones' refers to the volume (in percentage in respect of the inner volume) where velocity ranges in the interval $0.05 < v < 1$ m/s, whereas the 'high velocity zones' refers to velocities higher than 1 m/s.

The best solution, considering the same daily energy consumption E, is given by the gas mixing solution. In fact, in Table 8 it is shown that dead regions are about a tenth of mechanical mixing (4.8% vs 50.6% for Mixer 1 and 51.3% for Mixer 2) while spatially averaged velocity is about four times greater (0.31 m/s vs 0.07 m/s for Mixer 1 and Mixer 2). This is basically due to the corresponding low number of revolutions for the adopted Mixers ($rpm_1 = 29.9\ min^{-1}$ and $rpm_2 = 21.6\ min^{-1}$, respectively). In López-Jiménez *et al.* (2015) the simulation of flow patterns was carried out using a propeller rotating from 400 to 750 rpm, which is one order of magnitude greater. Dead zones, however defined on the less restrictive criterion v< 0.05 m/s were 0.21% and 4.2% for non-Newtonian sludge with TS = 2.5% and 5.4% respectively. Manea & Robescu (2012) recommended axial mixers having four to six blades, with a tilt angle between 15° and 45° and shaft speeds between 100 and 800 rpm. In addition, six new simulations (three per mixer) were carried out with the parameters listed in Table 5, to compare the effect of increased mixing speeds of 50, 100 and 200 rpm on the percentage of dead zones (DVP), without caring of the mixer rpm operational range (see specifications in Table S1). Once again, dead volumes were assessed on the basis of the condition v < 0.05 m/s. Results are summarized in Table 9.

Daily energy consumptions E are derived from Equations (2) and (3), for Mixers 1 and 2, respectively, under the same condition of mixing operating 24 h per day. As can be noted, the increase of rpm corresponds to a fast decrease of DVP but at the expense of higher E levels. Above rpm = 100, stagnant regions occupy less than 1% of the digester's volume, at the cost of tripled energy

Table 8 | Main numerical results

	Gas mixing			
Parameter	**Mean value**	**Standard deviation**	**Mixer 1**	**Mixer 2**
Max velocity [m/s]	3.03	0.20	1.33	1.00
Spatially averaged velocity [m/s]	0.31	0.09	0.07	0.07
Spatially averaged turbulent kinetic energy [m^2/s^2]	0.23	0.10	0.001	0.001
Dead zones [m^3]	63.64 (4.8%)	42.08 (3.2%)	665.83 (50.6%)	674.91 (51.3%)
Intermediate velocity zones [m^3]	1,237.64 (94.1%)	26.89 (2.0%)	649.12 (49.4%)	639.87 (48.7)%
High velocity zones [m^3]	13.68 (1.0%)	19.74 (1.5%)	0.00 (0.0%)	0.00 (0.0%)

Table 9 | Impact of mixing speed (rpm) on dead volume percentages (DVP) and consumed energy (E) for Mixer 1 and Mixer 2

Mixer 1			Mixer 2		
rpm [min^{-1}]	DVP [%]	E [kWh]	rpm [min^{-1}]	DVP [%]	E [kWh]
29.9	50.6	140	21.6	51.3	140
50	21.6	243	50	2.9	324
100	0.4	496	100	0.1	648
150	0.1	750	150	0.0	972

values or more, compared with the reference value E = 140.4 kWh. Geometry optimization of the mechanical mixing systems can lead to a drastic reduction of dead zones (Singh *et al.* 2019) as well. This implies a sensitivity analysis based on the geometry of the mixer (number of impellers, number of blades per impeller, the blade's profile) which is out of the scope of this paper.

In terms of turbulent agitation, mechanical mixing does not exhibit significant levels, proving that this technology is appropriate only for convective movement.

CONCLUSIONS

Anaerobic digestion is largely applied for the stabilization of sewage sludge and landfill leachate. The production of biogas is beneficial for the environment, helping the reduction of greenhouse emissions. The efficiency of digestion process is affected by several operating parameters including the rate of mixing, which was commonly studied in the past at a laboratory scale.

In this study, a three-dimensional CFD steady/unsteady model was developed and applied to quantify mixing in a full-scale anaerobic digester. Non-Newtonian properties of the sludge, consisting of a pseudo-plastic fluid, were taken into account in the closure of governing equations. Stirred and gas mixing solutions were compared in terms of flow patterns, turbulent kinetic energy and dead zones, keeping fixed the daily energy consumption. In the case of gas mixing, the real configuration of the lances and their operating conditions were adopted. For the mechanical mixing, two central draft tube mixers with two (Mixer 1) and three (Mixer 2) impellers, respectively, were comparatively studied. The number of rounds per minute were derived from the given P–rpm curves, under continuous mixing. Gas mixing was found to be preferable to mechanical mixing in terms of mixing performances, namely:

- maximum velocity was about three times larger than that associated with mechanical mixing systems;
- dead zones percentage was one order of magnitude lower (about 5% against 50%);
- turbulent kinetic energy was two orders of magnitude larger (0.24 m^2/s^2 against 0.001 m^2/s^2). Maximum values were attained over the upper part of the digester, with a positive effect against the formation of crusts.

Increasing impeller speed helps reduce stagnant regions but at the cost of higher electric energy consumption.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2020.248.

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First received 6 June 2019; accepted in revised form 11 May 2020. Available online 18 May 2020