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# Hydrodynamic properties in a hydrogen production fermenter using sugary wastewater

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ABSTRACT

The biohydrogen production performance was investigated in both of the continuously stirred anaerobic bioreactor (CSABR) and the egg-shaped external circulation hydrogen production bioreactor (EEC-HPBR) in this study. It was found that the biohydrogen production rate in EEC-HPBR was higher than that in the CSABR when the hydraulic retention time (HRT) was varied from 8 to 2 h. The hydrodynamic properties such as the bubble diameter, bubble rising velocity and phase holdups were carried out in a 2-D bioreactor to simulate the real 3-D bioreactor. The seed sludge in the 2-D bioreactor was taken from the CSABR at the same operational condition with a substrate concentration of 20 g total sugar/L. It was found that the average bubble diameter was 0.33 mm with a mild change during the HRT from 8 to 1 h. The bubble rising velocity against the substrate feeding rate increased linearly. The gas ($\varepsilon_g$) and solid ($\varepsilon_s$) phase-holdups increased with a decrease of the liquid ($\varepsilon_l$) phase-holdup when HRT was shortened. The flow regime and mass transfer effects will change according to the bubble formation in the bioreactor. Finally, the study demonstrates that the parameters such as bubble diameter, bubble rising velocity and phase-holdups support bioreactor scale-up. Also this applies to the conditions for steady-state operations of the hydrogen production bioreactor from sugary wastewater.


## Introduction

Bioreactor designs were usually controlled by environmental factors, such as temperature, pH, nutrients, metabolites, microbial communities, cell culture environment, etc [1]. The hydrogen-producing bacteria's metabolic balance is highly dependent on the operating conditions, such as pH, hydraulic retention time (HRT) and gas partial pressure, etc. Therefore, these environmental conditions that affect bacterial growth will determine the final amount of fermentation product. The method of adjusting the HRT to control microbial growth is very effective because methanogenic inhibitors are not needed, and also it complies with the dynamics of microbial growth [2]. But because of the different reactor designs, regulatory HRT has different hydrogen production efficiencies. When HRT is too low this will cause bacterial washout, and significantly reduce the hydrogen yield. To overcome bacterial

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wash out, carrier-induced granular sludge bed (CIGSB) [3] reactor, continuously stirred biohydrogen reactor (CSABR) [4] and agitated granular sludge bed (AGSB) [5] systems have been used to retain biomass within the systems. The authors had proved stable operating conditions at HRT 0.5 h, and the maximum hydrogen production rate was 362.2 L $H_2$/d/L. These bioreactors operated at extremely low HRT allowed the microorganisms to be aggregated to produce granular sludge, and greatly enhanced the performance of hydrogen production and cell concentration. The Egg-Shaped Digester is one of the most efficient and cost-effective anaerobic systems for sludge treatment. Its double-curvature shape, small top liquid surface area and liquid mixing system help reduce scum, grit build-ups and dead zones. Thus, the vessel does not have to be taken out of service for cleaning. Recently, the Egg-Shaped anaerobic digester system has led to simplified mechanical systems, which have further improved the life cycle benefits [6–11].

The biohydrogen fermenter scale-up process includes a hydrogen production mechanism, microbial communities and the bioreactor design, where is based on kinetics and hydrodynamics. The recent study is mostly about kinetics and only a few researchers are studying the hydrodynamic phenomena of the biohydrogen fermenter [12–15]. Wang et al. [16] used the hydrodynamic properties of the binding reaction kinetics model to simulate the phases change of gas-liquid-solid, and then used a hydrodynamic model to predict the flow regime in bioreactor.

The particle image velocimetry (PIV) and a high-speed camera were used to quantify the relative motion of the biogas bubbles from liquid flow and bioparticles. There are also several studies focused on the effect of computational fluid dynamics (CFD) parameters on the performance of bioreactors [17,18]. This method is also used to predict other related phenomena of fluid flow, heat transfer, mass transfer and reaction, etc [19]. Traditional methods are not accurate and cost-effective for a well designed bioreactor, where reactor functions and operating conditions are vital. Wang et al. [1] was first time binding reaction kinetics and hydrodynamics to simulate the three-phase biological reactors. They found that substrate concentration and hydrodynamic conditions for biogas production are very important factors. Particle image velocimetry (PIV) and high-speed cameras to measure liquid flow field have been used to research the mutual motion of the particles of sludge bacteria and biogas bubbles. The PIV system, in addition to measuring the biogas bubble formation and growth from the liquid flow regime, can also do quantitative research by image analysis techniques [20]. Higher gas production rate resulted in larger bubble size, but the frequency of big bubbles are less than small bubbles, so the increase of gas production rate and biological particle sizes will cause bubbles to gather and form granules [21]. Using the semi-empirical approach to simulate bioreactor efficiency and scale-up design has some restrictions. There are few researches reported quantifying the impact on hydrodynamic parameters on the performance of the bioreactor [17,18]. The status and characteristics of the hydrodynamic property has a significant impact on the wastewater treatment of suspended bacteria growth reactors, which includes bioparticle size distribution, compressibility and sludge sedimentation rates, etc [22]. Since the CSTR system needs to operate on a larger scale, it must be strengthened by changing the shape of the reactor and implementing mix methods to achieve the desired state reaction [23].

Traditional biohydrogen fermentation produces large amounts of biogas, causing bubbles to be produced in the tank. The biogas bubbles flow upward and the flow patterns change in the fermenter. This will affect the reaction kinetics and mass transfer rate, which will result in a poor accuracy of scale-up of bioreactor in the future. Obviously this will affect the stability of operations as well. In this study, the differences of hydrodynamic properties were explored between the continuously stirred anaerobic bioreactor (CSABR) and the egg-shaped external circulation hydrogen production bioreactor (EEC-HPBR). The continuously stirred anaerobic bioreactor (EEC-HPBR) was used to strengthen the shape of the reactor, reduce the dead zone of the reactor, and increase the degree of mixing within the reactor. It is desirable to enhance the hydrogen production rate from the bioreactor. In addition, the bubbles inside the reactor may change by its inner diameter, this can cause bubble rise extrusion and division, so that the fluid within the reactor is well mixed.

High-speed streaming cameras (MS30K, MegaSpeed) and PIV (particle image velocimetry) image analysis software (Dynamic Studio v3.40) were used to observe the dark fermentative hydrogen production process, hydrogen production rate, bubble size, bubble rise velocity, and phase-holdups. The direction of movement and the size of the bubbles can be observed through high-speed cameras that film the process. The liquid metabolites and the bacteria community in the fermenters also discussed to establish the scale-up technique for a biohydrogen fermenter that provides stable operating condition parameters of a real plant.

## Materials and methods

### *Experimental setup and procedure*

The schematic diagrams of continuously stirred anaerobic bioreactor (CSABR) and egg-shaped external circulation hydrogen production bioreactor (EEC-HPBR) were shown in Figs. 1 and 2. In this study, both of the CSABR and EEC-HPBR reactor are made of glass. The specifications of the reactors are shown in the Table 1. High efficiency hydrogen producing bacteria were fed into the EEC-HPBR and CSABR bioreactor. The substrate of sugary wastewater from food industry wastewater was controlled at 20 g total sugar/L which accompanied with Endo nutrient. A peristaltic pump was installed to control the feeding rate. The substrate was injected into the bottom of the bioreactor. The operating temperature was maintained at 40 °C. The pH and ORP were monitored and recorded. The substrate was then overflow to the gas–liquid separator from the top outlet of the bioreactor after digestion. The biogas is discharged from above of the gas–liquid separator, and the gas production is recorded by a wet gas flow meter.

The components of biogas were analyzed by gas chromatography (SHIMADZU GC-14B with TCD). The liquid phase was analyzed by gas chromatography (SHIMADZU GC-14B with

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