Computers and Electronics in Agriculture 103 (2014) 114–121

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

Gas equilibrium regulation by closed-loop photo bioreactor built on system dynamics, fuzzy inference system and computer simulation

Dawei Hu [b,c,*], Liang Li [b,c], Yanchao Li [a], Ming Li [b], Houkai Zhang [b,c], Ming Zhao [a,*]

[a] College of Information and Electrical Engineering, China Agricultural University, Beijing 10008,China
[b] Lab of Environmental Biology and Life Support Technology, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China
[c] State Key Laboratory of Virtual Reality Technology and Systems, School of Computer Science and Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 4 September 2013
Received in revised form 22 December 2013
Accepted 5 February 2014

Keywords:
Photo bioreactor
Mathematical modeling
Digital simulation
Fuzzy logic control

ABSTRACT

It is vitally important to robustly stabilize gases (O_2 and CO_2) concentrations in the Bioregenerative Life Support System at nominal levels on space mission. The blue algae, *Spirulina platensis*, having special advantages of high growth rate, controllability and metabolism flexibility were therefore utilized to maintain gas equilibrium. In our research, photo bioreactor (PBR) cultivating *S. platensis* was built for investigation on effective design and optimization of advanced PBR. Firstly, a mathematical model expressed in terms of a set of parameterized nonlinear first-order differential equations for sufficient description of inner structure and processes of PBR was developed by system dynamics based on related mechanisms and experimental data. Secondly, a fuzzy inference system (FIS) was constructed and used as feedback fuzzy logic controller (FLC) of PBR. Finally, the parameters in PBR model and member functions were optimally specified by a predetermined response curve. The results demonstrated that FIS–FLC could effectively control and regulate the system's inputs, light intensity and flow rate of air in aerating pipe, to robustly stabilize the system's output at a target O_2 /CO_2 ratio of 214 in the gas phase of PBR with satisfactory dynamic process.

1. Introduction

When long-term and far distance human space travel is conducted in the future, Bioregenerative Life Support System (BLSS) is necessarily established to provide O_2, food, drinking water and other basic living necessities for astronauts and recycle the waste, which is achieved by the combined actions of crew members, higher plants, animals, microorganisms and artificial environment. In order to fulfill life support task, it is critically important for BLSS to maintain gases (mainly refer to O_2 and CO_2) concentrations at the set levels on space mission (Gitelson et al., 2003). However, BLSS will probably undergo unanticipated disturbances which might break the delicate balance of O_2 and CO_2 concentrations during the long-term mission. If this unfavorable situation persists for an excessively long time, BLSS will suffer catastrophic failure seriously imperiling astronauts' safety. In the circumstances, it is significant to seek out solution to resume normal O_2 and CO_2 concentrations by means of biological approaches (Bartsev and Okhonin, 1999; Gitelson et al., 2003).

Compared with higher plants and animals, microalgae having special advantages like high growth rate, controllability and metabolism flexibility could be selected as an extremely attractive tool for regeneration and control of O_2 and CO_2 concentrations in BLSS under emergencies (Gitelson et al., 2003; Garland, 2007). For example, microalgae, *Chlorella vulgaris*, was selected for gas phase composition modulation applicable to BIOS-1$\sim$3 (Gitelson et al., 2003), and *Cyanothece sp.ATCC51142* was used to accelerate gas recirculation as well as supply protein and fat for astronauts (Sehncegurt, 1996). The blue algae, *Spirulina platensis* (*S. platensis*), was also cultivated for O_2 regeneration and waste disposal to fulfill life support task (Travieso et al., 2001; Godia et al., 2002).

BLSS and its subsystem are multivariate complex systems with intricate internal structure, numerous parameters and complicated dynamic behaviors, and some important physical quantities in the system might change in the large scopes without fixed operating points, so traditional control approach like Proportional plus Integral plus Derivative (PID) control based on the linearization of the nonlinear systems would be infeasible, and the proper nonlinear controller could not also be designed exactly by analytical and synthetical methods due to high nonlinearity and uncertainty.

* Corresponding authors. Address: College of Information and Electrical Engineering, China Agricultural University, Beijing 10008, China. Tel.: +86 13681027032 (M. Zhao).
E-mail addresses: hudawei@buaa.edu.cn (D. Hu), zhaoming@cau.edu.cn (M. Zhao).

http://dx.doi.org/10.1016/j.compag.2014.02.002
0168-1699/

Furthermore, BLSS and its subsystem often encounter unanticipated internal variations and external disturbances during the operation and, hence, the open-loop control without feedback information, extensively used in current BLSS studies, is also unable to work well due to lack of stability (Travieso et al., 2001; Gitelson et al., 2003).

Since obtaining the mathematical model of controller of complex systems through analytical method is very difficult and even impossible, fuzzy logic might be an ideal alternative to differential or algebraic equations for control strategy development (Yamakawa, 1992). In our research, a photo bioreactor (PBR) efficiently cultivating *S. platensis* was firstly built as a specific prototype of BLSS subsystem, and a highly valid mathematical model of PBR was developed by system dynamics and coefficient estimation based on related mechanisms and experimental data. Then a Mamdani-type fuzzy inference system (FIS) consisting of proper membership functions and fuzzy logic rules was designed and used as a fuzzy logic controller (FLC) for feedback regulation and control of system behavior. Finally, the closed-loop PBR with FIS–FLC was dynamically optimized by digital simulation, and accredited and real-time simulation, i.e., the target O_2 /CO_2 ratio in the gas phase of PBR could be robustly stabilized at a desired level of 214 with satisfactory dynamic response performance to control actions and perturbations.

2. Materials and methods

2.1. Prototype of PBR

The PBR used in our research was a 1.5 L plate-type bioreactor where *S. platensis* were cultivated in semicontinuous mode using synthetic human urine and CO_2 as substrates introduced separately through an inflow pipe and an aeration pipe located at the bottom of PBR. The O_2 generated from *S. platensis* photosynthesis was transmitted from liquid phase to the gas phase and finally expelled out of PBR through a vent pipe. The 10 ml of buffer solution containing $NaHCO_3$ (13.6 g L^{-1}) and Na_2CO_3 (4.0 g L^{-1}) was also added in culture medium to adjust the pH of liquid phase to 9 consistently during the PBR operation. Under condition of temperature 30 °C and pressure 1 atm, the *S. platensis* cultivation was illumined by light emitting diodes (LED) designed with red (680 nm) and blue (425 nm) lights, and the total intensity ranged between 100 μmol m^{-2} s^{-1} and 300 μmol m^{-2} s^{-1} regulated in pulse-width modulation (PWM) mode. The flow rate of air in aerating pipe varied from 20 L h^{-1} to 220 L h^{-1} was adjusted by an electromagnetic valve in order to both meet CO_2 requirement of *S. platensis* and wash out the internal wall of vessel to prevent biofilm formation (Soletto et al., 2005; Yang et al., 2008).

2.2. Hypothesis and flow chart in modeling PBR

In order to thoroughly and profoundly investigate the complicated gases dynamics in PBR, it was necessary to develop a grey-box mathematical model expressed in terms of a set of parameterized nonlinear first-order differential equations based on related mechanisms and experimental data. Three phases were considered in the PBR: biological, liquid, and gas, and mass balance equations were derived according to the following assumptions:

- PBR was considered as a nonlinear, continuous and lumped parameter system.
- PBR operated in normal circumstances, and all environmental factors influencing the growth of *S. platensis* were in their permissible ranges.
- $[CO_3^{2-}]$ in the liquid phase was only affected by CO_2 hydrolyzation and buffer solution addition.
- According to the practical operation of PBR, effects of minerals, organic acids, vitamins and bacteria on the *S. platensis* growth were all neglected.
- Main kinetic process in PBR was microalgae growth, and other processes pertinent to it were specified accordingly by coefficient conversion.

According to system analysis, process assumption and actual experimental, the flow chart (Fig. 1) was drawn for mathematical modeling of PBR.

2.3. State variables

The mathematical model of PBR contained 9 state variables: microalgae biomass concentration (X: g L^{-1}), O_2 concentration in liquid phase ($[O_2]_d$: g L^{-1}), O_2 concentration in gas phase ($[O_2]_g$: g L^{-1}), CO_2 concentration in liquid phase ($[CO_2]_d$: g L^{-1}), CO_2 concentration in gas phase ($[CO_2]_g$: g L^{-1}), culture metabolite concentration (P: g L^{-1}), CO_3^{2-} concentration ($[CO_3^{2-}]$: g L^{-1}), O_2 partial pressure in gas phase (p_{O_2}: Pa) and CO_2 partial pressure in gas phase (p_{CO_2}: Pa).

2.4. Rate equations

Rate equations were obtained from quantifying the dependencies and relationships between entities and environmental factors in the PBR, and the coefficients in rate equations used in scenarios were estimated by applying nonlinear least-squares approach and digital simulation based on time-domain experimental data or directly defined by taking from the literature (Jorgensen, 1979; Amini et al., 2012).

2.4.1. Microalgae growth and related rates

The growth rate of microalgae (v_b: g L^{-1} h^{-1}) could be modeled as follows:

$$v_b(t+\tau) = \mu X \Longleftrightarrow v_b = \mu X(t-\tau) \quad (1)$$

where X was biomass concentration, and τ (3.84 h) was an average time delay of *S. platensis* growth response to light intensity and CO_2

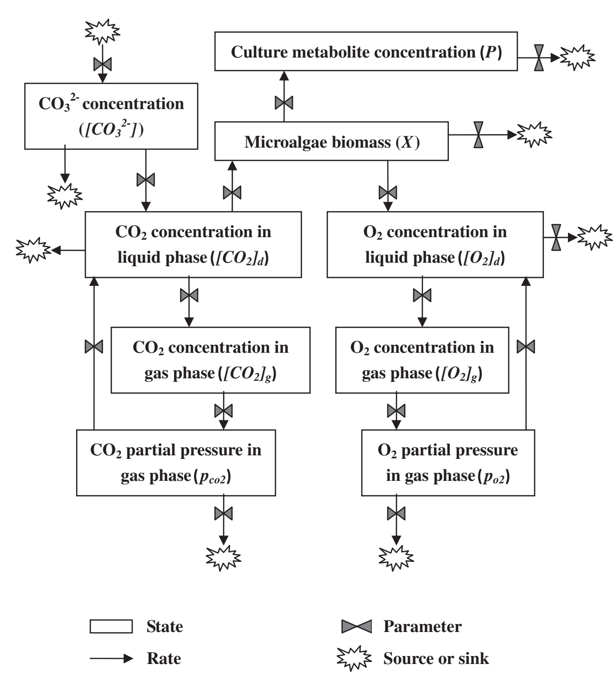

Fig. 1. Flow chart of PBR.