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Fluid-dynamics characteristics of a vortex-ingesting stirred tank for biohydrogen production

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A B S T R A C T

In this work, a novel stirred tank for the production of biohydrogen by fermentation of organic wastes is presented. The bioreactor is designed for ensuring effective mixing of the liquid phase, full contact between the substrate and the biofilm and energy efficient hydrogen recovery. A vortex-ingesting dual impeller stirred vessel equipped with a central draft tube containing the support for the attached-growth process is proposed. The local hydrodynamics features of the system have been investigated experimentally by Particle Image Velocimetry (PIV) and Digital Image Processing methods for determining the velocity fields of the two phases, the bubble size distribution and the central vortex shape at different working conditions. Additionally, power consumption was measured by a strain gauge technique for quantifying energy requirements. The results confirm that the reactor hydrodynamics characteristics are adequate for the selected application and that it can ensure the external gas recirculation towards a gas separation unit for the hydrogen recovery and purification, without additional energy input with respect to that provided for stirring.

Keywords: Stirred bioreactor; Vortex-ingesting; Turbulent flow; Attached-growth process; PIV; Biohydrogen

1. Introduction

The production of biological hydrogen from fermentation of organic wastes has recently received considerable attention due to the growing interest on renewable and environmental friendly energy sources (Levin et al., 2004; Wang and Wan, 2009; Nanqi et al., 2011). Full understanding of the process and its optimization for industrial application is a very challenging task, due to the complex interaction among many different factors involving chemical, biological and physical phenomena. One of the main bottlenecks for industrial application is related to the low H_2 yield and productivity of the fermentation processes. In this realm, improvements in the overall process performance can be expected from optimization of the configuration design and of the operating conditions of the production units (Gavala et al., 2006; Chen et al., 2008; Wang and Wan, 2009).

Most investigations on continuous processes have been carried out so far by using dispersed-growth reactors, while the productivity of such processes could be significantly increased by employing packed-bed biofilm reactors that are generally characterized by higher cellular concentrations (Rachman et al., 1998; Ahn et al., 2005) and are not affected by long start-up times and "washout" effects. As a result, in order to optimize the performance of a biohydrogen production process, appropriate design methods are required, which have to be developed on the basis of a comprehensive understanding of the reactor hydrodynamics (Ding et al., 2010).

Generally, scale-up of bioprocesses is particularly complex due to the non-ideal or even unknown fluid flow behaviour at large scale (Amanullah et al., 2004). In this realm, the research efforts devoted so far to the experimental and computational characterization of multiphase fluid mixing can be usefully applied to the design, to the experimental characterization

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Nomenclature

D	impeller diameter (m)
d_{eq}	equivalent bubble diameter (mm)
d_{32}	bubble Sauter diameter (mm)
F_r	Froude number
H	tank height (m)
H_L	liquid height (m)
N	impeller speed (rpm)
N_P	power number
P	consumed power per unit volume (W/m^3)
P_s	P/N^3 (W/m^3/rps^3)
r	radial coordinate (m)
r_c	critical radius (m)
T	tank diameter (m)
z	axial coordinate (m)

Greek symbols

α, ξ_c	Busciglio's model parameters
Ψ	dimensionless vortex distance

and, subsequently, to the scale-up by numerical modelling of stirred bioreactors suitable for the production of hydrogen from organic wastes.

The novel, dual impeller stirred bioreactor presented in this work was designed to fulfil the requirement of a specific biohydrogen production process, that is based on the results recently obtained by Cappelletti et al. (2012) in glass vials of about 100 mL. A successful H_2 production from molasses and cheese whey was obtained by selected *Thermotoga* strains, which are strict anaerobic bacteria, under batch and attached-growth conditions. The bioreactor has allowed to effectively transfer the millilitre scale results to a larger scale, thus opening the way to identify a production scale process for H_2 production and recovery.

In this work the attention is specifically focused on the characterization of the turbulent gas–liquid hydrodynamics due to the ingesting vortex configuration. Previous investigations have already highlighted the advantages of adopting gas-induced stirred tanks provided with draft tubes for different applications, ranging from the ozonation reaction of reactive dye (Hsu and Huang, 1996) to ozone gas–liquid contactor for wastewater treatment (Jafari and Soltan Mohammadzadeh, 2005) and gas–liquid and gas–solid–liquid operations (Conway et al., 2002; Scargiali et al., 2007a, 2012). The modelling of the bioreactor proposed in this work is expected to be particularly demanding, due to the geometrical and hydrodynamic complexity. Full characterization is, therefore, required for a first assessment of the appropriateness of the design to the specific application and for establishing a basis for a detailed evaluation of the modelling techniques. In this work, a combination of experimental techniques is adopted in order to gain full description of the system behaviour under different operating conditions.

2. Experimental

The schematic representation of the overall hydrogen production and recovery process, which includes a self-inducing stirred bioreactor and a gas separation unit (*e.g.* a membrane separation module), is depicted in Fig. 1a.

The dual-impeller bioreactor is equipped with a draft tube and supports for the attached growth fermentation, which are placed inside the draft tube only (Fig. 1b). In case of processes requiring larger surface for biofilm attachment, further supports can be added outside the draft tube. The reactor is suitable for being coupled with a membrane module for gas mixture separation, thus allowing pure hydrogen recovery. The driving force necessary for the movement of the hydrogen containing gas is achieved by inducing a gas phase external circulation towards the membrane module. The challenge of obtaining a flux across the membrane without introducing any compressor/fan for moving the gas phase is obtained through vortex-ingestion. Moreover, stripping of the dissolved gaseous fermentation products takes place by the recirculation of the retentate gas accumulating in the headspace of the reactor. The consequent reduction of the H_2 concentration in the liquid phase is expected to improve H_2 production, on the basis of previous results (*e.g.* Mizuno et al., 2000; Massanet-Nicolau et al., 2010; Nguyen et al., 2010; Ngo et al., 2011).

Working pressure in the stirred tank above the ambient conditions could be necessary for increasing the driving force for the H_2 separation in membrane modules. These high pressure conditions are compatible with the *Thermotogales*, which can withstand elevated pressures (Van Ooteghem et al., 2002).

It is worth mentioning that this particular application can be well included among those mentioned by Middleton and Smith (2004), for which gas ingestion can be considered as an alternative to gas sparging, since very moderate stripping gas flow rates have been shown to be sufficient to overcome the problem of production limitation due to the increase of H_2 concentration (Ngo et al., 2012). Additionally, as pointed out by Conway et al. (2002), vortex-ingestion is preferable to gas sparging when the gas is hazardous to compress. Finally, the retentate gas recirculation avoids the requirement of complete H_2 separation, which would result in very costly membrane separation operations.

The experiments presented in the following have been carried out under simplified conditions: demineralised water at ambient conditions and air were adopted as the model fluids, only the inert supports were contained in two bags placed inside the draft tube and the external gas circulation took place through a simple tube.

2.1. *The stirred vessel*

The stirred bioreactor investigated in this work consisted of a fully baffled, flat-bottomed cylindrical vessel of diameter $T = 0.232$ m and height $H = 2T$, provided with a co-axial draft tube of internal diameter equal to 0.40T and height of 1.36T. Both the stirred reactor and the draft tube were made of Perspex. The vessel was closed with a flat lid, on which the draft tube and the external tube for gas recirculation were fixed.

The draft tube, schematically represented in Fig. 1b, was provided with five holes. The liquid passage from the external volume of the vessel to the inside of the draft tube was ensured by four equally spaced 26 mm (0.112T) holes placed at 45° with respect to the baffles at a distance of 0.135 m (0.58T) from the vessel top. An additional 28 mm (0.12T) hole was made at 60 mm (0.26T) from the vessel top to ensure gas recirculation from the external zone. Two bags containing the inert solids were placed inside the draft tube and fixed by metal bars. The draft tube to tank diameters ratio of 0.4 was selected for ensuring a mixture velocity in the draft tube greater than the bubble rising velocity, thus promoting gas ingestion,