Photobioreactor Design for Hydrogen Production

Fayrouz Kaidi\textsuperscript{a}, Rachida Rihani\textsuperscript{a}, Amel Ounnar\textsuperscript{a}, Lamia Benhabyles\textsuperscript{a} and Mohamed Wahib Naceur\textsuperscript{b}

\textsuperscript{a}Bioenergy and Environment Laboratory, Research Center of Renewable Energy and Development, BP.62, route de l’observatoire, Bouzareah, Algiers, Algeria

\textsuperscript{b}Department of Chemical Engineering, University of Saad Dahlab, Blida.

Abstract

The goal of the present study consist of understanding the hydrodynamic of air-water multi-phase flow inside a bubble column. Experiments in a 0.04m diameter, 0.86m height were carried out to determine: gas holdup, bubble diameter, axial dispersion. In such case the effect of superficial gas velocity was studied. The gas holdup was obtained by liquid height measurements. Residence time distribution experiments were carried out by determining the tracer evolution. The used tracer was potassium chloride which was injected as impulsion to characterize the mixing of the liquid phase in batch mode. It was found that the gas holdup, increased with increasing superficial gas velocity. Empirical correlations have been proposed to predict air-water system in the bubble column. The diameter of the bubbles formed using porous spargers varies from 2.5 mm to 8.5 mm. The flow behaviour inside the bubble column was modeled by the dispersed plug flow model, the results are in agreement with the model. The results of this work provided a tool to design bubble column reactors in applications such as fermentation, especially to hydrogen production from microalgae. In the latter case experiments are carried out under sulfur-deprived-medium.

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* Corresponding author.
E-mail address: f_kaidi@hotmail.com
1. Introduction

Bubble column reactors are mainly used in different industries such as: chemistry, petrochemistry, food, biochemistry, bioenergy, metallurgy, and biological waste water treatment processes, because of their simple construction, excellent heat and mass transfer properties [1], better handling of solids, low operating costs and easier to operate. These authors reported that the use of high height to diameter ratio (H/D) minimize the effect of gas distributors where small bubbles are generated. It was found that the gas distributor design depended on the system properties [2]. In bubble columns, the source of agitation is the pneumatic power input provided by isothermal expansion of gas-sparged [3].

Extensive research on mixing has been carried out in bubble column reactors [4,5] and empirical correlations have been given for gas holdup, however the flow inside these reactors remains complex. Often three flow regimes have been assumed in bubble columns (homogeneous, transition and heterogeneous) with the increase of gas velocities [6-8].

Comprehension of the hydrodynamics inside the bubble column reactors is important for modeling and optimization of gas-liquid reactors. The use of bubble column as photobioreactor for photobiological hydrogen production has meet several conditions and it is challenged by the type of agitation system.

Several different biological H\(_2\) production systems have been proposed, including those using photosynthetic microorganisms such as green algae [9], cyanobacteria [10] and photosynthetic bacteria [11] as well as non photosynthetic microorganisms such as nitrogen–fixing bacteria. Among these systems, the use of microalgae and the light have the advantage because the last one provides the energy to oxidize water to hydrogen and oxygen.

Hydrogen production by microalgae was assumed as clean because when it burns in air it forms water and powerful energy carrier, may be the appropriate solution in the future for mankind. Also, it does not lead to environmental pollution during combustion.

Previous studies deals about hydrogen production from microalgae which are carried out in bottles devices and used artificial light [12]. According to Kosourov et al. [13] studies showed that the behavior of sulphur-deprived algae carried out through five phases: an aerobic phase, an O\(_2\)-consumption phase, an anaerobic phase, a H\(_2\)-production phase followed by a termination phase.

Various factors can influence both the microalgae growth and the hydrogen production: (temperature, pH, light intensity, medium culture, etc). So to improve this process it was necessary to carried out experiments in different geometry which ensure better biophysics and electrochemical parameters and give homogeneous light distribution inside the reactors.

The present paper deals on the one hand, about the hydrodynamic characteristics in the bubble column reactor and on the other hand, about the hydrogen production from Algerian strain of microalgae isolated locally.

2. Materials and methods

2.1. Description of the experimental set-up

Experiments were performed using air-water system. The column has a height of 0.86 m and an inner diameter of 0.04m. Two types of glass frit spargers (40 and 150 µm pore size) were used in the column and appear at the bottom, in such case the flow was checked through the rotameter (ROTA). The cylindrical sections have several sampling ports alongside, used to draw samples. For hydrogen production the microalgae culture was maintained under continuous illumination (7800 Lux). The gas collection was ensured by sampling port situated at the top of the bubble column.

Tap water and compressed air were used as the liquid and the gas phases in the experiments, respectively.
3. Results and discussion

3.1. Gas hold up

Gas hold up is one of the more important parameters characterizing the gas–liquid systems. It is necessary to the hydrodynamic design in different industrial processes because it governs gas phase residence time and gas–liquid mass transfer [14]. It depends mainly on the superficial gas velocity and the type of sparger. Michaud [15] reported that there is not a significant difference of gas holdup according to the type of sparger used. In this study the gas holdup, \( \varepsilon_G \), was calculated by the following equation:

\[
\varepsilon_G = \frac{\Delta H}{\Delta H + H_L}
\]

where:

\( \Delta H \): Height of the liquid before injection of gas.
\( H_L \): Increase in the level of the liquid after gas expansion.

The dependence of the gas holdup on the superficial gas velocity, \( U_G \), can be written as:

\[
\varepsilon_G = C U_G^\alpha
\]

For a Newtonian fluid, \( \alpha \) depends only on the flow regime while \( C \) depends on both flow regime and physical fluid properties.

Our experimental data have been correlated and given in the following table:

| Sparger | Homogeneous | Heterogeneous |
|---------|-------------|---------------|
| 1 (150\(\mu\)m) | \( \varepsilon_G = 1.7 U_G^{0.866} \) | \( \varepsilon_G = 1.078 U_G^{0.5301} \) |
| 1 (150\(\mu\)m) | \( \varepsilon_G = 2.65 U_G^{1.1504} \) | \( \varepsilon_G = 0.82 U_G^{0.3853} \) |

According to Shah et al. (1982), the exponent \( \alpha \) varies usually from 0.7 to 1.2 in the bubbly flow regime and from 0.4 to 0.7 in the case of heterogeneous regime [16]. Our results are in agreement with the ones given by these authors.

Figure 1 shows the influence of superficial gas velocity on the gas holdup according to two spargers. It was seen that the increase of superficial gas velocity strongly increased the gas holdup, these observations are in agreement with those found by Thomas [17]. For low superficial gas velocities less than 0.04 m.s\(^{-1}\), the two spargers give the same gas holdup, less than 0.21. As \( U_G \) increased beyond 0.04 m.s\(^{-1}\), the gas holdup obtained for sparger 1 is higher than the one obtained in the case of sparger 2. In such conditions it seems that the type of sparger influences the gas holdup. In fact, sparger 1 (150 \(\mu\)m) generates large bubbles as a consequence increases the gas holdup in the whole of the column.

Figure 2 illustrates our experimental results (sparger 1) compared to those given in the literature. So, for low superficial gas velocities a good agreement was observed between the experimental data and the literature. However, for the high gas velocities, the results diverge due mainly to both operating conditions and the type of spargers used.
3.2. Bubble diameter

The bubble size was the most important parameter for better understanding the dispersion of the gas inside the bubble column reactor. The variation in the average bubbles diameter depends on the type of sparger [16], and increases slightly with the increase of superficial gas velocity.

The average bubble diameter was measured by a photographic method. Special care was taken to avoid bubble photos in the near zone of sparger. The pictures recorded, treated and the bubble diameter was then calculated, it was found mainly ellipsoidal in shape.

The local bubble was calculated using the following relationship:

\[ d_i = \frac{1}{2} \sqrt{a^2 + b} \]  

where \( a \) and \( b \) are the height and the width of the ellipsoid respectively.

For each superficial gas velocity, the average Sauter diameter was calculated by the following equation:

\[ d_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \]  

\( n_i \): the number bubbles formed with respect to the individual diameter \( d_i \).

Figure 3 shows the bubbles size variation versus the superficial gas velocity. It was seen that the average bubbles diameter increases with the increase of superficial gas velocity, these observations are in agreement with those given by Mouza [18]. Bubbles coalescence was observed for gas flow of 6l/min, in such case it’s difficult to obtain a good data. Generally, in this study, the bubbles appeared ellipsoidal for the two spargers. The bubbles diameter varied from 2.5 mm to 8.5 mm.

Figure 4 compares the Sauter mean diameter for two spargers. It can be observed that the two spargers give the same trends with respect to the superficial gas velocity. The 40µm sparger gives more numerous and smaller bubbles (7.5mm) than the 150µm sparger (5mm). This is probably due to the increase liquid velocity circulation which generates large bubbles.
3.3. Axial dispersion model

The residence time distribution (RTD) was an important parameter characterizing the flow pattern inside the reactor. The tracer dispersion inside the bubble column reactor was modeled using axial dispersion model. It was simple and adequately represented the mixing and the flow pattern occurring inside the bubble column reactor. The model takes into account two effects: convection and dispersion. There are two types of contributions to dispersion: radial and axial [19]. The radial effect is negligible in comparison to axial effect when the ratio L/D is higher than 4. In this case, the tracer concentration is described by the following equation:

$$\frac{\partial C}{\partial t} = D_z \frac{\partial^2 C}{\partial z^2} - u \frac{\partial C}{\partial z}$$

where $C$ is the tracer concentration, $u$ the fluid velocity, $D_z$ the axial dispersion coefficient, $z$ the axial coordinate, and $t$ the time.

The solution of the equation (5) is:

$$\frac{c(t, z)}{c_0} = 1 + \frac{2L}{\pi\beta} \sum_{n=1}^{\infty} \left[ \frac{1}{n} \sin \left( \frac{n\pi}{L} \beta \right) \cos \left( \frac{n\pi}{L} z \right) \exp \left( -\left( \frac{n\pi}{L} \right)^2 D_z t \right) \right]$$

The figure 5 (a, b) represents the tracer exit for sparger 1 (150µm) under different flows ($Q_G = 1l/min$ and $Q_G = 3l/min$).

The model and the experimental data were reported in figure 5. It was seen that the results of the model fit quite well the experimental data for two types of sparger.
3.4. Biological production of hydrogen

The strain microalgae was grown in Tris-Acetate-Phosphate (TAP) medium, pH = 7 under a continuous white light intensity of 7800 Lux at 25°C (figure 6). The algal cells were harvested by centrifugation and resuspended in the TPA-minus-sulfur medium, as described previously by Kosourov et al. [13].

Figure 7 represents the optical density variations according to time. The growth of strain is characterized, like many microorganisms, according to four phases: lag phase (A), exponential or log phase (B), stationary phase (C), and death phase (D). The maximum cells is reached after 98 hours of culture, during this phase, the growth rate slows as a result of nutrient depletion. The micralsge begin to exhaust the resources that are available to them.

The anoxic conditions are reached before 38h, the sulfur-deprived-medium led to the inactivation of the photosynthetic fraction apparatus which releases the oxygen and preserves only fraction which synthesizes ATP, this induce hydrogen production. The hydrogen amount produced remains weak. The gas produced by the cells was analyzed by a gas chromatography with TCD detector (Perkin-Elmer F33) and was equipped with column of 3*3mm with 5A molecular sieve. Detection was carried out by thermal conductivity using argon as carrier gas with a flow of 26 l/min. The temperature of the oven is of 80°C and that of the detector is of 100°C.
4. Conclusion

The bubble columns equipped with porous spargers offer a greater gas-liquid contact area, because the bubbles created by this type of sparger are numerous and far smaller. So, the use of porous sparger seems to be advantageous that the other types of spargers because they offer multiple points of injection.

In this work, it was seen that the type of sparger influences the gas holdup. Also, the gas holdup is closely related to the superficial gas velocity. This work showed that the diameter of the bubbles increases with the increase of superficial gas velocity. Let us note that the gas holdup and the Sauter diameter agree well with previous works.

The hydrogen production from microalgae showed that the anoxic conditions are reached before 38h, the sulfur-deprived-medium led to the inactivation of the photosynthetic fraction apparatus and induce hydrogen production.

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