Diurnal and nocturnal pH control in microalgae raceway reactors by combining classical and event-based control approaches

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Abstract

The pH control in raceway reactors is crucial for an optimal performance of the system. Classical pH control is exclusively performed during the daytime period for cost saving reasons. This paper demonstrates that pH can be controlled 24 hours a day by using both a continuous-based and an event-based control approaches, being able to improve the system's performance reducing costs at the same time. Thus, experimental tests on a raceway reactor for several days are presented to show a comparison between traditional control algorithms during the daytime period versus an event-based control approach operating during both daytime and nighttime periods. As a result, the combination of classical PI control for the daytime period and the event-based control for the nighttime period is presented as a promising pH control architecture in raceway reactors.

Keywords: Microalgae, pH control, Raceway reactor

Introduction

The advantages in the cultivation of microalgae have allowed its use to be extended in the last years. These advantages lie in the capability of microalgae to carry out photosynthesis consuming CO_2 to increase biomass, which can be used in a wide range of applications, such as pharmaceutical companies, fish farms, agriculture, or even in the production of biofuel. In addition, the microalgae biomass process can be coupled with wastewater treatment to allow its use in agriculture while generating biomass (Bahadar and Bilal Khan (2013)).

There are two types of reactors: closed photobioreactors and open reactors. On the one hand, closed photobioreactors allow precise control of operating conditions and are focused on high-value microalgae that are susceptible to contamination. From this type, tubular photobioreactors are the most commonly used, where quality is more important than production volume. On the other hand, open reactors are characterized by higher biomass production volumes and are oriented to resistant microalgae strains, since it is not possible to control all the variables that affect the microalgae growth. The most extended and widespread open reactors are the raceway reactors, which are more economical and simpler to maintain than closed photobioreactors; and for these reasons are the ones used in this paper.

Microalgae growth depends on several variables, the main ones being solar radiation, medium temperature, pH and dissolved oxygen (Costache et al. (2013)). The incidence of solar radiation and temperature conditions are determined by the orientation and location of the reactor, so they are not controllable variables and act as disturbances (Pawlowski et al. (2015)). Indeed, pH and dissolved oxygen are the controlled variables in the process, being the pH the most critical due to its influence on the photosynthesis process. Thus, pH is the controlled variable considered in this work.

Traditionally, raceway reactors are operated only during the daytime period by performing a pH control using an On/Off control architecture applied to the CO_2 injection valve. The photosynthesis process performed by the microalgae changes the acidity of the culture medium, increasing the pH, while CO_2 injections reduce its value. An adequate control is required in this type of processes, since the pH has an optimum range that maximizes biomass production, as well as influencing the health of microalgae, being lethal if it exceeds certain limits. On the other hand, CO_2 injections should not be arbitrary. An excessive supply of CO_2 produces losses to the atmosphere and unnecessary waste.

Therefore, it is essential to design a correct control architecture that allows optimal pH control by reducing CO_2 injections and losses. In the last years, some control examples using Proportional-Integral-Derivative (PID) controllers have been proposed in the literature, as they are widely used in industry with satisfactory results and can be used for this type of processes. An example of a linear Proportional-Integral (PI) controller with feedforward compensation for pH control in tubular photobioreactors can be found in Fernández et al. (2010). In Hoyo et al. (2017), a robust PID controller for pH in raceway reactors based on Quantitative Feedback Theory (QFT) is used. Recently, a PI for pH control in raceway reactor based on Wiener models is presented in Pawlowski et al. (2019). On the other hand, event-based control is gaining a great interest for this kind of processes. Concerning this type of control, in Pawlowski et al. (2014a), a controller with a sensor deadband achieves a considerable reduction of CO_2 losses in a microalgae tubular photobioreactor. Another example can be seen in Pawlowski et al. (2014b), where an event-based Generalize Predictive Controller (GPC) with a disturbance compensation approach is used for the effective use of CO_2 in a raceway reactor. Subsequently, this GPC scheme was improved in Pawlowski et al. (2015) and combined with a selective control for dissolved oxygen. A simulation study using Proportional-Integral (PI) and GPC controllers plus a feedforward compensator in raceway reactors is presented in Pawlowski et al. (2018). More recently, in Hoyo et al. (2019), a predictive linear control law for pH in a raceway reactor is used to design a GPC based on a simplified First-Order-Plus-Dead-Time (FOPDT) model of the reactor. In Rodríguez-Miranda et al. (2019), a simulation study is carried out with daytime and nighttime control with PI control and event-based control over traditional On/Off control, obtaining satisfactory results related to reductions in CO_2 consumption. In this last work, it was the first time where the pH control was performed during 24 hours a day instead of during the diurnal period only. However, these results were only in simulation and it was never validated on experimental facilities. Thus, this is the main contribution of this work, to design and to implement the event-based control approach presented in Rodríguez-Miranda et al. (2019) in a real raceway facility.

Usually, pH control in raceway reactors is executed exclusively during the daytime period, allowing this value to evolve freely overnight. This effect produces variations in pH between day and night, which can become considerable and affect the health of microalgae. In addition, due to this difference between night and day, the On/Off control performs a larger injection at the beginning of the day to reduce the error, consuming large amounts of CO_2. Other control schema can solve the effect, but the variation of pH during the night still continues. The nighttime pH control would avoid this problem and reduce the injection of CO_2 that occurs during daytime, especially with the On/Off control, since the pH would remain close to the set-point during the night. Moreover, the event-based control allows the establishment of a relationship between performance and control effort to maintain the pH at optimal values without performing a large number of injections, therefore reducing CO_2 injection. In this work, the advantages of using PI and event-based control during the whole day (daytime and nighttime periods) against traditional On/Off control (performed only during daytime period) are demonstrated experimentally. First, open-loop experiments were performed to obtain the process models, and afterwards, the different control approaches were designed and implemented for several days to compare the closed-loop behaviour. Notice that simulation comparisons were performed in Rodríguez-Miranda et al. (2019) and are omitted here for saving space.

This paper is organized as follows. Section 2 describes the raceway reactor and the control architectures used, as well as, the resulting pH models. Section 3 deals with the experimental control results performed in the reactor and presents discussions about the obtained results. Finally, the paper ends with some conclusions in section 4.

Material and methods

This section collects detailed reactor information, as well as the control architectures used in the development of pH control tests in the raceway reactor.

Raceway reactor

The microalgae raceway reactor used for the test (Figure 1) is located at the IFAPA center, next to the University of Almería (Almería, Spain). The reactor has a total surface of 80 m^2, composed of two 40 m long channels connected by a 1 m wide U-shaped bends. The reactor is operated at a constant liquid height of 0.1 m to give the best overall hydraulic performance in terms of power consumption to reduce dark zones, providing a total reactor volume of 10 m^3. The mixing is made by a paddlewheel of aluminum blades with a diameter of 1.5 m, driven by an electric motor (W12 35 kW, 1500 rpm, Ebarba, Barcelona, Spain), with gear reduction (WEB Ibérica S.A., Barcelona, Spain). The paddlewheel speed is controlled with a frequency inverter (CFW 08 WEB Ibérica, S.A., Barcelona, Spain) at a constant velocity of 0.2 m/s. Carbonation is performed in a sump located 1.8 m downstream of the paddlewheel, dimensions of 1 *m* depth, 0.65 *m* length and 1 *m* width. In this sump, CO_2 gas or air can be injected through three plate membrane diffusers at the bottom of the sump (AFD 270, EcoTec, Spain). The raceway channels are made of low density polyethylene of 3 *mm* thickness while the curves and sump are made of high density polyethylene of 3 *mm* thickness.

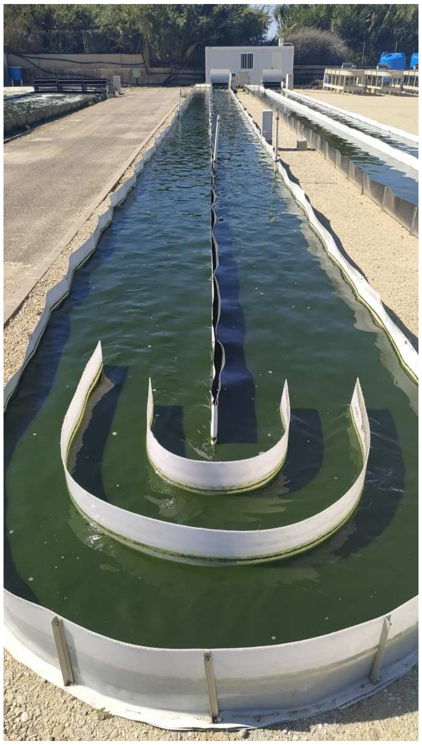

Figure 1: Microalgae raceway reactor located at the IFAPA center, in the University of Almería.

In the reactor, there are five pH probes and five dissolved oxygen probes, the arrangement of which is shown in Figure 2, where every red point consists of a pair of pH and dissolved oxygen probes. Points 1, 2 and 3 contain a pH and a membrane dissolved oxygen probes from Crison, while points 4 and 5 contain a pH and an optical dissolved oxygen probes from Hamilton.

For control purposes, the pH sensor used as feedback is that corresponding to point 1, that is the furthest away from the CO_2 injection point as it is located at the end of the loop, where microalgae have completed a cycle so that the effects of a control action can be better evaluated. This is the most unfavorable point of the reactor from the control point of view.

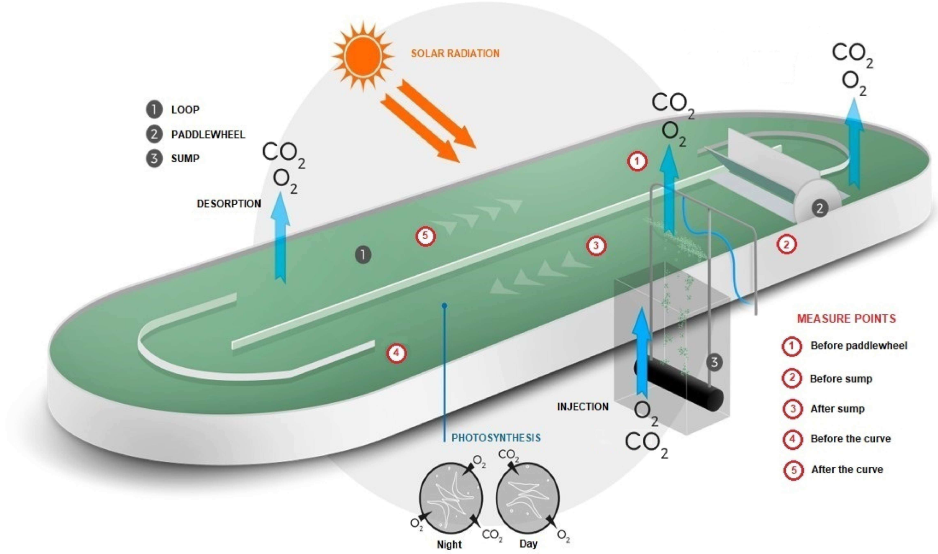

Figure 2: Reactor scheme representing the shape and parts of which it is composed in black, the location of the probes in red and the photosynthesis process schematically.

Microalgae strain

The microalgae strain used in the reactor corresponds to *Golenkinia*. This microalgae is characterized by its use in wastewater treatment because its resistance to contaminants. The pH range varies from 6 up to 11, with an optimum value around 8. Thus, for the executed tests, a pH set-point of 8 was selected.

Simplified raceway reactor model

For the design of the control architecture, two models, named as $G(s)_{daytime}$ and $G(s)_{nighttime}$, have been identified. They represent the pH dynamics during the daytime and the nighttime periods, with respect to CO_2 injections. These models are described as FOPDT transfer functions (Åström and Hägglund, 2006), where the delay or dead time represents the time it takes for a cell to reach the final part of the reactor, considered as the measurement point 1 in figure 2 (that is, the time it takes to see the effect of a CO2 injection on the output pH). It was decided to identify two models due to the differences observed in the dynamics between daytime and nighttime periods. So, open-loop experiments were performed for a pH range from 7.4

to 8.2, taking into account an operating point of pH equal to 8. The resulting transfers functions (which are models expressed in the Laplace domain by the complex variable s) relating the pH to the CO_2 are the following:

$$G(s)_{daytime} = \frac{-0.0911}{7380\,s + 1}\,e^{-180\,s} \tag{1}$$

$$G(s)_{nighttime} = \frac{-0.1293}{10378\,s + 1}\,e^{-180\,s} \tag{2}$$

Figures 3 and 4 represent the validation of the daytime and nighttime models contrasted with real data.

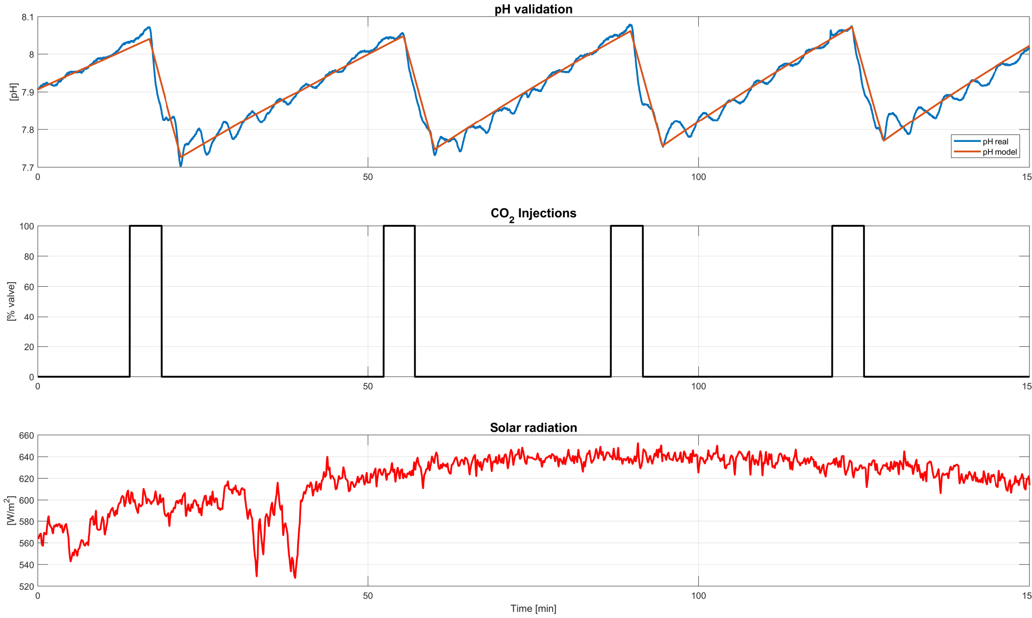

Figure 3: Model validation during daytime period. First graph represents the evolution of the real pH (blue) and the estimated one (red). Second graph represents the valve opening, input for the model. Third graph represents the environmental global solar radiation disturbance.

The input variable for both models is the opening of the CO_2 valve, being in a range from 0% to 100% (which represents the opening of the valve), while the solar radiation acts as a disturbance during the daytime (figure 3), causing the pH to rise. In theory, for obtaining a linear model (transfer function) relating CO_2 injection to pH, constant conditions of disturbances are required. Nevertheless, this is not possible in this kind of systems and tests have been done in (almost) clear day conditions, so that variations in solar irradiance and temperature are small and smooth, and thus they considered constants during the test. The same applies to biomass concentration, that changes in a slower time scale.

Notice that the models represent the dominant dynamics of the system. There is an oscillatory behaviour which period corresponds to the residence time of the system. However, it is not modelled here to be used for control design purposes as it would increase the control effort without a noticeable improvement in performance. An example of control application taking into account both dynamics (FOPDT plus second order oscillatory behaviour) can be found in Berenguel et al. (2004).

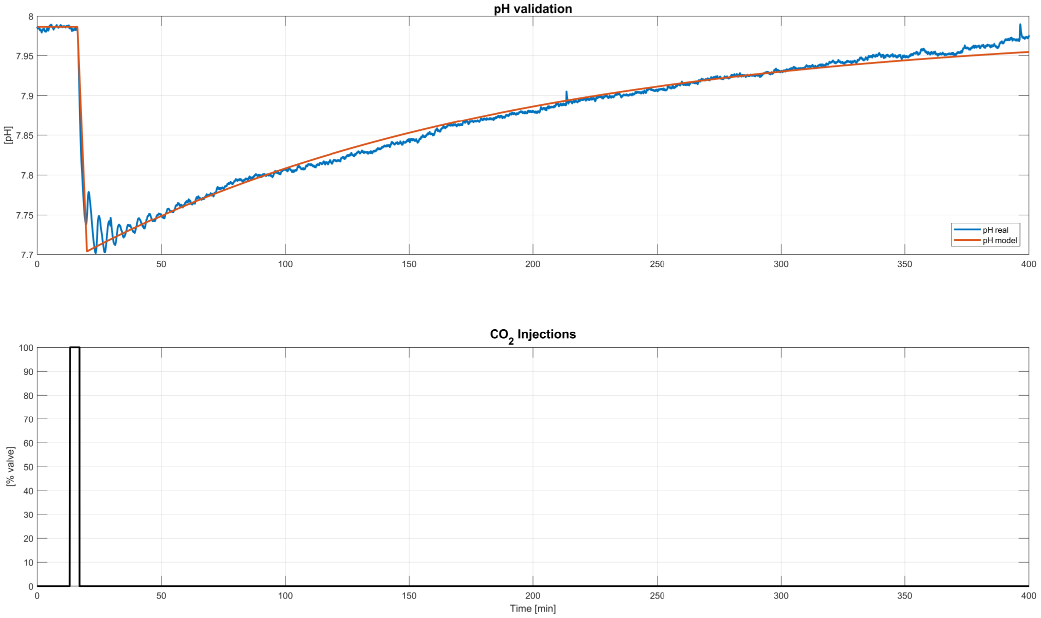

Figure 4: Model validation during nighttime period. First graph represents the evolution of the real pH (blue) and the estimated one (red). Second graph represents the valve opening, input for the model.

During the nighttime period (figure 4), solar radiation is zero and the process dynamics is much slower, with a rise in pH caused by an imbalance in the concentrations of the different compounds in the medium. A phenomenon called bicarbonate buffer appears allowing the stabilization of the pH of the culture medium, causing a pH decrement when CO_2 is supplied and a pH increment when no CO_2 is externally provided and that already present in the medium is consumed by the cells. This is due to the equilibrium of the different inorganic carbon forms present in water (CO_2, HCO_3^-, $CO_3^=$). Due to these dynamics, the pH control during the nighttime period is less critical (require less actions) than during the daytime period, but it is in any case necessary because the rise in pH can be very high (over values of 9.5 sometimes).

Control architecture

The control problem of the microalgae biomass process consists of maintaining the pH of the culture at certain levels. In that area, the injection of CO_2 reduces the pH value due to the formation of carbonic acid, while the photosynthesis process increases the pH due to consuming CO_2 and producing O_2. If CO_2 is injected in excess, it cannot be completely dissolved in the water and it is released into the atmosphere, being harmful to the environment. Therefore, an adequate control is required to look for a tradeoff between the pH control and the CO_2 consumption. Furthermore, better use of CO_2 leads to increased biomass production and reduces stress on microalgae. Summarizing, the control scheme is presented in the following way: the process output is the culture pH, the aperture of CO_2 valve is the manipulated variable, and the solar radiation acts as the main disturbance.

The CO_2 injections are made by using an On/Off valve controlled from a Supervisory Control And Data Acquisition (SCADA) system, where different types of control algorithms are implemented. The pH sensor located at the measurement point one is considered as the output of the system. As previously mentioned, due to its position relative to the injection point, a time delay appears in the transfer function relating CO_2 injection to pH.

Daytime On/Off control

The On/Off control is the most common method of operation for raceway reactors, where the pH is controlled only during the daytime period. The operation of this type of control is the simplest that can be applied, in which, when the pH exceeds a setpoint value, the valve opens to the maximum to decrease its value. The pH control is carried out exclusively during the daytime period, leaving it free during the nighttime period.

PI control

Many examples of pH control in raceway reactors by means of PI controllers can be found in the literature with satisfactory results such as discussed in the Introduction section. Notice that the pH presents different dynamics at the diurnal and nocturnal periods as observed in models (1) and (2). Thus, two controllers have been designed for each model depending on the period of the day, named as $C(s)_{daytime}$ and $C(s)_{nighttime}$.

To design both controllers, the SIMC tuning rule has been used (Grimholt and Skogestad (2012)). This tuning rule states that a closed-loop time constant greater than or equal to the system delay should be used for robustness purposes. In this case, closed-loop time constants of 369 and 180 seconds were set for the daytime and the nighttime periods, respectively. These values are calculated according to 0.05 times the open-loop time constant for the daytime, to ensure a quick response while avoiding aggressive control actions. On the other hand, for the nighttime period a 180 seconds closed-loop time constant value has been used, corresponding to the delay time. In both cases, simulations were performed to select those control parameters providing adequate results. Therefore, the following transfer functions for the PI controllers were obtained:

$$C(s)_{daytime} = -149 \cdot \left(1 + \frac{1}{2192\, s}\right)$$

$$C(s)_{nighttime} = -224 \cdot \left(1 + \frac{1}{1440\, s}\right)$$

Because the CO_2 valve is discontinuous, Pulse Width Modulation (PWM) transformation has been performed to control the opening range from 0 to 100%, corresponding with a flow from 0 to 15 $[L/min]$.

Event-based control

The event-based control architecture used in this work is shown in figure 5, and it represents a PI control loop with an error treatment corresponding to an event-based method (notice that an evaluation of the Δ effect was done in Rodríguez-Miranda et al. (2019), that corresponds to the error deadband around the set-point). This event-based method is called Symmetric-Send-On-Delta (SSOD) method presented in Beschi et al. (2012) and is a modification of the so-called Send-On-Delta (SOD) event-based method (Miskowicz (2006)).

As can be seen in figure 5, this event-based method is coupled with a PI controller that can be designed by any tuning rule. This is one of the most powerful advantages of this event-based method, being able to convert any PI controller into an event-based controller, just adding the SSOD block into the

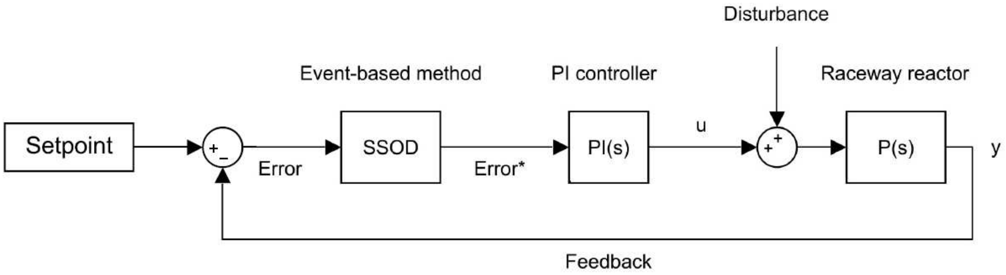

Figure 5: Control scheme of the SSOD-PI event-based control architecture. The SSOD block represents the error treatment performed by the Symmetric-Send-On-Delta method.

control loop, before the PI controller. This event-based method was applied with the PI controllers previously designed to evaluate different deadbands in the pH error. More details about the control approach design can be found in Rodríguez-Miranda et al. (2019). The tolerance in the error deadbands is established with the Δ parameter, being one more variable parameter in the control architecture.

Results

This section presents the results obtained during the tests performed on the microalgae raceway reactor for the pH control problem during several days. Specifically, two-days tests will be presented for each evaluated control structure.

The aim is to establish a comparison between the classical On/Off control operation of the reactor and a time-based controller architecture, in addition to the SSOD-PI event-based method. First, the reactor is operated with the classical On/Off control performed only during the daytime period. Second, the PI time-based control architecture is applied to control the system during the whole day with two controllers, corresponding to the daytime and nighttime periods. Afterwards, the SSOD-PI event-based method is proposed combined with the PI controllers previously designed and compared with the other control architectures applied.

On/Off control results

The results obtained during the two days test performed with the On/Off control architecture are presented in figure 6. The traditional On/Off control is characterized for a simple and fast control that does not take into account error limitations. With this type of control, the CO_2 valve opens to the maximum until the pH drops below the reference and the error decreases, but without acting against the lowering of pH below the reference that occurs.

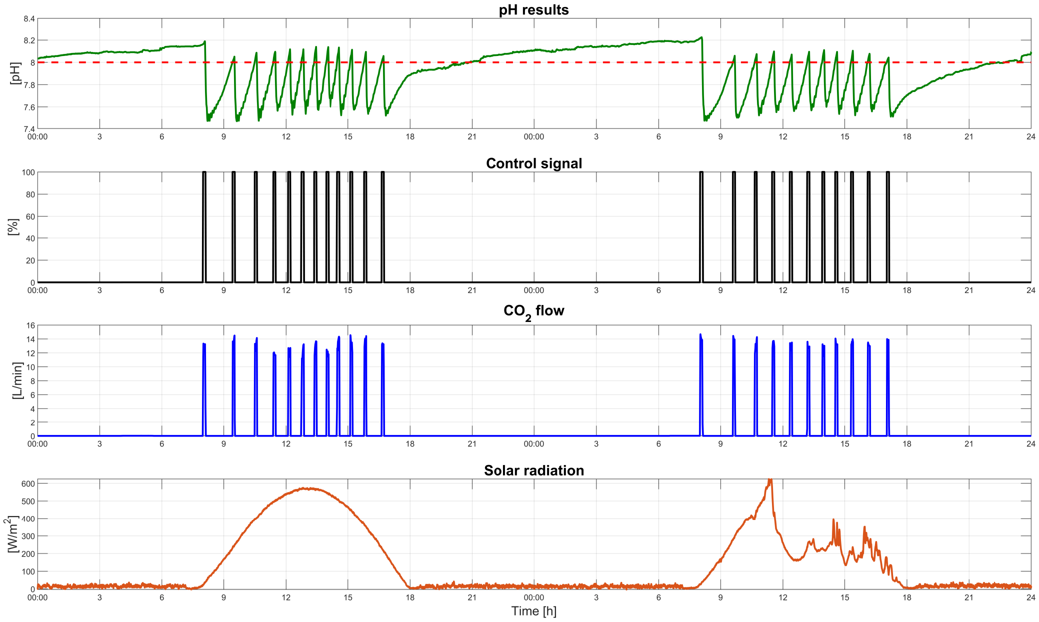

Figure 6: On/Off control architecture results. First graph represents the evolution of the pH (continuous green) and the set-point established (dashed red).

From figure 6, the effects of the On/Off control on the pH can be observed, which considerably oscillates, moving away from its optimal production value. In fact, this behavior causes CO_2 injections with an excessive duration, which causes the pH to drop.

PI control results

The PI control results obtained during daytime and nighttime periods are presented in figure 7. The variation in pH ranges from 7.97 to 8.04, being on the optimal production zone. To maintain the pH on this range, during the nighttime the PI control (input for the PWM) signal maintains approximately a 10% of the total injection flow, corresponding to a CO_2 flow of 2 L/min; and a 20% of the total injection flow during daytime, corresponding to a CO_2 flow of 0.5 L/min.

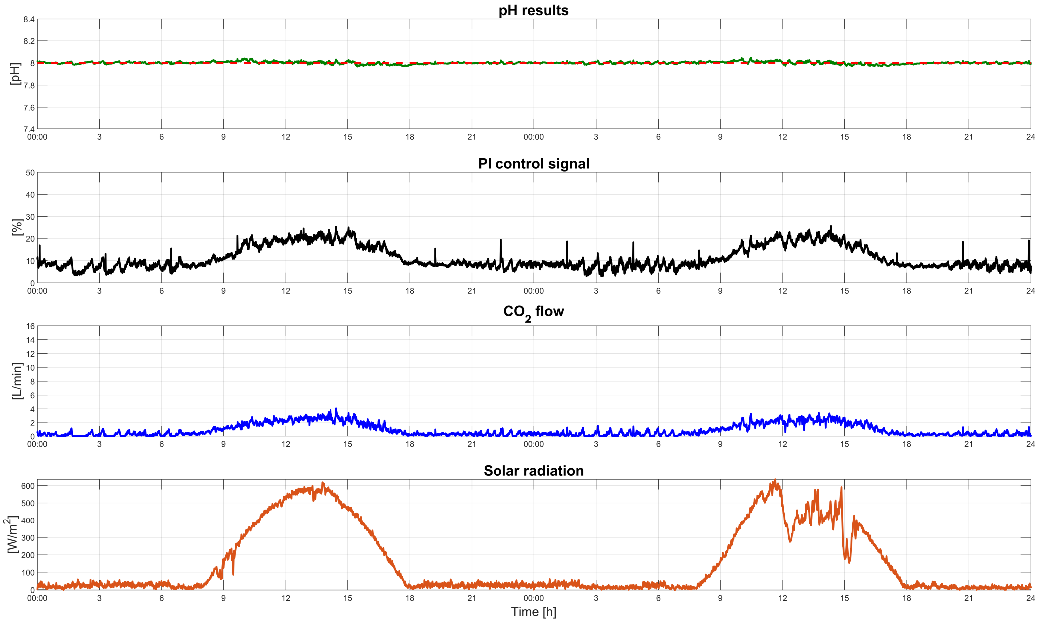

Figure 7: PI control architecture results. First graph represents the evolution of the pH (continuous green) and the set-point established (dashed red).

Event-based SSOD-PI control results

Figure 8 shows the results performed with the SSOD-PI event-based control architecture during two days. A value of $\Delta = 0.1$ has been used in the event-based method. This value of Δ establishes the change amplitude in the error signal deadband, so the system error is increased or reduced in Δ intervals. This behavior can be seen in the evolution of the pH, which varies between 7.9 and 8.1 during the nighttime, with the slow dynamic characteristic of this period. On the other hand, during the daytime the pH varies between 7.9 and 8.2 because of the disturbances caused by solar radiation. The control signal during the nighttime period shows a behavior similar to the On/Off control, with pulses of smaller amplitude occurring when the pH exceeds the threshold of the error band imposed by the Δ parameter. During the daytime period, the PI control signal is more active than at nighttime. Regarding the CO_2 flow, it is characterized by injection pulses of varying amplitude and duration depending on the period of the day when the pH exceeds the threshold of the error zone. During nighttime, flow pulses are short and with an amplitude of 5 L/min, while, during daytime, the flow pulses become longer with an average amplitude of 6 L/min.

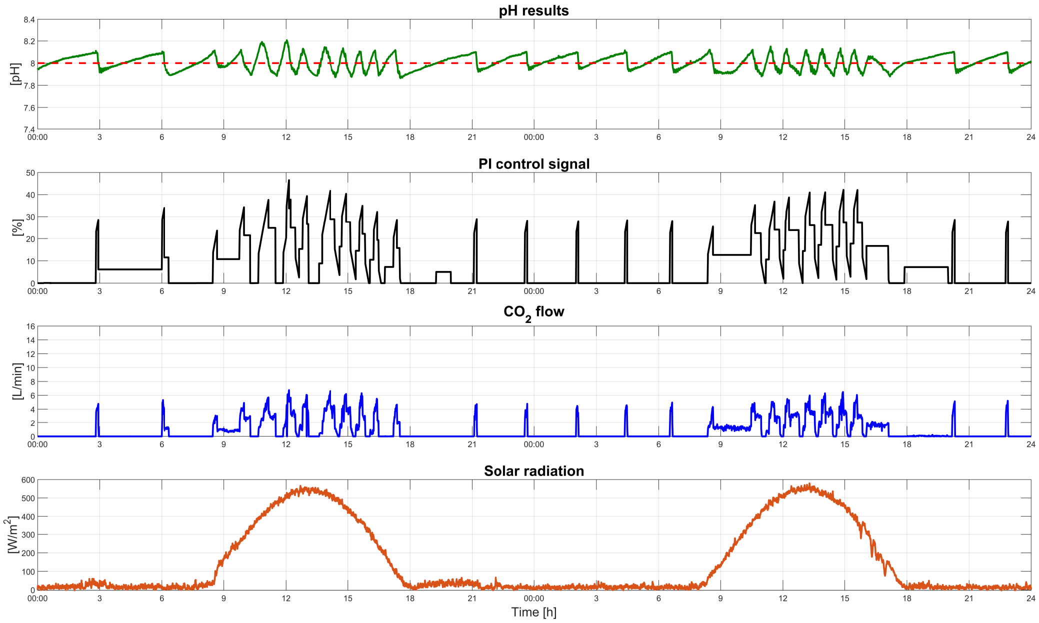

Figure 8: SSOD-PI event-based architecture results. First graph represents the evolution of the pH (continuous green) and the set-point established (dashed red).

Performance indexes

To make a comparison between all control architectures, three performance indexes have been taken into account. The *Integrated-Absolute-Error* (IAE) is used to quantify how much the pH varies with respect to the reference over the two days of the test. The *Injection Time* (IT) represents the duration in minutes of the total CO_2 injection during the two days. The index Gas is the total amount of CO_2 consumed. Finally, the oxygen production (PO_2) is index to establish system performance, which is in relative units with respect to the On/Off control. Table 1 shows the performance indexes described for the three control architectures calculated only based on the first day evolution, as in this day the three evaluated control approaches have the same operating conditions (similar levels of solar radiation, ambient temperature and biomass concentration). During the second day, both the On/Off controller and the PI controller suffer from disturbances coming from variations in the solar radiation. So, table 2 shows the performance indexes for the complete two-days test performed for the control architectures under different weather conditions and in the case of PO_2, this table shows the mean oxygen production for the two days. Notice that environmental conditions cannot be fixed in experimental tests (only in simulation this is possible as it was done in Rodríguez-Miranda et al. (2019)).

Index [1 day]	**On/Off control**	**PI control**	**SSOD-PI control**
IAE	12793	683.5	4940
IT [min]	82.3	1440	723.7
Gas [L]	993.2	1302.1	1172.4
Gas (daytime)	993.2	1132.7	1046.5
Gas (nighttime)	0	169.4	125.9
PO_2	1	2.3	1.7

Table 1: Performance indexes computed for the first day due to equal conditions comparing the three control architectures presented on the results part. IAE represent the Integrated-Absolute-Error, IT represents the Injection Time, Gas represents the CO_2 total gas consumption, in addition to the consumption during the daytime and nighttime periods. PO_2 represents system performance.

Index [2 days]	**On/Off control**	**PI control**	**SSOD-PI control**
IAE	28282	1372	9402
IT [min]	157.7	2880	1405
Gas [L]	1933.3	2540.4	2446.9
Gas (daytime)	1933.3	2179.9	2182.7
Gas (nighttime)	0	360.5	264.2
$\overline{PO_2}$	1	1.9	1.7

Table 2: Performance indexes computed for the two-days tests. IAE represent the Integrated-Absolute-Error, IT represents the Injection Time, Gas represents the CO_2 total gas consumption, in addition to the consumption during the daytime and nighttime periods. PO_2 represents system performance.

Discussion

The differences between the On/Off control and the PI control are evident by looking at figures 6 and 7, in addition to the indexes in tables 1 and 2. Regarding the pH, the PI control reduces the variation, keeping it in an optimum range, but at the expense of injecting during the whole day. The total gas consumption is slightly higher in the PI control compared to the traditional control, but it is understandable considering that the control is carried out even during the nighttime period, with better results in pH, reflected in the IAE parameter, which is reduced approximately a 95% with respect to the On/Off control. The increase in gas consumption is not high and translates into greater biomass production as can be seen in the PO_2 index, which increases approximately a 50% with respect to the On/Off control. The pH is maintained at an optimal level and without variation, thanks to a higher pH stability, which could generate stress on the microalgae and reduce its performance, situation that happens with the On/Off control.

On the other hand, the SSOD-PI event-based control presents a behavior in pH very similar to that shown by the On/Off control architecture, but with a controlled amplitude, varying around the reference. Thus, the IAE error is reduced by 61% (table 1 on equal conditions), at the expense of slightly higher consumption, as in the case of the PI control. Also, the oxygen production of tables 1 and 2 are higher, with an increase of 40% with respect to the On/Off control. Comparing this architecture with the PI control, both show a similar consumption (as can be seen in Tables 1 and 2), being lower the one related to the event-based control. Injections performed during the nighttime are punctual and scarce, instead of the continuous injection of CO_2 caused by the PI control architecture. Instead, by observing tables 1 and 2, it can be seen that the IAE error is greater for the event-based control with respect to the PI control, due to the oscillation of the pH caused by the tolerance in the error, determined by the Δ parameter. As for the performance of the system observed in the production of oxygen (PO_2), the PI control improves the production by approximately 20% with respect to the event-based control, at the cost of higher gas consumption.

Regarding the CO_2 consumption of each period of the day, represented in tables 1 and 2, it can be seen that the consumption during the daytime period is practically the same for the PI and the event-based control architectures, the PI control being the one that reduces the most the error and increases the oxygen production, but also with a more variable control signal. On the other hand, the consumption during the nighttime period shows a reduction of CO_2 in the case of the event-based control, with fewer injections, as can be seen with the control signal in figures 7 and 8. This fact yields interesting control architecture, such as the combination of the PI control during the daytime period and the use of the event-based control during the nighttime period. As stated earlier, the nighttime period is not as critical as the daytime and tolerance in the error bands could be controlled by the Δ parameter, characteristic of the SSOD method.

Conclusion

This paper has presented a comparison between the traditional daytime pH control on microalgae raceway reactors and a PI control architecture during the daytime-nighttime periods, in addition to an event-based control. The aim is to demonstrate the advantages of the daytime and nighttime pH control on the gas usage and error reduction, improving the operation conditions of the reactors over classical On/Off control, executed only during daytime period.

The results regarding the pH error show that the PI control reduces the error by 95% respect the On/Off control architecture, keeping the pH very close to the reference, at the optimum production value during 24 hours. To achieve this, the PI control increases the CO_2 consumption slightly but increases system performance by 50%. On the other side, the SSOD-PI event-based control architecture increase the IAE error with respect to the PI control, but reduces the CO_2 consumption during the nighttime period, improving control effort and gas utilization.

As conclusion, a control structure that combines the PI control for the daytime period and the event-based control for the nighttime period would be a promising control architecture with the advantages of both types of control. Future works will be focused on evaluating this control architecture experimentally for whole year production.

Acknowledgments

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