Chemical Engineering Science 123 (2015) 207–219

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Nonlinear control of continuous cultures of *Porphyridium purpureum* in a photobioreactor

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HIGHLIGHTS

- Experimental validation of a control strategy of a microalgae culture in a continuous photobioreactor with experimental data.
- Biomass concentration is regulated using a linearizing control law and a PI-controller.
- Anti-windup compensation is added to the PI-controller, improving closed-loop system performance.
- Biomass concentration is estimated with an Extended Kalman filter using available on-line measurements.
- The presented procedure can be applied to any microalgae species.

ARTICLE INFO

Article history:
Received 6 June 2014
Received in revised form
24 September 2014
Accepted 4 November 2014
Available online 13 November 2014

Keywords:
Microalgae
Photobioreactor
Linearizing control law
Kalman filtering

ABSTRACT

Advanced control strategies proved to be promising tools to improve the performances of microalgae production systems, especially in the perspective of large scale cultivation plants. This paper proposes the validation of a nonlinear control strategy with experimental results. Additionally, the on-line estimation of the biomass concentration in a photobioreactor is presented. The proposed control law maintains the biomass concentration at a targeted level. This is achieved by a state feedback linearizing control law in an inner loop, in addition to a Proportional Integral regulator with an anti-windup compensation in an outer loop. To cope with the lack of on-line biomass concentration measurements, this variable is estimated on-line by an Extended Kalman Filter, based on available on-line measurements (pH, incident light intensity and dissolved carbon dioxide concentration). Performance and robustness of the proposed control strategy are assessed through experimental results obtained with cultures of the microalgae *Porphyridium purpureum* in a laboratory-scale continuous photobioreactor.

1. Introduction

Microalgae are photosynthetic organisms that convert carbon dioxide to biofuels, foods, feeds and high-valuable products (such as long-chain polyunsaturated fatty acids, polysaccharides, vitamins and pigments).

Microalgae cultures also find applications in energy production (e.g. hydrogen, biofuel, methane) and environmental remediation (e.g. wastewater treatment, carbon dioxide capture, reducing consequently the greenhouse gas emissions) (Benemann, 1997, 2000; Chisti, 2007; Hallenbeck and Benemann, 2002).

Recently, biological CO_2 mitigation by microalgae has attracted much attention because microalgae use photosynthesis to generate biomass from light and CO_2, with potential for high productivity and fast growth (Tebbani et al., 2014b). Several species have already shown their potential to resist concentrations of CO_2 from 40 to 100% (v/v) in the feed gas. Additionally, bioremediation of heavy metals using microalgae represents another environmental application of microalgae (Malik, 2004).

Microalgae cultures are classically carried out in open ponds. However, closed photobioreactors seem to be more efficient than open ponds (e.g. higher biomass productivities are obtained), especially when applying real-time control laws to microalgal cultivation (Chisti, 2007). Open ponds and closed photobioreactors can operate in continuous and non-continuous (batch) regimes.

Microalgae are usually grown under photoautotrophic conditions where they grow using light and inorganic carbon (carbon dioxide typically). However some species are able to use organic

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http://dx.doi.org/10.1016/j.ces.2014.11.016
0009-2509/

compounds in presence or absence of carbon dioxide. Moreover, environmental parameters such as pH, temperature, light and concentrations of carbon dioxide and nutrients strongly affect microalgae growth and biomass productivity (Li et al., 2004; Mata et al., 2010; Olaizola, 2003; Ras et al., 2013; Soletto et al., 2008; Sorokin and Krauss, 1958).

One of the goals of a bioprocess control is to ensure that the system operates at constant biomass concentration, in spite of environmental disturbances (e.g. changes in light, pH, etc), thus keeping high biomass productivity.

Control of microalgae cultures is a relatively recent concern. Indeed, the application of control laws for microalgal photobioreactors has been recently popularized with the installation of more powerful real-time computer systems. However, microalgae bioprocess control was found to be a difficult task because of the highly nonlinear behaviour of the system dynamics due to cell growth which is strongly linked to light attenuation (Bernard, 2011).

Nevertheless, some studies report the development and the application of control strategies to cultures in photobioreactors for biomass concentration monitoring (Abdollahi and Dubljevic, 2012; Alford, 2006; Bernard, 2011; Hu et al., 2008; Ifrim et al., 2013; Mailleret et al., 2005; Tebbani et al., 2014a).

Mainly nonlinear control laws were developed for microalgae production systems, such as linearizing input–output control laws (Ifrim et al., 2013), feed-forward controllers (Kandilian et al., 2014), output feedback controller (Mailleret et al., 2005) and Nonlinear Model Predictive Control (Tebbani et al., 2014a).

In this paper, a state feedback linearizing control law was selected and developed. It consists in an exact linearization of the bioprocess model, which is then controlled with classical linear control techniques.

The feedback control strategy used in our work needs the knowledge of all system states. However, biomass concentration is not measured on-line since the physical sensors available to quantify this variable are expensive or inaccurate. Consequently, a software sensor for the estimation of the biomass concentration was developed, based on available on-line measurements. Several estimation techniques are proposed in the literature for this application, such as high gain observers (Bernard et al., 1998), Extended Kalman filtering (Becerra Celis et al., 2008a; Li et al., 2003), Unscented Kalman filtering (Marafioti et al., 2009; Tebbani et al., 2013b), interval observers (Goffaux et al., 2009; Rapaport and Dochain, 2005; Tebbani et al., 2014a) and Moving horizon estimator (Abdollahi and Dubljevic, 2012; Tebbani et al., 2013a). The Kalman filtering is selected in this paper as it is the most frequently used estimation technique for bioprocess monitoring. As the system dynamics is nonlinear, an Extended Kalman filter (EKF) is used. It consists in linearizing the process model along the estimated trajectory determined by minimizing the variance of the estimation error. The EKF will estimate the biomass concentration on-line based on measurements of dissolved carbon dioxide concentration, incident light intensity and pH.

The aim of this paper is to propose a control strategy to maintain the biomass concentration at a constant value, in a continuous photobioreactor, by adjusting the medium feed flow rate. The proposed procedure will involve well-known estimation and control techniques applied to a microalgae culture. Moreover, the efficiency of these approaches is demonstrated with experimental data.

The control strategy is carried out in three steps. First, in order to determine the effect of carbon dioxide and incident light intensity in microalgae cultures, experimental assays are performed in a lab-scale photobioreactor operating in batch and continuous modes. Afterwards, a mathematical modelling approach is developed. Model parameters identification is assessed by fitting the experimental data obtained in the exponential phase of batch cultures. Model validation is then carried out. In a second step, an Extended Kalman filter is developed based in Total Inorganic Carbon (TIC) concentration and physical variables measurements (pH and incident light intensity). In the last step, the biomass concentration control is done by developing a nonlinear control law, made of a state feedback linearization associated with a Proportional Integral controller with an anti-windup mechanism. Finally, the control strategy performance and robustness are evaluated using experimental data of continuous cultures.

This paper is organized as follows. The next section describes the experimental set-up followed by the system modelling. The design of the EKF observer will be presented in Section 3 and the control strategy will be then detailed in Section 4. Experimental results are given and discussed in Section 5. Finally, concluding remarks and perspectives are stated at the end.

2. Materials and methods

2.1. Microalgae inoculum and media composition

The strain *Porphyridium purpureum* SAG 1830-1A (obtained from the Sammlung von Algenkulture Pflanzenphysiologister Institut der Universität Göttingen, Germany) is cultured and maintained in Hemerick (1973) medium. The medium is sterilized at 121 °C during 20 min. Cultures are maintained at 25 °C in 500 mL flask containing 400 mL culture under continuous light intensity of 70 $\mu E\, m^{-2}\, s^{-1}$, aerated with air containing 1% (v/v) CO_2 at 100 rpm in an orbital shaker. Every two weeks, 200 mL of the culture in exponential phase of growth is transferred to a new flask containing fresh medium. This culture is then used to inoculate the photobioreactor.

2.2. Description of the photobioreactor

The microalgae cultures are carried out in a bubble column photobioreactor (Fig. 1) with a working height and diameter of 0.62 m and 0.17 m, respectively. The total culture volume is 9.6 L. The cylindrical reactor has an illuminated area of 0.31 m².

Air containing 2% CO_2 (v/v) is continuously supplied at a flow rate of 2.5 VVH (gas volume per liquid volume per hour) at the bottom of the column allowing carbon dioxide supply and culture mixing.

The lab-scale photobioreactor (PBR) can operate in either batch or continuous modes.

The air flow entering the photobioreactor is filtered through 0.22 μm Millipore filters and is regulated using mass flow meters (Red-y Smart Series, Vötglin Instruments).

An arrangement of four OSRAM white fluorescent tubes (L30W/72) and four OSRAM pink fluorescent tubes (L30W/77) around the bubble column is used as an external light source. The incident light intensity at the reactor's surface is measured using a flat-surface quantum sensor LI-COR LI-190SA.

When the PBR operated in continuous mode, the culture medium is supplied using a peristaltic pump through an input located at the top of the reactor. The supply flow rate is controlled by a NATIONAL INSTRUMENTS board, which manages the rotation speed of the pump through the imposed voltage. The maximal flow rate given by the pump is $F_{max} = 1.5\ L\, h^{-1}$. The effluent is collected as an overflow of the reactor. Its volume is then weighted to check the outlet flow.

The culture temperature is controlled at 25 °C by circulating water at this temperature through the bioreactor's double envelope.