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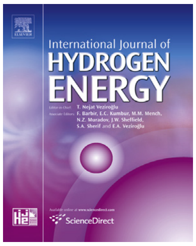

Increasing the bio-hydrogen production in a continuous bioreactor via nonlinear feedback controller

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ABSTRACT

In this work, a novel controller is proposed in order to regulate the dynamic behavior of a class of continuous bioreactor for biogenic hydrogen production, the closed-loop performance of the considered bioreactor increase considerably the hydrogen production successfully. A mathematical model for the anaerobic fermentation of the non-sulfur bacteria *Rhodobacter capsulatus* is considered as a benchmark system to implementing the proposed methodology. A theoretical sketch of proof of the asymptotic closed-loop stability of the proposed controller is given, considering that the main nonlinearities of the bioreactor's model are bounded. Numerical experiments were carried out in order to show the satisfactory performance of the proposed controller in comparison with an adequately tuned linear PI control law.

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Introduction

Hydrogen is considered an important energy carrier, which can be generated from pyrolysis, biomass gasification, methanol and ethanol reforming and water electrolysis; but also, as biological decomposition of organic compounds [1–3]. Biological processes of hydrogen generation might be a sustainable and cheap way for clean energy production. Therefore, hydrogen production by fermentation, employing cellulose biomass, solid waste from various industry branches or wastewater is an interesting biological process alternative.

Several microorganisms for hydrogen production have been studied, including algae, fermentative bacteria, cyanobacteria and photosynthetic bacteria [4]. In particular, the photosynthetic bacteria have been chosen as the stellar microorganisms for industrial production due to their high substrate conversion capacities and ability for using a wide types of substrates either for growth or hydrogen generation.

From an industrial point of view, improving the hydrogen production efficiency in a bioreactor is the limiting step to make it also economically viable. It is well known that high cell density and hydrogen production activity is the key to accomplish that goal [5].

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It was demonstrated that high cell density of fermentative bacteria could be achieved in contínuos stirred bioreactors [6,7], Therefore, it provided a feasible way to achieve the industrialization of hydrogen production biotechnology [8]. Among them, photosynthetic bacteria, such as *Rhodobacter capsulatus*, are favorable candidates for large scale production due to their high energy-conversion efficiencies and their ability to use a wide variety of substrates for growth and hydrogen production [9,10]. Nevertheless, the rate and yield of hydrogen production vary greatly depending on the carbon sources used and physiological growth conditions, such as light intensity. In research targeting large-scale biological hydrogen production, while black-box analyses of model reactors provide the most reliable basis for further studies [11,12], an integrated view of the overall hydrogen production metabolism is also necessary in order to interpret the results property and facilitate the design of experiments *R. capsulatus* and other PNS bacteria produce molecular hydrogen under anaerobic and nitrogen-limiting conditions by using light as primary energy source and organic compounds as carbon source. The nitrogen-limiting condition (brought about by having a high C/N ratio) forces the bacteria to ‘dump’ the excess energy and reducing power through the production of hydrogen. The overall hydrogen production mechanism comprises several individual components: the enzyme systems (nitrogenase and hydrogenase enzymes), the TCA cycle (carbon flow) and the photosynthetic membrane apparatus [13].

The quality of the final product from a bioreactor depends mainly on the control loop employed to monitor and control the microbial growth based on the reference input. Apart from this, incidental external and internal disturbances in a reactor may result in reactor failure. Therefore, the control scheme is generally designed for a specific bioreactor behavior. This is further related with the fact that microorganism cultivation systems require the fulfillment of a large set of specific conditions. In the open literature, several kinds of methods have been proposed to implement control laws for bioreactors operating at single or multiple steady-states with great success [14].

In general, the control methodologies are based on linear and nonlinear approaches and between them the model-based methodologies, and the non model-based control techniques. The linear controllers present some important advantages, as easy implementation and tuning and closed-loop stability can be assured under the conditions design, however they must be applied on specific operating regions; generally linear approaches are not robust against external disturbances, despite that exist several proposals dealing these topics [15]. On other hand, the nonlinear controllers are applied to wide operation regions and some robust designs considering external disturbances, measurements noisy has been proposed [16], for this type of control laws the closed-loop stability analysis is complex and generally the tuning of the named control's gains is heuristic [17]. Related with model-based control design, the obvious drawback is the necessity of well performed mathematical representation of the system to be controlled, such that the presence of large model uncertainties and/or unmodeled dynamics can destabilizing the closed-loop system operation [18], this situation is avoided with the non-model-based strategies, where generally some basic properties of the system must be known to implement these methodologies [19]. From the above, the early successful application of process control is evidenced by the evolution of the PID controller and Ziegler–Nichols tuning method [20]. Till nowadays, a high percent of the controllers implemented in the process industries are from the PID-type [21,22]. However, as (i) the industrial demands (ii) the computational capabilities of controllers and (iii) complexity of the systems under control increase, so the challenge is to implement advanced control algorithms increases [23,24]. Under this frame, hyperbolic tangent laws have been proposed in order to overcome the PID controller's deficiencies [25,26]. Advanced process control structures, such as internal model control (IMC), sliding mode control (SMC) and model predictive control (MPC) have been implemented with interesting applications to nonlinear systems [27–29].

Recently, a number of studies have been reported concerning the optimization of processes via design of nonlinear control laws, particularly in hydrogen production, for example, a proposed approach uses a high gain based controller in order to achieve the control objective [30,31]. The other hand, robustness properties of a sliding mode controller have been investigated, this controller is applied to proton exchange membrane fuel cells (PEMFC) have proved to be the most suitable fuel cell technology for both transportation and stationary applications of hydrogen [32]. A model predictive control (MPC) method is applied for the current-sharing control of parallel fuel cell generation systems [33]. Aceves-Lara et al. [34] proposed a closed-loop optimization of the bio-hydrogen production in continuous fermentation using a model predictive control (MPC) strategy.

Therefore, in this work is presented a novel feedback control structure in order to increase the biogenic hydrogen production regulating the substrate concentration [9,10], which is considered the measured bioreactor's output, manipulating the input flow (dilution rate), which is considered as the control input. The proposed controller is applied to a fermentative bioreactor with non-sulfur bacteria *R. capsulatus*, ensuring that the asymptotic closed-loop stability of the continuous bioreactor operation is reached.

Model development

For biological systems, the unstructured models are the simplest of all modeling philosophies used to describe the biological process. They consider the cell mass as a single chemical species and do not consider any intracellular reactions occurring within the cell. Unstructured modeling typically describes the growth phenomena based on a single limiting substrate and consider only substrate uptake, biomass growth, and product formation in the modeling framework [35,36].

The considered model was presented in Refs. [37–39] and represents the biogenic hydrogen production via photo fermentation process with *R. capsulatus*. The model parameters used were obtained by Obeid et al. [39]. The specific cell growth rate model is giving by a Monod equation, as follows:

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