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On-line heuristic optimization strategy to maximize the hydrogen production rate in a continuous stirred tank reactor

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ABSTRACT

This work presents a simple heuristic approach to maximize the hydrogen production rate (HPR) using an on-line optimization strategy in a continuous stirred tank reactor. An initial investigation of the relationship between the organic loading rate (OLR) and HPR was used to propose the objective function of a nonlinear optimization problem, subject to a limited range of hydraulic retention times (HRTs) and a maximum productivity standard deviation. The inlet flow was the optimized variable while the influent substrate concentration was fixed at a constant value. The results showed a maximum HPR of 25.4 L H_2/(L d), reached for an optimal OLR of approximately 100 g COD/(L d) and an HRT of approximately 4 h. Following the optimization strategy, the specific HPR was increased from 7.52 to 16.35 L H_2/(gVSS d). The hydrogen yield increased from 1.8 to 2.32 mol H_2/mol glucose, representing an improvement of 29%. Finally, during the optimization period, the specific hydrogen production rate increased from 3.3 to 16.35 L H_2/(gVSS d), which suggested that the substrate was used by hydrogen-producing biomass rather than by other competing microorganisms.

1. Introduction

As a renewable and clean energy carrier, hydrogen is emerging as a technology with the potential to address current energetic and environmental problems. Hydrogen has a great advantage in terms of energy efficiency (when applied in fuel cells), and its combustion generates only water with very low concentrations of nitrous oxides and without carbon dioxide (CO_2) [1]. Hydrogen can be produced by conventional processes such as methane reforming, but can also be produced by biological processes. Biological process that have been used to generate hydrogen include direct biophotolysis, indirect biophotolysis, photo-fermentation, and dark fermentation [2]. The fermentative step of anaerobic digestion is one of the most promising processes because this method can produce hydrogen and valuable liquid products simultaneously [3,4].

During the fermentative production of hydrogen in a mixed culture, there are many interactions between hydrogen-active and non-active biomass. Part of the non-active biomass corresponds to communities competing for the substrate and generating reduced organic compounds such as ethanol and lactic acid, which do not correspond to metabolic pathways for hydrogen production. Furthermore, the presence of hydrogen consumer communities like homoacetogenic and methanogenic microorganisms and nitrate and sulfate-reducing bacteria may affect process stability and decrease process productivity [5]. In other words, this complex diversity of microbes could make the acidogenesis fermentation process unstable. In order to achieve a stable and highly productive hydrogen production process, optimization strategies must be implemented.

On-line optimization is a key approach that can be used to improve the performance of biotechnological processes. In recent years, several strategies have been applied to different processes. Model predictive control (MPC) is the most popular scheme that has been considered due to the simplicity of formulating a nonlinear optimization problem, which can be normally solved by standard numerical methods [6–8]. Nevertheless, recently, extremum seeking control (ESC) has emerged as a promising on-line optimization strategy [9–12]. The main advantage of ESC over MPC is that a formal and rigorous analysis can be carried out in order to assure the stability of the closed-loop dynamics and the convergence of the algorithm to the optimal solution.

In particular, anaerobic digestion has received special attention due to its increasing use in wastewater treatment and bioenergy production. For example, in a highly loaded anaerobic digestion process [13], a control strategy has been developed to maintain organic loading rates as high as possible despite variations in the

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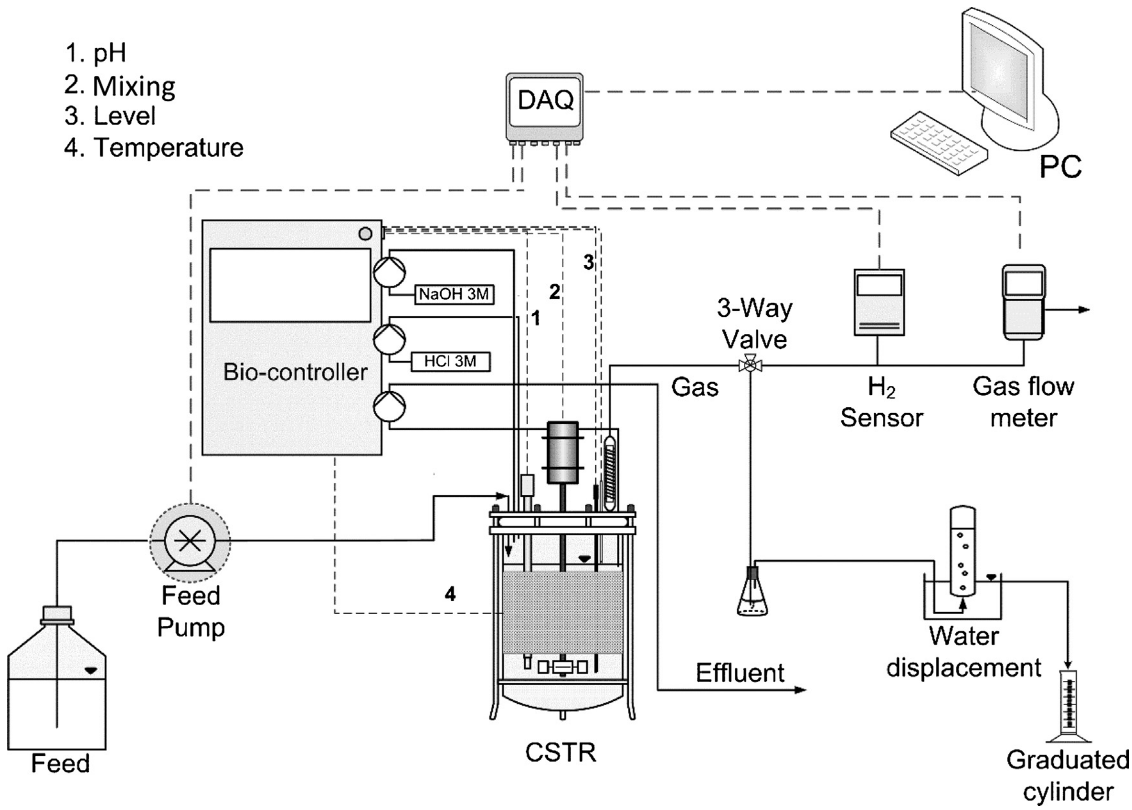

Fig. 1. Scheme of the continuous fermentative hydrogen production system.

influent concentration. At the same time, the effluent concentration has been kept low and stable. More recently, a multi-objective strategy to control the effluent quality and maximize the methane production rate was proposed for an upflow sludge bed-filter reactor used in the anaerobic treatment of winery wastewater [14].

Several optimization strategies have been considered to achieve optimal operation in biological hydrogen production systems [15–20]. Nevertheless, on-line optimization methods have been poorly explored. To the best of our knowledge, few optimization strategies have been implemented on-line to achieve optimal operation in fermentative hydrogen production systems. For example, in continuous anaerobic digesters, hydrogen production has been optimized using a model predictive control approach [6]. In that study, a dynamic optimization combining an optimal closed-loop control with state and input variable estimations by an asymptotic observer was investigated. In another study, a fuzzy control-based on-line optimization strategy was examined to maximize productivity by determining the optimal pH and temperature, according to a set of inference rules [21].

In this paper, a simple heuristic approach to maximize the hydrogen production rate (HPR) using an on-line optimization strategy in a continuous stirred tank reactor (CSTR) is presented. The approach models the effect of the organic loading rate (OLR) on the hydrogen production rate; this relationship is used to define an objective function to maximize. The bioreactor has two inputs, the influent substrate concentration Glu_{in}, considered in this study as an uncontrolled input (disturbance), and the inlet flow rate Q_{in}, considered as a controlled input. In addition, the total gas flow rate Q_{gas} and the hydrogen fraction at the reactor output are measured. Since the inlet flow rate is a controlled input, Q_{in} is selected as the variable to optimize, while the influent substrate concentration is fixed at a constant value. Thus, the aim of this study is to evaluate whether a simple relationship between OLR and HPR is suitable for optimization purposes, as well as whether the glucose concentration at the reactor input remains constant throughout the implemented strategy. The fixed value was established such that the bioreactor operated close to the substrate saturation boundary (overloading operation).

2. Materials and methods

2.1. Inoculum and composition of the culture medium

Granular anaerobic sludge from a wastewater treatment UASB reactor operated in a brewing industry was used as inoculum after thermal pretreatment as described previously [22]. Glucose was used as both a carbon and energy source, and it was added to the culture medium at concentrations of 5, 10, 15 and 20 g/L. For every gram of glucose and liter of solution, the following amounts of mineral salts were added (adapted from [23]): K_2HPO_4, 50 mg; NH_4Cl, 104 mg; $MnCl_2{\cdot}4H_2O$, 0.1 mg; $MgCl_2{\cdot}6H_2O$, 5 mg; $FeSO_4{\cdot}7H_2O$, 5 mg; $CoCl_2{\cdot}6H_2O$, 0.5 mg; $Na_2MoO_4{\cdot}2H_2O$, 0.5 mg; H_3BO_4, 0.5 mg; $NiCl_2{\cdot}6H_2O$, 0.5 mg; $ZnCl_2$, 0.5 mg. The feed solution was prepared using tap water and refrigerated at 4 °C to minimize fluctuations in composition.

2.2. Experimental setup, startup and reactor operation

The experiments were conducted in a 1.25-L continuous stirred tank reactor (CSTR) with a working volume of 0.9 L and equipped with an ez-control controller (Applikon Biotechnology, Schiedam, the Netherlands). A complete scheme is shown in Fig. 1. The reactor was operated at 35 °C and 100 rpm, and the pH was maintained at 5.5 by adding 3 N NaOH solution. The liquid level in the reactor was kept constant by a conductivity-based on–off controller. Initially, the reactor was flushed with nitrogen to establish an anaerobic environment. The feed flow rates (for the different glucose