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# Fluid dynamic analysis of a continuous stirred tank reactor for technical optimization of wastewater digestion

F.J. Hurtado*, A.S. Kaiser, B. Zamora

*Dpto. Ingeniería Térmica y de Fluidos, Universidad Politécnica de Cartagena, Doctor Fleming s/n, 30202 Cartagena, Spain*

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ABSTRACT

Continuous stirred tank reactors (CSTR) are widely used in wastewater treatment plants to reduce the organic matter and microorganism present in sludge by anaerobic digestion. The present study carries out a numerical analysis of the fluid dynamic behaviour of a CSTR in order to optimize the process energetically. The characterization of the sludge flow inside the digester tank, the residence time distribution and the active volume of the reactor under different criteria are determined. The effects of design and power of the mixing system on the active volume of the CSTR are analyzed. The numerical model is solved under non-steady conditions by examining the evolution of the flow during the stop and restart of the mixing system. An intermittent regime of the mixing system, which kept the active volume between 94% and 99%, is achieved. The results obtained can lead to the eventual energy optimization of the mixing system of the CSTR.



## 1. Introduction

Anaerobic digestion is a common process for stabilizing and reducing the excess biological sludge from wastewater treatment plants. This process takes place inside a Continuous Stirred Tank Reactor (CSTR) anaerobic digester, in which the biodegradable material is maintained at constant temperature and broken down by methane-producing bacteria in the absence of oxygen. The performance of anaerobic digestion mainly depends on feed characteristics, feeding patterns, pH, temperature, redox potential, hydraulic retention time and mixing characteristics.

One of the key factors of the digestion in a CSTR is the mixing. The mixing process provides adequate dispersion and contact between the active biomass and the substrate, avoids settling of the heavy solid particles to the bottom, minimizes non-uniformities in pH and temperature, reduces sludge stratification and prevents short-circuiting. The mixing process can be accomplished by mechanical agitation, hydraulic recirculation or gas injection, and comprises a great part of the energy consumption of the digester due to its continued operation and power requirements. Although the mixing

* *Corresponding author*. Tel.: +34 652 625 599.
E-mail address: frnc.hurtado@gmail.com (F.J. Hurtado).
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**Nomenclature**

| | |
|---|---|
| C | tracer concentration |
| $C_L$ | constant related to $t_L$ |
| $C_\mu$ | empirical constant of the $k$-$\varepsilon$ turbulence model |
| $E(t)$ | tracer concentration function |
| $F(t)$ | cumulative distribution function of $E(t)$ |
| $h$ | height (m) |
| $I$ | turbulent intensity (%) |
| $k$ | turbulent kinetic energy ($m^2\ s^{-2}$) |
| $L_e$ | eddy length scale (m) |
| $\dot{m}$ | mixing mass flow rate ($kg\ s^{-1}$) |
| HRT | hydraulic residence time (s) |
| $t$ | time (s) |
| $t_e$, $t_{cross}$ | eddy characteristic and eddy crossing times, respectively (s) |
| $t_p$ | particle–flow interaction time (s) |
| $t_L$ | Lagrangian flow time scale (s) |
| $U_j$, $u_j$ | averaged and turbulent components of velocity, respectively ($m\ s^{-1}$) |
| $U_p$ | particle velocity ($m\ s^{-1}$) |
| $u_\tau$ | friction velocity, $u_\tau = (\tau_w/\rho)^{1/2}$ ($m\ s^{-1}$) |
| $v$ | velocity magnitude ($m\ s^{-1}$) |
| $\bar{v}$ | average velocity ($m\ s^{-1}$) |
| V | active volume (parts per unit) |
| x, y, z | Cartesian coordinates (m) |
| $y^+$ | $y_1 u_\tau/\nu$, dimensionless |
| $y_1$ | distance between the wall and the first grid point (m) |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | dissipation rate of $k$ ($m^2\ s^{-3}$) |
| $\zeta$ | normally Gaussian distributed random number |
| $\mu$ | viscosity ($kg\ m^{-1}\ s^{-1}$) |
| $\nu$ | kinematic viscosity, $\mu/\rho$ ($m^2\ s^{-1}$) |
| $\rho$ | density ($kg\ m^{-3}$) |
| $\tau_w$ | wall shear stress ($N\ m^{-2}$) |
| $\chi$ | particle relaxation time (s) |

*Abbreviations*

| | |
|---|---|
| CARPT | Computer Automated Radioactive Particle Tracking |
| CFD | Computational Fluid Dynamics |
| CT | Computed Tomography |
| CSRT | Continuous Stirred Tank Reactor |
| HRT | Hydraulic Residence Time |
| PRESTO | Pressure Staggering Option |
| RTD | Residence Time Distribution |
| SIMPLE | Semi-Implicit Method for Pressure Linked Equations |
| WWTP | Wastewater Treatment Plant |

quality will determine the performance of the anaerobic digester in terms of uniformity, dead space and short-circuiting (Hendricks, 2006), it seems clear that the impact of the mixing intensity and/or mixing regime on the efficiency of the anaerobic bacteria is still under discussion. Some studies (McMahon et al., 2001; Gómez et al., 2006; Bridgeman, 2012) report that the performance of the anaerobic digester in terms of biogas production can be maintained at velocity gradient values significantly below those recommended in the literature. Therefore, the mixing process is a relevant factor to take into account in the optimization of a given design, for achieving a high performance of the biological process, along with a suitable energy efficiency of the anaerobic digester.

In order to optimize the mixing process, a detailed study of the hydrodynamics and the mixing conditions in the CSTR should be conducted. The hydrodynamic behaviour of the reactor and the presence of dead zones, channelling or short-circuiting, can be determined through the analysis of the Residence Time Distribution (RTD) and the experimental results can be compared with those obtained via mathematical models of a CSTR under ideal conditions (Levenspiel, 1972). The RTD of the CSTR can be obtained through experimental methods by the injection of chemical tracers at the inlet of the reactor and the measurement of the concentration evolution of the tracer at inlet and outlet of the reactor (Olivet et al., 2005; for instance). However, these results do not yield information on the characteristics of the flow inside the digester. Non-invasive techniques like Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT) can be used to identify the mixing patterns of flow inside lab-scale digesters and to calculate several parameters as velocity and turbulence stresses (Karim et al., 2004).

The experimental methods are costly and time consuming, require internal placement of instrumentation and sometime may not be feasible in a full-scale plant. Computational Fluid Dynamics (CFD) modelling emerges as an effective method to design and optimize many applications in the wastewater treatment field (Wu, 2013; has conducted a detailed review). By means of the numerical modelling of the fluid flow inside the CSTR is possible to analyze the mixing process and the distribution of residence times (Patwardhan, 2002; Terashima et al., 2009), to predict fluid velocity vectors, turbulence, streamlines and particle trajectories or the volume of dead zones in a CSTR (Yu et al., 2011; Meroney, 2009) and to determine the influence of the total solids concentration on flow characteristics (Yu et al., 2011; Bridgeman, 2012). The large scale of the motion in the interior of tanks makes the flow essentially turbulent. Wu (2010) investigated turbulence models for mechanical agitation in anaerobic digesters with non-Newtonian fluids. Moreover, the design of the CSTR and the mixing process can be optimized by CFD modelling. The optimum position of the propeller inside a draft tube for mechanical mixing in egg-shaped anaerobic digesters was analyzed by Wu (2010). The effects of draft tube size and the design of the conical tank bottom on flow pattern were studied by Vesvikar and Al-Dahhan (2005). Furthermore, design of specific parts can be analyzed by numerical simulation; for instance, a flow deflector above the draft tube was studied by Craig et al. (2013).

The present work studies the sludge flow in the CSTR for anaerobic digestion of the wastewater treatment plant (WWTP) located in Alcantarilla (Murcia, Spain). Numerical modelling that simulates the CSTR behaviour is carried out. The distribution of particle residence times, velocity vectors, the turbulence intensity and the active volume in the CSTR are studied under nominal operating conditions of the WWTP.