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Event-based selective control strategy for raceway reactor: A simulation study ⋆

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Abstract: This work presents a simulation study of an event-based selective control strategy for a raceway reactor. The control system aims are to maintain simultaneously a pH and dissolved oxygen within specific limits. In the analyzed control scheme, the pH value is prioritized over the dissolved oxygen, since it has a critical influence on the process performance. Besides, the dissolved oxygen also influences the photosynthesis rate and should be kept within the limits. The control structure is evaluated through simulation, where a nonlinear model for microalgae culture in the raceway photobioreactor is used. Analysis of different configurations allows to determine the most adequate control system setup to achieve the desired goals. The obtained results show that combination of an event-based approach with selective control allows to increase the overall productivity as well as to address effective CO_2 utilization and aeration system energy minimization.

Keywords: raceway reactor, microalgae, pH control, dissolved oxygen control, selective control,

1. INTRODUCTION

Depending on the properties one is looking for, microalgae culture can be grown in photobioreactors with different architectures. When a high-value algal biomass from particular strains is required, closed photobioreactors are generally used, e.g. tubular photobioreactors. On the contrary, when high production volume is the priority, open photobioreactors are usually employed. The most popular in this group is the raceway photobioreactor. However, independent of the physical configurations, all photobioreactors are designed to assure optimal microalgae growth conditions. As reported in (Costache et al., 2013), the most important variables in microalgae culture are: solar irradiance, medium temperature, pH, and dissolved oxygen (DO). Furthermore, the response of the photosynthesis rate to solar irradiance changes depends on other variables, making the microalgae culture process a complex system. For the raceway photobioreactor, light requirements and operating temperature are determined by the reactor architecture and cannot be manipulated during normal operation. The remaining microalgae bioprocess variables such as pH and DO should be handled using the proper control techniques. The pH and DO values are highly dynamic since they depend on the photosynthesis rate and need to be kept close to their optimal values.

Except for solar irradiance and temperature, pH is the most important variable that influences the photosynthesis rate. It is well known that the application of CO_2 has a direct influence on the pH value since it changes the acidity of the microalgae growth medium. Overabundance of CO_2 can strongly reduce pH thus damaging the culture. Conversely, insufficient CO_2 supply can reduce the inorganic carbon concentration below the minimum resulting in limited growth (Benemann et al., 1987; Berenguel et al., 2004). Although CO_2 limitation can easily be avoided by supplying it in excess, the use of carbon dioxide represents a relevant operational cost for microalgae culture (de Godos et al., 2014). Another important aspect of uncontrolled supply is related to CO_2 losses as unnecessary emission to the atmosphere needs to be minimized by providing efficient control techniques (Benemann et al., 1987; Pawlowski et al., 2014c; Bernard, 2011). Exploiting this interdependence, the control system uses the pH value to determine both the time instant and the amount of carbon dioxide to be injected. Therefore, the trade-off between pH regulation accuracy and minimization of CO_2 losses should be considered in the control approach.

The dissolved oxygen content is another variable that has a significant influence on the microalgae photosynthesis rate and in consequence affects the amount of final product. Dissolved oxygen at high concentrations in the cultures would pose a severe threat to microalgae growth (Peng

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et al., 2013; Ugwu et al., 2007). In raceway ponds, it is assumed that no DO control is required since dissolved oxygen excess should be automatically removed to the atmosphere. However, in practice this assumption is incorrect as DO concentration can reach as high as 500 % air saturation (Mendoza et al., 2013; Peng et al., 2013). To minimize DO influence on culture growth, it is necessary to provide an aeration or stirring mechanism. In both cases, the required equipment may add complexity to the photobioreactor and increase the production cost. As reported in (Peng et al., 2013) and (Mendoza et al., 2013), the DO evacuation issue remains a significant challenge despite the considerable technical advances in this field.

Considering aforementioned features, it can be observed that both objectives for pH and DO processes are adversative, because applying the aeration mechanism can deteriorate CO_2 assimilation. Moreover, for economic reasons it is common practice to provide the same supply structure for both variables. In such a case, the CO_2 and air supply system can be commuted when necessary and only one variable can be controlled (only one quantity can be supplied). To deal with those issues, the selective control control system with an event-based approach was introduced in (Pawlowski et al., 2015). The application of this control scheme allows to merge the specific objectives, limiting undesired interactions. Moreover, due to the event-based approach this control system can adapt the actuation rate to the process dynamics and process distrubances (Pawlowski et al., 2011). This feature is especially useful in bioprocess application, as was confirmed in several recent works (Beschi et al., 2014; Pawlowski et al., 2014a,b,c).

In this study we extend the selective control system configurations presented in (Pawlowski et al., 2015), considering discrete-time Proportional-Integrate (PI) controller for the DO control purposes. Beside, the pH process is controlled with event-based Generalized Predictive Controller (GPC) that was successfully evaluated for this purpose in (Pawlowski et al., 2014c). The evaluation of the modified approach is performed through a simulation study, where the raceway photobioreactor is modelled using a first principle approach. The developed nonlinear model is used as a process simulator as well as a test bed for different control system configurations. In such a case, the effectiveness of prosed control scheme can be verified analyzing the influence of the control system parameters. The modified approach, provides a possibility to reduce the energy required for aeration system and effective use of flue gases (used as CO_2 source). The obtained results are confirmed by several control system performance indexes, including the raceway reactor productivity measures.

2. SYSTEM DYNAMICS AND MODELS

The experimental raceway reactor used for modelling purposes is situated at the Estación Experimental Las Palmerillas owned by the Fundación CAJAMAR (Almería, Spain). The raceway has a total surface area of 100 m^2 and consists of two 50 m channels, each 1 m wide and connected by U-shaped bends (see (Mendoza et al., 2013) for details). An appropriate model in microalgal production system must consider the relationship between light availability and photosynthesis rate, the mixing and the gas–liquid mass transfer inside the system.

The culture growth can be modelled as a function of the photosynthesis rate. The main parameter that determines the photosynthesis rate is the available light, based on external irradiance, culture characteristics and reactor geometry (Acién et al., 1999, 2013):

$$I_{av}(t,x) = \frac{I_0(t)}{K_a C_b(t,x) h}(1 - exp(-K_a C_b(t,x)h) \quad (1)$$

where t is the time, x the space, I_0 is the solar irradiance on an obstacle-free horizontal surface, K_a is the extinction coefficient, C_b is the biomass concentration, and h is the liquid height on the channels.

The available average irradiance is correlated with the photosynthesis rate by a hyperbolical function as proposed in (Molina et al., 1996). This function is completed by adding the rest of factors that limit the microalgal growth (under sufficient conditions of nutrients). So, the influence of the pH culture value and dissolved oxygen of the culture have been modeled as described in (Costache et al., 2013):

$$\begin{aligned} P_{O_2}(t,x) = (1-\alpha_s)\frac{P_{O_{2,max}} I_{av}(t,x)^n}{K_i exp(I_{av}(t,x)m) + I_{av}(t,x)^n} \\ \left(1 - \left(\frac{[O_2](t,x)}{K_{O_2}}\right)^z\right) \\ \left(B_1 exp\left(\frac{-C_1}{pH(t,x)}\right) - B_2 exp\left(\frac{-C_2}{pH(t,x)}\right)\right) - \alpha_s R_{O_2} \end{aligned} \quad (2)$$

where P_{O_2} is the photosynthesis rate (oxygen production rate per biomass mass unit), $P_{O_{2,max}}$ is the maximum photosynthesis rate for microorganisms under the culture conditions, n is the form exponent, and the term in the denominator is the irradiance constant, that increases as an exponential function of average irradiance, K_i and m being form parameters of this relationship, K_{O_2} is the oxygen inhibition constant and z is a form parameter. For the pH influence on the photosynthesis rate, B_1, B_2 are the preexponential factors and C_1, C_2 the activation energies of the Arrhenius model. Furthermore, a constant respiration rate R_{O_2} was included in order to represent the respiration phenomenon, and a solar distributed factor α_s as the shadow projection on the perpendicular axis of the reactor walls.

The pH value of the culture is related to other species such as dissolved carbon dioxide, $[CO_2]$, carbonate, $[HCO_3^-]$, or bicarbonate, $[CO_3^{2-}]$ by several equilibrium equations, as can be seen in (Camacho et al., 1999), being necessary the balance of one of them to obtain predictions of pH along time and space. In this work the total inorganic carbon concentration, $[C_T]$, is modelled taking into account the photosynthesis process performed by the microalgae culture, and the transport phenomena due to the recirculation of the culture along the raceway. Assuming constant velocity, v, and constant cross-sectional area obtained by the multiplication between the liquid height, h, and the channel width, w.

$$\begin{aligned} wh\frac{\partial[C_T](t,x)}{\partial t} = -whv\frac{\partial[C_T](t,x)}{\partial x} + wh\frac{P_{CO_2}(t,x)Cb(t,x)}{M_{CO_2}} \\ + whK_{laCO_{2_c}}([CO_2^*](t,x) - [CO_2](t,x)) \end{aligned} \quad (3)$$

where P_{CO_2} is the carbon consumption rate, $K_{laCO_{2_c}}$ is the mass transfer coefficient for CO_2, M_{CO_2} is the molecular