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Experimental and numerical investigation of hydrodynamics and mixing in a dual-impeller mechanically-stirred digester

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HIGHLIGHTS

- Mixing is investigated in an anaerobic digester devoted to biohydrogen production.
- Mixing time is measured at low power input (<10 W/m^3), comparing several techniques.
- CFD simulations based on unsteady RANS calculations agree with PIV data.
- Changes in the lower impeller design strongly affect hydrodynamics and mixing time.
- CFD can explain these trends from the spatial distribution of macro/micromixing times.

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ABSTRACT

The aim was to investigate the influence of mixer design and operating conditions in an anaerobic digester designed for BioH$_2$ production. Distributive mixing was studied through different dual-impeller configurations with various impeller size, clearance and types. Advanced optical experimental techniques, such as Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) were used to determine mixing time and the flow pattern in the bioreactor. PLIF, decolorization and conductimetric methods were compared for mixing analysis. CFD was used to achieve a more detailed analysis of hydrodynamics and mixing. Experiments and simulations were limited to power input lower than 10 W/m^3, which is a necessary condition to achieve sustainability and corresponds to 50–150 rpm in this work. Nine designs of dual-impeller configurations were compared in an unbaffled tank. Experimental results suggest that mixing was strongly modified by changing the geometry of the lower impeller and, to a lesser extent, the off-bottom clearance and the injection position for dual-impeller devices. Macromixing time t_m derived from the conductimetric technique always agreed with PLIF, but was higher than values from chemical decolorization when an axial-tangential flow pattern validated by PIV and CFD data was reported. CFD was able to predict the mean flow and the turbulence features, so that their respective role on mixing could be compared. Finally, a non-conventional mixer dual-impeller device was shown to counterbalance lower turbulence and power input by an enhanced axial flow circulation that made t_m weakly dependent on the position of the injection and favored dispersive mixing.

1. Introduction

Biohydrogen (BioH$_2$) from agriculture and lignocellulosic waste appears as a serious alternative to conventional fuels; it is considered as an ideal vector and a clean energy for sustainability [1]. 2nd generation BioH$_2$ can be obtained through acidogenic fermentation, or dark fermentation, an anaerobic digestion process that couples the treatment of organic waste to renewable energy production. BioH$_2$ production through dark fermentation follows a biological pathway similar to conventional anaerobic digestion, except that methanogenesis is suppressed and that a digestate enriched in Volatile Fatty Acids (VFAs) is also produced. VFAs can be used to enhance bioenergy recovery or as platform molecules for the production of basic chemicals and polymers [2].

Mixing plays a key role in this process, as a three-phase system is involved: namely, an aqueous solution enriched in soluble sugars

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and fatty acids, a suspended lignocellulosic waste and a gas phase composed of CO_2 and H_2. Agitation must enable the suspension of organic waste, homogenize pH and local concentrations, and enhance hydrogen desorption at the same time, but agitation intensity is limited because shear stress may impair the biological processes [3–5]. In practice, mixing in anaerobic bioreactors devoted to methane or $BioH_2$ production is poorly known and understood in comparison to aerobic bioreactors. The first reason is that anaerobic digestion for methane production must be driven at less than 8 W/m^3 according to US EPA recommendation for sustainability [5]. Even though no similar rule has been established for acidogenic fermentation, the same standards (*i.e.* 5–10 W/m^3) should be applied, with a larger variability as a function of digestate valorization. So, these bioreactors are commonly stirred using impellers with diameter-to-tank ratio larger than 1/3 and at very low rotation speed, which strongly differs from the conventional conditions investigated in the abundant literature on mixing. The second reason is that the number of experimental and theoretical studies devoted to the influence of mixing in such reactors remains very small. The hydrodynamics of these bioreactors is nearly unexplored, as only a few studies using Radioactive Particle Tracking (RPT) [6–9] or Particle Image Velocimetry (PIV) [10,11] can be found in the literature. This means that neither the features of the main flow pattern under laminar or turbulent flow regime, nor the turbulence properties under turbulent flow conditions are clearly established. Similarly, numerical simulations based on Computational Fluid Dynamics (CFD) are scarce [11–13], even though it is commonly admitted that the presence of dead zones can induce local pH or redox gradients and hydrogen supersaturation, so that less biologically-active zones could arise with the different microbial communities as a function of their microenvironments [14,15]. Locally, a switch of metabolic pathways may also be observed, for example due to dissolved CO_2 accumulation [16]. This is a key point for $BioH_2$ production which is possible in a small range of pH, between 5.5 and 6, and requires pH control by alkaline addition. The third reason is that the properties of digestates cover a wide viscosity range as a function of biomass feedstocks, *e.g.* from wastewater to viscous liquid manure [17,18], which means that laminar, transitional or turbulent flow conditions must be covered. The fourth reason is, finally, that unbaffled tanks are the rule to avoid the accumulation of solid deposits because baffles create microenvironments close to the wall [5,13], but this situation also differs from most of the published data on stirred tank bioreactors which deals with baffled vessels.

The aim of this work is, therefore, to investigate the influence of mixer design and operating conditions in an anaerobic digester designed for $BioH_2$ production, so that critical limiting factors, *e.g.* insufficient mixing, inhomogeneous nutrient or pH distribution, and slow gas-liquid mass transfer, may be identified early in the design process. In this paper, nine dual-impeller configurations in an unbaffled tank are compared because dual-impeller devices have been shown to be efficient to enhance solid suspension and gas-liquid mass transfer at the same time [13]. Mixing time is studied, first, as a function of rotation speed and the position of the injection point for each design, using a local conductimetric method, PLIF (Planar Laser Induced Fluorescence) and acid-base decolorization for comparison purpose [19,20]. 2D PIV is also used to understand how mixing proceeds and identify the difference in flow pattern due to any change in impeller type, position or off-bottom clearance. The local flow field from 2D PIV is also used to validate a CFD model, so that CFD simulations can give access to fundamental quantities, such as turbulence length and time scales [21,22].

2. Materials and methods

2.1. Experimental setup

To investigate the effect of the mixer design both on hydrodynamics and mixing, experiments were conducted in a laboratory-scale unbaffled, round-bottomed, 5-L mechanically-stirred tank bioreactor with a diameter, T, equal to 0.170 m and liquid height, H, equal to 0.270 m. A detailed description of this experimental setup can be found in previous works [11,13]. Mixing was investigated through different dual-impeller configurations with various impeller size, clearance and types. Three configurations were investigated:

- an elephant ear turbine [21], denoted 3EE82 (82 mm diameter, down-pumping mode) as the upper impeller, associated with a four-blade Rushton disk turbine, denoted 4RT56 (56 mm diameter), as the lower impeller;
- the same upper impeller, associated with a radial six-blade Rushton disk turbine, denoted 6RT70 (70 mm diameter), as the lower impeller;
- again, 3EE82 as the upper impeller, associated with a marine propeller as the lower impeller, denoted 3MP77 (77 mm diameter).

The inter-impeller clearance was always 11 cm, but three values of the off-bottom clearance values C_b were tested per configuration, as these had been shown to affect straw suspension and vortex formation in a previous work [11]. The respective C_b/H values were 0.25, 0.22 and 0.18. This leads to nine impeller configurations, denoted for example 3EE82/4RT56-0.25 when 3EE82 is the upper impeller, 4RT56 the lower impeller and C_b/H is 0.25.

In our previous work [11], the rotation speed N at which power input could be maintained was defined, which limited N between 50 and 150 rpm and Reynolds number between 4,000 and 12,000.

2.2. Particle image velocimetry

The time-averaged liquid mean velocity components (u_x, u_y, u_z) were estimated using a two-component PIV technique to describe the local hydrodynamics of the single phase flow. The mechanically-stirred tank was immersed in a square vessel filled with water to minimize optical distortion. The experimental setup included a compact *RayPower Laser* (2 W, 532 nm wavelength) operated in the continuous mode (*Dantec Dynamics*, Denmark) and a high speed *PCO.Dimax* CMOS camera (2016 × 2016 pixels^2, *PCO AG*, Germany). Fast Fourier transform-based cross correlation was applied for the analysis of image pairs. The seeding particles were hollow glass spheres of polyamide (*Dantec Dynamics*, Denmark). The dimensions of the smallest interrogation area were 16 × 16 pixels^2 with 50% overlap, which corresponded to a spatial resolution of 0.75 × 0.75 mm^2. Vertical planes parallel to the shaft of the impeller and horizontal planes at the middle-height of the top impeller were studied, as shown in Fig. 1.

The mean flow and the turbulence properties were estimated from 960 image pairs recorded at 400 Hz using the free PIV software *PIVLab* (V.1.41) [23]. From PIV data, the turbulent kinetic energy k and the turbulent kinetic energy dissipation rate were derived from 2D data using the following approximations using cylindrical symmetry in a r-z vertical plane [21,24]:

$$k = \frac{3}{4}\left(u_r'^2 + u_z'^2\right) \tag{1}$$