FLUID-DYNAMICS CHARACTERISTICS OF A VORTEX INGESTING STIRRED TANK FOR THE PRODUCTION OF HYDROGEN FROM ORGANIC WASTES FERMENTATION

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Abstract. In this work, a novel stirred tank for the production of H₂ by the biological fermentation of organic wastes is presented. The bioreactor design must ensure effective mixing of the liquid phase, full contact between the substrate and the biofilm and energy efficient biogas recovery. A vortex-ingesting dual impeller stirred vessel equipped with a central draft tube containing the packing support for the attached-growth process is proposed. The local hydrodynamics features of the system have been investigated experimentally at different working conditions by Particle Image Velocimetry and Digital Image Processing for determining the velocity fields of the two phases, the bubble size distribution and the central vortex shape. The results confirm that the reactor is suitable for the selected application and that it can ensure the external gas recirculation towards a membrane separation unit for the hydrogen recovery and purification, without additional energy requirements with respect to that provided for stirring.

Keywords: vortex ingesting, bioreactors, attached-growth process, PBT, PIV, vortex shape.

1. INTRODUCTION

The production of biological hydrogen from the fermentation of waste organics has recently received considerable attention due to the growing interest on renewable and environmentally friendly energy sources [1]. 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 H₂ 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 [1,2], whose fluid-dynamic features play an important role [3].

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 characterised by higher cellular concentrations [4,5] and are not affected by long start-up times and “washout” effects. As a result, in order to optimize the performance of a bio-hydrogen production process, appropriate design methods are required, which have to be developed on the basis of a comprehensive understanding of the reactor hydrodynamics [3]. 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 and, subsequently, to the numerical modelling of stirred bio-reactors to be adopted for the production of hydrogen from organic wastes. The novel, dual impeller stirred bio-reactor design presented in this
work specifically requires the characterization of the turbulent gas-liquid hydrodynamics of the ingesting vortex. The modelling of such a system 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 will be adopted in order to gain full description of the system behaviour under different operating conditions.

2. EXPERIMENTAL

The main operational features of the stirred tank for the hydrogen fermentation of agricultural scraps are depicted in Figure 1.

2.1 The geometrical configuration of the stirred vessel

The stirred reactor 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 0.096 m and height of 0.316 m. Both the stirred reactor and the draft tube were made of Perspex.
Overall, five holes were made in the draft tube. 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 holes made at 45° with respect to the baffles at a distance of 0.135 m from the vessel top. An additional 28 mm hole was made at 60 mm from the vessel top to ensure gas recirculation from the external zone. The two bags containing the inert particles suitable for micro-organism attachment were placed inside the draft tube to expose them to a vigorous flow field and fixed by metal bars.

A dual down-pumping impeller was selected for the agitation: the lower agitator was a four-bladed 45° pitched blade turbine (4-PBT) of diameter equal to 9.4 cm (0.41 T), placed just outside the draft tube at the distance 0.6 T from the vessel base, the upper one was a six-bladed 45° PBT (6-PBT) of diameter equal to T/3, placed inside the draft tube at a distance of 18 cm (0.77 T) above the lower 4-PBT. The impeller types and the geometrical configuration were selected for ensuring the desired gas-liquid circulation. A few preliminary tests had been performed for selecting the impeller type, size and clearance. Failure of gas circulation was visually observed when adopting a radial turbine as the bottom impeller, which could have been more successful for gas dispersion.

In order to minimize optical distortion of the light sheet in the PIV measurements, the vessel was contained inside a square tank filled with water.

Single phase and gas-liquid operating modes were investigated. The gas-liquid mode was obtained by allowing vortex ingestion from the gas headspace at impeller speeds greater than the critical impeller speed for the ingestion onset.

2.2 The measurement techniques

The gassed and ungassed liquid velocity fields were determined using the PIV technique. The system consisted of a pulsed Nd:YAG laser sheet source (New Wave SOLO, light wavelength equal to 532 nm, frequency equal to 15 Hz) and one digital camera (HiSense MK II, 1344×1024 pixels CCD) provided with an optical filter centred on the fluorescent seeding particles emission wavelength, which maximum value was equal to 590 nm. Poly-methylmethacrylate particles coated with fluorescent Rhodamine-B were adopted for seeding the liquid. In one selected condition, also the gas flow field was determined using the two-phase PIV technique described by Montante et al. [6].

The time interval between two laser pulses was varied in the range 150-500 μs, depending on the impeller speed, and that from a pulse pair to another was equal to 0.2 seconds (5 Hz).

At least 500 image pairs were required to obtain statistical convergence on mean velocities in the single-phase systems, while at least 1000 image pairs were necessary to ensure sample-independent liquid mean velocity under gassed conditions, due to the lower number of valid instantaneous vectors for each interrogation area that contribute to the mean value determination. The interrogation area was set at 32×32 pixel for single-phase and 64×64 pixel for two-phase flow measurements, respectively. The cross-correlation of the image pairs was performed on a rectangular grid with 50% overlap between adjacent cells.

A vertical plane placed midway between two baffles and orthogonal to the bags containing the inert support was always considered for the measurements, thus obtaining the axial and radial velocity components. For improving measurement accuracy, the view area of the cameras was restricted axially to the two impeller zones and to the upper zone where the vortex formation takes place. In the following, r and z are the radial and axial coordinates, respectively, and the origin of the coordinate system is fixed at the centre of the vessel bottom. The mean axial and radial velocity, U and V, are positive if directed upwards and towards the vessel wall, respectively.

For determining the bubble size and the vortex shape, the stirred vessel was illuminated with diffused light from the back and images were captured with a digital camera placed at the side opposite to the lamps with a small aperture. For each operating condition, a variable
number of images was acquired and the minimum number ensuring an accurate mean result was identified.

As for the bubble size and bubble size distribution (BSD) measurement, each picture was processed with the Shadow processing software (Dantec Dynamics) – the details of these procedures can be found elsewhere [7]. Since bubbles smaller than one pixel could not be detected with this method, the measurable minimum equivalent diameter was 0.15 mm, which was revealed at the minimum possible distance of the camera from the vessel box external wall.

As for the vortex shape determination, each digital image was processed by an ad hoc developed MatLab programme: the digital black-and-white image was converted into a binary image by fixing a suitable threshold and then the perimeter corresponding to the vortex shape was determined. Finally, a mean value was obtained at increasing impeller speeds from over 500 instantaneous profiles until bubble ingestion was visually observed, that corresponds to vortex breakage.

3. RESULTS AND DISCUSSION

The reference velocity field was obtained under ungassed conditions and liquid level up to the vessel lid, that is equal to 2T. This corresponds to the simplest fluid dynamic condition under which the reactor can operate. In the following, only the PIV results related to two-phase flow will be shortly presented. Overall, 1000 instantaneous velocity measurements were performed, but in most locations a much lower number of instantaneous vectors did actually contribute to the calculation of the mean velocity field.

When vortex ingestion takes place the fluid dynamic behaviour of the vessel changes significantly respect to the single-phase case. The gassed liquid velocity field around the two impellers, shown in Figure 2, is modified with respect to the single-phase configuration; the vortex shape in the top region is only qualitatively tracked on the basis of the measured velocities.

![Figure 2](image_url)

(a) 2D liquid velocity field under gassed conditions (liquid level equal to 1.6T) around the 6-PBT (a) and the 4-PBT (b). H=1.6T; N=360 rpm.

The bubbles ingested through the vortex are drawn down along the draft tube by the top impeller. Due to intrinsic light attenuation, the bubble velocity field in the higher gas hold-up regions cannot be detected, but outside the draft tube bubble recirculation can be clearly appreciated as shown in Figure 3. In the lower region (Figure 3a), the gas bubbles follow the liquid phase closely enough, although the velocity magnitude is lower in the liquid down-flow region and higher in the liquid up-flow region, which is physically consistent with the
buoyancy action on the bubbles. In the top impeller region (Figure 3b) the bubbles move mainly upwards and the overall flow pattern clearly shows that the driving force for gas external circulation, which allows to avoid further power requirements, is effectively produced by mechanical agitation.

![Figure 3. Gas 2D velocity field around the 4-PBT (a) and the 6-PBT (b). H=1.6T; N=360 rpm.](image)

The bubble size measurements at the same conditions (liquid level equal to 1.6T and N=360 rpm) have lead to an average value of the Sauter diameter, $d_{32}$, ranging from 3.5 mm in the outer vessel region to 1.5 mm close to the lower impeller while the measurements were not possible inside the draft tube due to the high gas hold-up. The cumulative BSD obtained as an average of 300 instantaneous measurements performed close to the lower impeller is shown in Figure 4 at two different impeller speeds (N=360 rpm and 460 rpm).

![Figure 4. BSD close to the 4-PBT blade tip.](image)

As can be observed, little difference is apparent although at the higher impeller speed a slightly higher number of smaller bubbles is detected. These small differences are probably due to the balance of two different effects: at an increased impeller speed the flow rate entrainment is bigger and consequently bubble coalescence is enhanced, while the impeller action is more vigorous thus increasing the bubble break-up.

In order to investigate vortex formation the analysis of the digital images of the upper part of the vessel has been performed. With the liquid level fixed at 403 mm from the vessel base (that is 1.74T), the vortex shape has been measured at different impeller speeds, ranging from...
a condition corresponding to an almost flat gas-liquid surface up to vortex ingestion onset: the results relevant to vortex shape are shown in Figure 5, where the progressive increase of vortex penetration towards the impeller is apparent. These profiles are in generic agreement with similar data available in the literature for a different geometrical arrangement [8]. The asymmetry of the profile with respect to the vessel axis is apparent; it is likely due to the geometrical features of the draft tube and, in particular, to the bigger hole connecting the draft tube to the external recirculation tube.

4. CONCLUSIONS

In this work the configuration of a new stirred bioreactor designed for the production of hydrogen from the biological fermentation of organic wastes has been presented. Its main hydrodynamic characteristics have been investigated experimentally under different operating conditions. The results confirm that from a fluid dynamic point of view the reactor is suitable for the selected application; in particular, it can ensure gas recirculation towards the separation unit without additional energy requirements with respect to that provided for stirring. The present experimental data will be adopted for the assessment of optimization and scale-up methods based on Computational Fluid Dynamics (CFD) techniques, which need extensive validation especially in the case of marked complexity of reactor geometry and system hydrodynamics.

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5. REFERENCES