Dynamic analysis and comparison of control techniques in the process of obtaining bioethanol

Análisis dinámico y comparación de técnicas de control en el proceso de obtención de bioetanol

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Abstract

Introduction— Previous reactor models have been used to study the dynamic behavior of bioethanol production systems, however, few have elaborated a comparative study of control strategies that stabilize and control the variables of interest.

Objective— The objective of this study is to analyze the stability of a fermentation system to obtain bioethanol, its dynamic behavior, the characterization of equilibrium points and bifurcation points of the mathematical model proposed by Jarzebski in 1992 for a continuous fermentation, taking into account the performance of the reaction in a bioreactor and the application of industrial control techniques for its optimization.

Methodology— Review and design methods of quantitative and systematized type were used.

Results— The comparison between two control strategies to control bioethanol production, PID control and Fuzzy.

Conclusions— This work shows the importance of the stability analysis of a continuous system and how it can define the regions of operational interest, in this case for ethanol production, showing that productivity is inversely proportional to the dilution rate. Finally, it is concluded that a better dynamic behavior of the system is obtained when a Fuzzy controller is used. This work also shows the importance of the stability analysis of a continuous system and how it can define the regions of operational interest, in this case for the production of ethanol.

Keyword— Alcoholic fermentation; PID control; Fuzzy control; non-linear systems; stability

Resumen

Introducción— Modelos de reactores anteriores han sido utilizados para estudiar el comportamiento dinámico de sistemas de producción de bioetanol, sin embargo, pocos han elaborado un estudio comparativo de estrategias de control que estabilicen y controlen las variables de interés.

Objetivo— El objetivo del presente estudio es analizar la estabilidad de un sistema de fermentación para obtención de bioetanol, su comportamiento dinámico, la caracterización de puntos de equilibrio y puntos de bifurcación del modelo matemático planteado por Jarzebski en 1992 para una fermentación continua, teniendo en cuenta el rendimiento de la reacción en un biorreactor y la aplicación de técnicas de control industrial para su optimización.

Metodología— Se utilizaron métodos de revisión y diseño de tipo cuantitativo y sistematizado.

Resultados— Se presenta la comparación entre dos estrategias de control para controlar la producción de bioetanol, el control PID y el control Fuzzy. Se observó un mejor comportamiento dinámico cuando se utilizó el controlador Fuzzy.

Conclusiones— Este trabajo muestra la importancia del análisis de estabilidad de un sistema en continuo y cómo éste puede definir las regiones de interés operativo, en este caso para la producción de etanol, mostrando que la productividad es inversamente proporcional a la tasa de dilución. Finalmente, se concluye que se tiene un mejor comportamiento dinámico del sistema cuando se utiliza un controlador Fuzzy.

Palabras clave— Fermentación alcohólica; control PID; control Fuzzy; sistemas no lineales; estabilidad

I. Introduction

Dynamic analysis and the application of control strategies allow bioethanol quality standards to be obtained, thus optimizing production processes, highlighting that the economic viability of bioethanol production, as an energy source, depends on its overall energy balance being favorable [2], [3]. Control strategies such as classical PID control and fuzzy control have a significant effect on stages such as product recovery and distillation, which are the stages that require the most energy in the whole process; therefore, the amount of energy applied to fuel production determines how economical the product must be.

The dynamic analysis of the bioethanol production process leads to improvements in the different production processes, which in the end translates into successful distillation stages and, finally, to obtaining economic viability in the industrial process.

Ethyl alcohol or bioethanol is a chemical product obtained from the fermentation of sugars found in vegetable products, such as cereals, beet, sugar cane, sorghum or biomass. These sugars are combined in the form of sucrose, starch, hemicellulose and cellulose.

In this process, hydrated alcohol is obtained, with an approximate content of 5% water, which after being dehydrated can be used as fuel in mixture with gasoline or alone. Bioethanol mixed with gasoline produces a high energy biofuel with characteristics very similar to gasoline(the process of producing ethanol fuel does not require more energy than the amount of energy contained in the fuel itself), but with a significant reduction of pollutant emissions in traditional combustion engines [4]. Compared to conventional gasoline, greenhouse gas was found reduced by 6.95% in E10.

The fermentation process for the production of bioethanol as a fuel has had a great deal of success as a solution to the problem of environmental sustainability presented by oil and its derivatives. An example of this is that since 2006 Colombia has been implementing gasoline-anhydrous ethanol blends [5]. Currently and as of March 1, 2018, the blend used in Colombia is 90% gasoline and 10% alcohol (E10) by volume [6].

This has increased the interest in studying and analyzing this process in the industrial sector based on biotechnology, and in increasing the yield and quality assurance of the product, applying automatic control techniques. Fuzzy logic has been increasingly used for the control of industrial processes, taking into account that its great advantage is that those processes that do not have a mathematical model available, but have expert personnel, can use this information to develop a practical and accessible control strategy, robust and can be used in non-linear processes [7].

The bioethanol production process [8], [9], [10], [11], as such is not discussed in this article but a discussion of the different factors that can affect bioethanol production from a dynamic point of view is made, which is of relative importance when it comes to implementing control structures.

It is very important to carry out a dynamic analysis of the bioethanol production reactor, which will lead to a better understanding of the kinetic constants, process response velocities and in general to the identification of the dynamic characteristics of the bioethanol production process [12], [13], [14], [15], [16].

Some authors have applied Fuzzy control strategies for temperature control in a vacuum distiller [17], while other research has applied optimization techniques using fuzzy logic to continuous reactors for bioethanol production [18]. Monitoring, modeling and the application of some control strategies are discussed in IIT Delhi [19]. Adaptive control techniques and some nonlinear estimation algorithms are presented in UCV [20], while IMC and PID are strategies used by some authors for the control of a bioreactor for bioethanol production [12].

II. Methodology

The methodology for the implementation of the control strategies is based on the model proposed by Jarzebski [1], describing the model and the dynamics of the process of obtaining bioethanol.

A. *Mathematical model*

In order to predict the dynamic behavior exhibited by microbial systems, several types of models have been proposed to describe cell growth. In general, such models are classified as: unstructured, structured [21]-[23], unsegregated and segregated [24]-[25]. In addition, the growth kinetics have been modified in order to take into account the inhibition effects suffered by microorganisms due to high concentrations of substrate and product (8). The analysis of the dynamic behavior has been carried out experimentally and theoretically for specific microbial systems; among them the processes of fermentation for alcohol production by Saccharomyces cerevisiae [26]-[29].

Ethanol production by fermentation with Saccharomyces cerevisiae yeast in a continuous stirred tank bioreactor is analyzed. The dynamic behavior of the system was evaluated using the model formulated by Jarzebski [1], to reproduce the oscillatory behavior of continuous cultures of this microorganism.

This model assumes that the tanks are well mixed and that there is no recycling. The cell population is divided into three groups: viable cells (X_v), non-viable cells (X_{nv}) and dead cells (X_d). Non-viable cells do not grow, but can produce ethanol.

The constants were estimated experimentally by Jarzebski [1]:

$$\mu_{max} = 0.25h^{-1},\ \mu_{max} = 0.21h^{-1},\ P_c = 70\ gl^{-1},\ P_c = 130\ gl^{-1},\ m_p = 2.6h^{-1},$$
$$m_s = 4.42h^{-1},\ Y_{x/p} = 0.235,\ Y_{x/s} = 0.095,\ K_1 = K_2 = 3gl^{-1}.$$

The equations that govern the model are (1), (2), (3), (4) and (5):

$$\frac{dX_v}{dt} = -DX_v + \left(\mu_v - \mu_{nv} - \mu_d\right)X_v \tag{1}$$

$$\frac{dX_{nv}}{dt} = -DX_{nv} + \mu_{nv}X_{nv} - \mu_d X_{nv} \tag{2}$$

$$\frac{dX_d}{dt} = -DX_d + \mu_d(X_v + X_{nv}) \tag{3}$$

$$\frac{dP}{dt} = -DP + \frac{\mu_v X_v}{Y_{X/P}} + m_p X_{nv} \tag{4}$$

$$\frac{dS}{dt} = D(S_{in} - S) - \frac{\mu_v X_v}{Y_{X/S}} - m_S X_{nv} \tag{5}$$

Where:

$D = F/V$: Dilution rate (h^{-1}).
F : Tank inlet flow rate (lh^{-1}).
K_1, K_2 : Saturation constants (gl^{-1}).
m_p : Ethanol maintenance factor (h^{-1}).
m_s : Substrate maintenance factor (h^{-1}).
P : Ethanol concentration (gl^{-1}).
P_c : Limiting ethanol concentration for viable cells (gl^{-1}).
P_c : Limiting ethanol concentration for non-viable cells (gl^{-1}).
P_r : Ethanol productivity ($gl^{-1}\ h^{-1}$).
S : Substrate concentration (gl^{-1}).
S_{in} : Initial feeding concentration (gl^{-1}), t is the time (h).
X_v : Concentration of viable cells (gl^{-1}).
X_{nv} : Concentration of non-viable cells (gl^{-1}).
X_d : Concentration of dead cells (gl^{-1}).
V : Reactor volume (l).
$Y_{x/p}$: Coefficient of performance in the conversion of biomass to ethanol.
$Y_{x/s}$: Coefficient of performance in the conversion of biomass into substrate.
μ_v : Growth rate of viable cells (h^{-1}).
μ_{nv} : Growth rate of non-viable cells (h^{-1}).
μ_d : Growth rate of dead cells (h^{-1}).
μ_{max} : Maximum growth rate of viable cells (h^{-1}).
μ_{max} : Maximum growth rate of non-viable cells (h^{-1}).
t : Time of residence (h).

The growth rate for product inhibition and substrate limitation are given by (6), (7) and (8):

$$\mu_v = \mu_{max} \frac{S}{K_1+S}\left(1-\frac{P}{P_C}\frac{S}{K_2+S}\right) \tag{6}$$

$$\mu_d = -\mu_{max} \frac{S}{K_1+S}\left(1-\frac{P}{P_C}\frac{S}{K_2+S}\right) \tag{7}$$

$$\mu_{nv} = -\mu'_{max} \frac{S}{K_1+S}\left(1-\frac{P}{P'_C}\frac{S}{K_2+S}\right)-\mu_v \tag{8}$$

All reaction speeds are assumed to be non-negative. In case one of them is negative due to different chemical reactions, this speed is reset to zero.

This model assumes that the tanks are well mixed and that there is no recycling. The cell population is divided into three (3) groups: viable cells (X_v), non-viable cells (X_{nv}) and dead cells (X_d). Non-viable cells do not grow, but can produce ethanol.

B. *Values for the starting point*

$$X_{v0} = 4\ g/_l;\ X_{nv0} = 0\ g/l;\ X_{d0} = 0\ g/l\ ;\ S_0 = 60\ g/l;\ P_0 = 40\ g/l.$$

Where:

X_{v0} : Initial condition of X_v.
X_{nv0} : Initial condition of X_{nv}.
X_{d0} : Initial condition of X_d.
P_0 : Initial condition of P.
S_0 : Initial condition of S.

C. *Dynamic analysis of the bioethanol production process*

The simulation of this process was achieved by designing an S-function using Matlab and Simulink, in order to analyze the dynamics of the system (Matlab is a high-level language that gives solutions for given problems with fewer lines of codes than traditional programming languages, such as C/C++ or Java, by utilizing built-in math functions.). The diagram in Simulink is shown in Fig 1. Here the inputs correspond to the dilution rate and substrate concentration D, which are routed to the reactor model programmed in an S-function, and the output signals P of the model in open loop are presented using scopes.

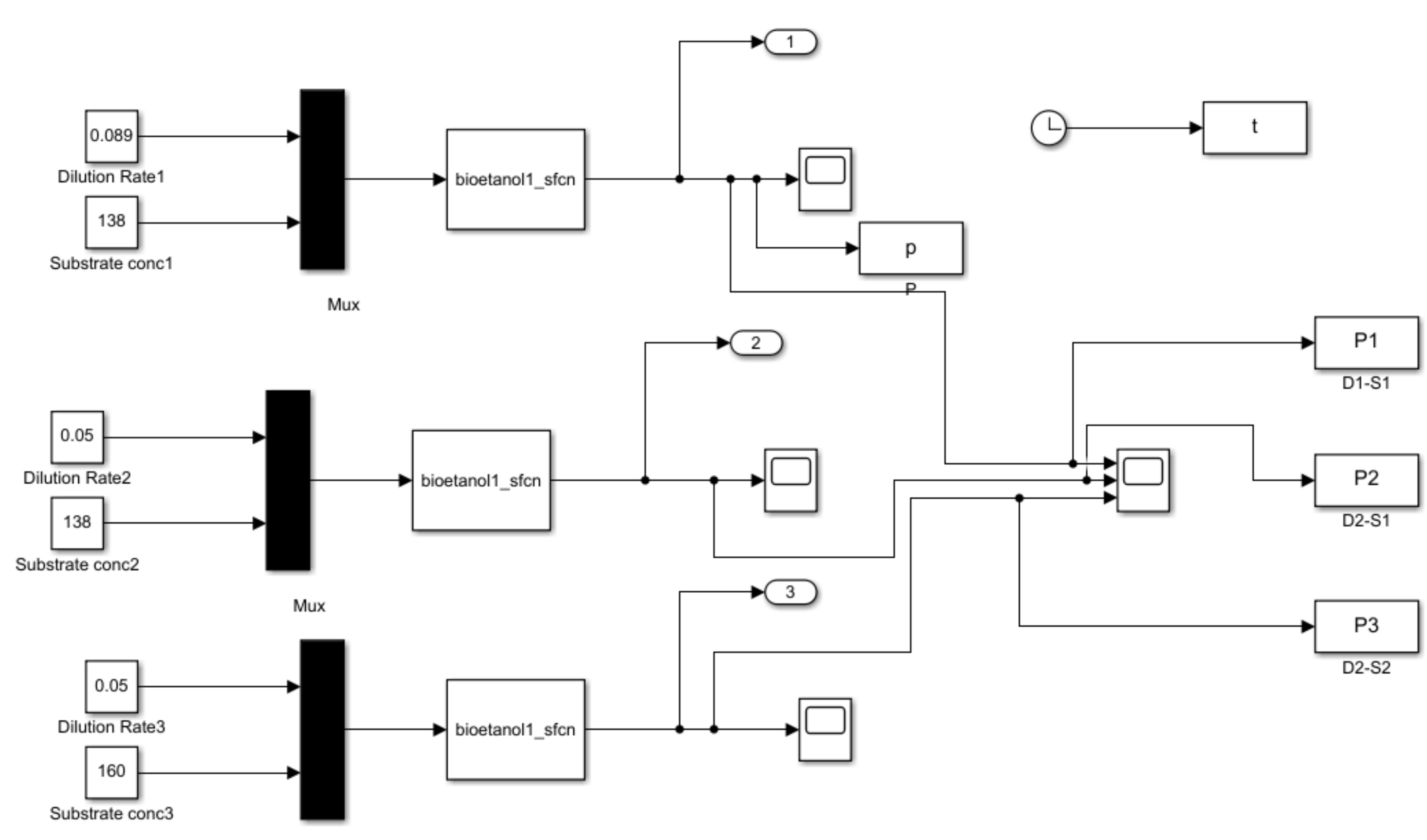

Fig. 1. Simulink diagram of the bioethanol production process.
Source: Authors.

The behavior of the open-loop system was analyzed as a function of the Dilution rate D in h^{-1} and the concentration of the substrate at the entrance of the reactor, S_{in} in gl^{-1} , as can be seen in the open-loop diagram in Fig. 2, taking as output the concentration of the product P at g/l; having values D = 0.089 h^{-1} and D = 0.089 h^{-1}, which were used by Jarzebski to study the biochemical parameters of the experimental data [1].

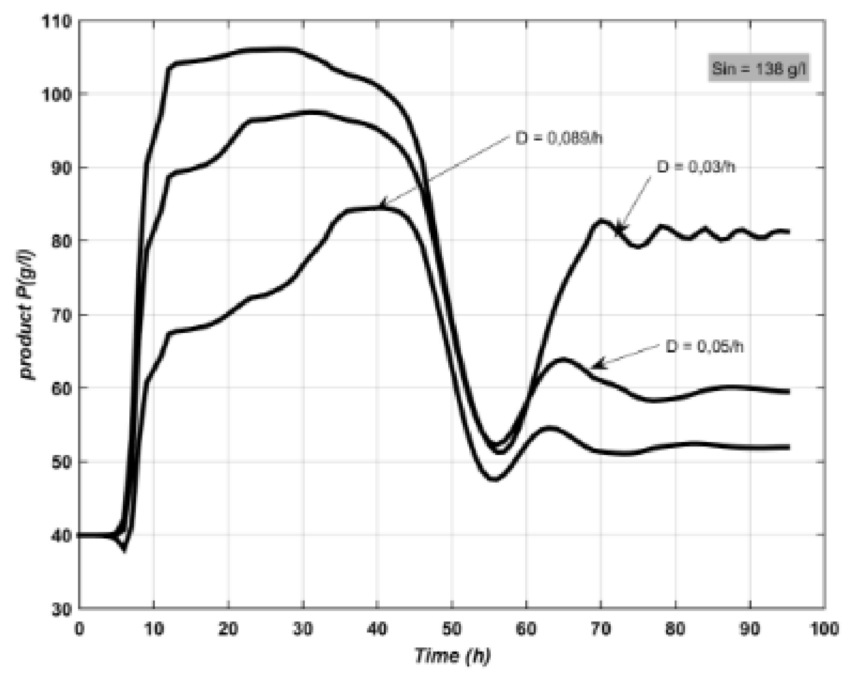

Fig. 2. Response of the open-loop reactor for different values of the Dilution Rate D.
Source: Authors.

Fig. 2 shows the response of the open-loop reactor for different values of the Dilution rate, D and for a concentration of the feed substrate S_{in} = 138 g/L, for regions where the system behaves stably. It is observed that increasing the dilution rate decreases the productivity.

By varying D from 0.089 h^{-1} to 0.05 h^{-1} and leaving S_{in} constant at 138 h^{-1}, according to the values worked by ENPC [30], it was found that there is a maximum concentration of ethanol than in the given initial conditions.

At the same time it is observed that the viable cells decrease faster, tending to stabilize the concentration of the product at 60 g/l in a longer time than for the first case, being observed the same as for when D = 0.05h^{-1} and S_{in} = 138 g/l, with the difference that the maximum concentration of the product is approximately 105 g/l.

Fig. 3 shows the open loop evolution of the product in the reactor for a fixed value in the dilution rate, D = 0.05h^{-1}, and for values of the input substrate concentration of S_{in} = 138 g/l and S_{in} = 160g/l respectively and for regions where the system behaves stably.

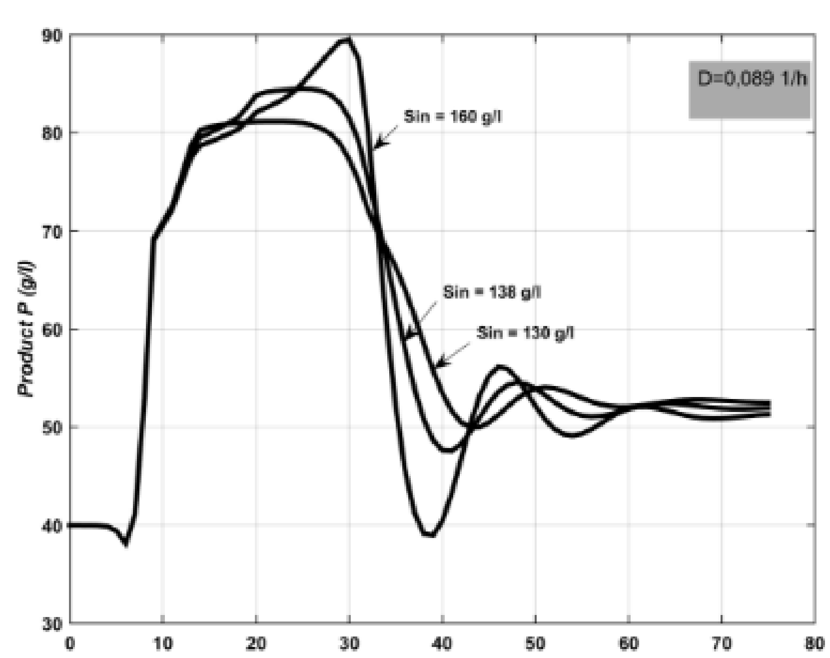

Fig. 3. Open-loop response to variations in initial substrate concentration.
Source: Authors.

Little impact on the productivity in the reactor is observed when varying the inlet substrate concentration, tending to increase a little at the beginning and then to decrease.

A dynamic analysis of the transient response, rise time, peak time, settling time, tolerance band and overshoot is presented below, varying the Dilution rate (D) and the input substrate concentration (S_{in}).

Case 1: *Constant dilution rate and S_{in} variable* (Table 1; Table 2).

TABLE 1.
$D = 0.089\ h^{-1}$ AND $S_{IN} = 138$ gl^{-1}.

	Rise time (t_r) in hours	Peak time (t_p) in hours	Settling time (t_s) in hours	Overshoot (O_s) in hours	Tolerance Band (BT)
	9	18.3	77.89	62.5	50.96 – 53.04
Output (P) in g/l	52	84.5	50.96		

Source: Authors.

TABLE 2.
$D = 0.089\ h^{-1}$ AND $S_{IN} = 160\ gl^{-1}$.

	Rise time (t_r) in hours	Peak time (t_p) in hours	Settling time (t_s) in hours	Overshoot (O_s) in hours	Tolerance Band (BT)
	8.7	21.15	74.1	73.83	50.18 – 52.22
Output (P) in g/l	51.2	8.9	50.18		

Source: Authors.

Case 2: *Variable dilution rate and constant S_{in}* (Table 3; Table 4).

TABLE 3.
$D = 0.05\ h^{-1}$ AND $S_{IN} = 138$ GL^{-1}.

	Rise time (t_r) in hours	Peak time (t_p) in hours	Settling time (t_s) in hours	Over shoot (O_s) in hours	Tolerance Band (BT)
	7.66	5.57	82.43	63.9	7.66
Output (P) in g/l	59.48	97.49	58.29		59.48

Source: Authors.

TABLE 4.
$D = 0.03\ h^{-1}$ Y $S_{IN} = 138\ gl^{-1}$.

	Rise time (t_r) in hours	Peak time (t_p) in hours	Settling time (t_s) in hours	Over shoot (O_s) in hours	Tolerance Band (BT)
	10	14.3	113.2	30.86	79.38 – 82.62
Output (P) in g/l	81	106	79.38		

Source: Authors.

Observing these values, it can be concluded that the lower the Dilution rate (D), the rise time increases as well as the ethanol concentration at the exit of the reactor, but at the same time it takes longer to enter the steady state region increasing the steady state error having a higher overshoot.

The washout conditions are given by the solution of the equations (1)-(5), for $P = X_v = X_{nv} = X_d = 0$ and $S = S_{in}$, which is known as trivial solution since there is no chemical reaction, which means that there is no loaded biomass inside the bioreactor and therefore the initial substrate concentration is equal to the feed substrate concentration.

The case was analyzed for $D = 0.089\ h^{-1}$ and $S_{in} = 126\ gl^{-1}$, where the reactor is not yet in washout. But for values less than 126 gl^{-1} for S_{in}, the reactor is in this state.

III. Results

Below are results related to the two control strategies applied, the Fuzzy control and the PID control.

A. *Bioreactor Control*

Two control strategies were compared in order to control bioethanol production: PID control and Fuzzy control. Having simulated the process, we proceeded to design the two controllers, one linear (PID) and one nonlinear (FUZZY) in order to analyze its behavior in closed loop. The dynamic analysis of the controllers was carried out through analysis of the transient and stationary response.

For system stability analysis, variations in the setpoint and variations in the feeding substrate were considered. Variations in the setpoint, in the feeding substrate, random signals and noise were introduced as perturbations. The experimental data obtained by Jarzębski [1] and the ranges in which the system has a stable behavior were taken into account. The model was analyzed using a selection of different dilution rates, taking into account that in some ranges it exhibits an oscillatory behavior.

B. *PID linear control*

Fig. 4 shows the response of the PID controller to different changes in the set point (upper part) starting with an initial value of 40 g/L for *P*, and the evolution of the concentration of viable cells, X_v and dilution rate, *D* (lower part).

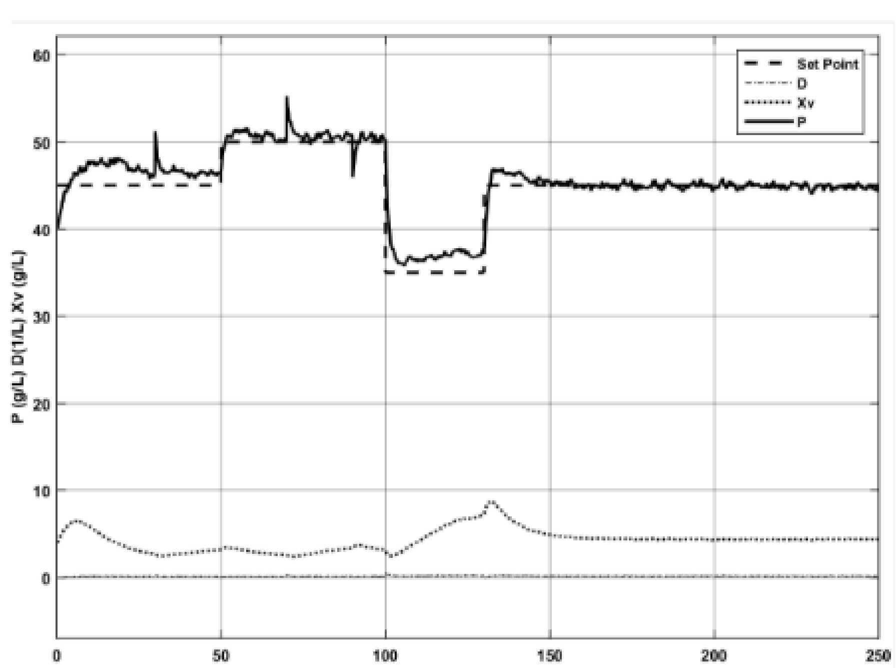

Fig. 4. PID controller for the product P.
Source: Authors.

It can be observed that the PID controller follows well the changes in the set point for product *P*, and that, in addition, the concentration of viable cells fluctuates between 1 and 9. The peaks shown in the figure correspond to some disturbances that have been added during the simulation. It can be seen how the controller returns the variable *P* to its set point, showing a steady state error of zero, which is explained by the effect of the integral action of the PID controller. Likewise, a fast reaction in the system response and a rather low over shoot are observed.

C. *Fuzzy Control*

Fig. 5 shows the response of the Fuzzy controller for a 45 g/L set point. The behavior is somewhat oscillatory, but with oscillations very close to the set point value.

Fig. 6 shows the response of the Fuzzy controller to different changes in the set point (upper part), and the evolution of the concentration of viable cells, X_v and dilution rate, D (lower part).

Fig. 5 and Fig. 6 present the dynamic evolution of product concentration P, for a fixed set point value of 45 g/L and for different changes in set point for the Fuzzy control strategy.

Smoother behavior is observed in the face of changes in the set point, while the evolution of viable cells is almost the same as in the case of the PID controller.

Mandani fuzzy rules were used for the design of the fuzzy controller.

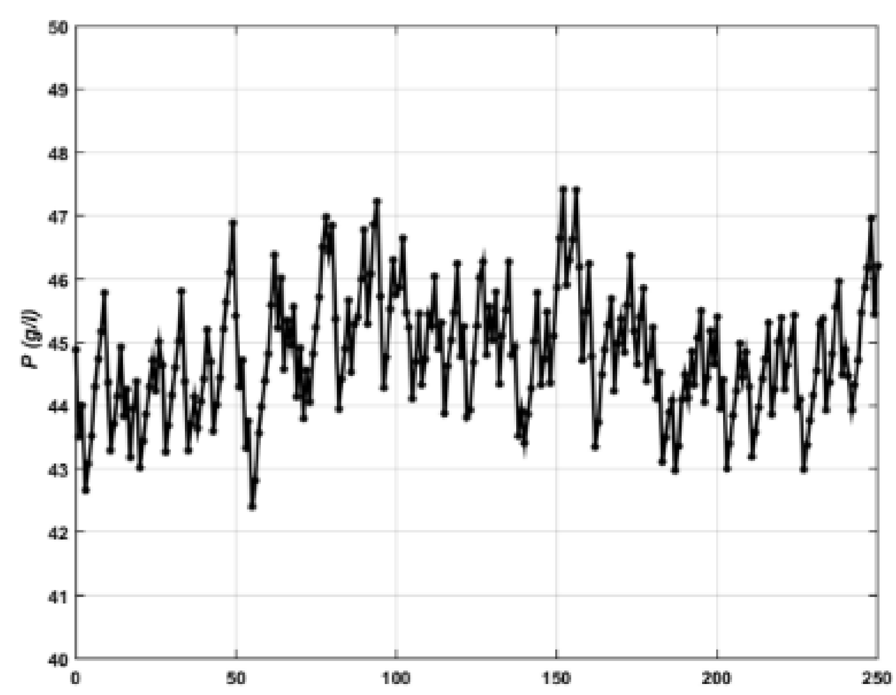

Fig. 5. Fuzzy controller for the product P.
Source: Authors.

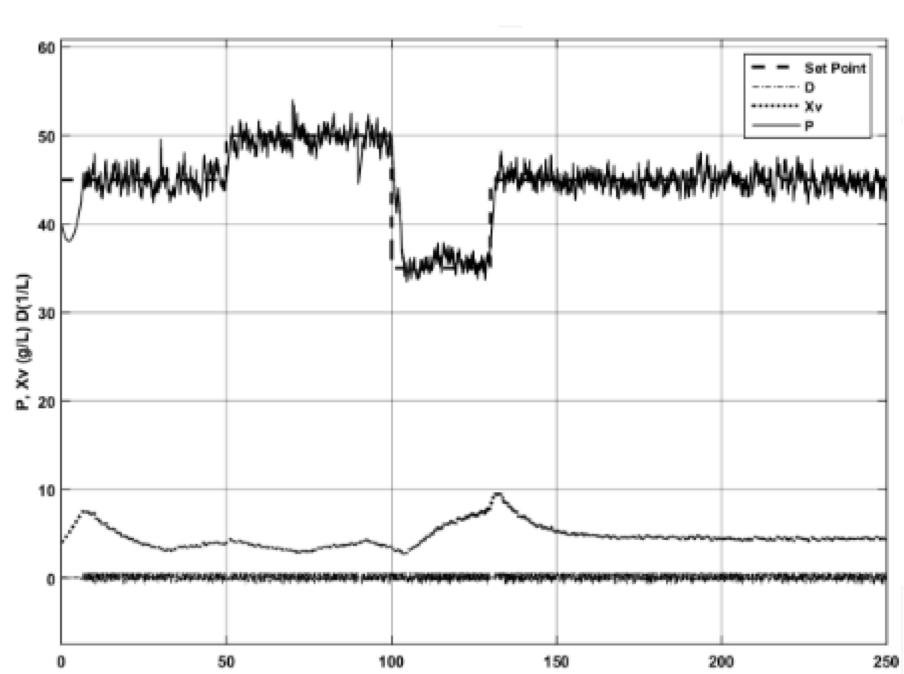

Fig. 6. Fuzzy controller for the product P.
Source: Authors.

D. *Comparison of control techniques*

The analysis is presented in Table 1 and Table 2, comparing the transient and stationary response (t_s: settling time, t_r: rise time, t_p: peak time, O_s: Overshoot) and the error in steady state, for each of the designed controllers.

It can be observed that when the Dilution rate D is kept constant, the Overshoot (O_s) keeps its value constant for all values of Sin, while the steady state error (e_{ss}) is smaller when the substrate concentration at the input is higher for the case of the PID controller and is zero in the case of the Fuzzy controller (Table 1).

In the second case, the substrate concentration at the S_{in} input is kept constant, while the Dilution rate D is varied.

A shorter settling time is obtained when D is higher (D = 0.089h^{-1}), in the case of the PID, while its is constant for the case of the Fuzzy controller (t_s = 10.34h).

The overshoot is not affected with the increase of S_{in}, maintaining a constant value for the two controllers.

A lower value of the steady state error is obtained when D is smaller, for the case of the PID controller, while the e_{ss} is zero in all cases for the Fuzzy controller (Table 2).

The following is a list of the symbols used in the following tables.

t_r	=	Rise time.
t_p	=	Peak time.
t_s	=	Setting time.
O_s	=	Overshoot.
e_{ss}	=	Error en estado estacionario.
BT	=	Banda de tolerancia.

Table 5.
Comparison of the response with PID and Fuzzy control for constant D and Sin variable.

	PID		FUZZY	
	Parameter	Product (g/l)	Parameter	Product (g/l)
D = 0,089 h^{-1} S_{in} = 138 g/l	t_r = 3.75 h	45	t_r = 6.6 h	45
	t_p = 13.6 h	48.2	t_p = 10 h	48
	t_s = 23.2 h	46.6	t_s = 10.34 h	44.1
	O_s = 7.11 %		O_s = 6.67 %	
	e_{ss} = 5.23 %		e_{ss} = 0%	
	BT = 46.55 – 48.45		BT = 44.1 – 45.9	
D = 0.089 h^{-1} S_{in} = 160 g/l	t_r = 3.75 h	45	t_r = 6.58 h	45
	t_p = 13.6 h	48.2	t_p = 10 h	48
	t_s = 28.3 h	45.65	t_s = 10.34 h	44.1
	O_s = 7.11%		O_s = 6.67%	
	e_{ss} = 3.23 %		e_{ss} = 0%	
	BT = 45.57 – 47.43		BT = 44.1 – 45.9	
D = 0.089 h^{-1} S_{in} = 127 g/l	t_r =3.4 h	45	t_r = 6.6 h	45
	t_p = 13.6 h	48.2	t_p = 10 h	47.9
	t_s = 28.45 h	46.06	t_s = 10,34 h	44.1
	O_s = 7.11%		O_s = 6.44 %	
	e_{ss} = 4.26%		e_{ss} = =0 %	
	BT = 46.06 – 47.94		BT = 44.1 – 45.9	

Source: Authors.

Table 6.
Comparison of the response with PID and FUZZY control for D variable and Sin constant.

	PID		FUZZY	
	Parameter	Product (g/l)	Parameter	Product (g/l)
$D = 0.089\ h^{-1}$ $S_{in} = 138$ g/l	$t_r = 3.75$ h	45	$t_r = 6.6$ h	45
	$t_p = 13.6$ h	48.2	$t_p = 10$ h	48
	$t_s = 23.2$ h	46.6	$t_s = 10.34$ h	44.1
	$O_s = 7.11$ %		$O_s = 6.67$ %	
	$e_{ss} = 5.23$ %		$e_{ss} = 0$%	
	$BT = 46.55 – 48.45$		$BT = 44.1 – 45.9$	
$D = 0.05\ h^{-1}$ $S_{in} = 138$ g/l	$t_r = 2.2$ h	45	$t_r = 6.17$ h	45
	$t_p = 13.6$ h	49.2	$t_p = 10$ h	48
	$t_s = 23.35$ h	47.53	$t_s = 11.5$ h	44.1
	$O_s = 9.33$%		$O_s = 6.67$%	
	$e_{ss} = 7.23$ %		$e_{ss} = 0$%	
	$BT = 47.53 – 49.47$		$BT = 44.1 – 45.9$	
$D = 0.03\ h^{-1}$ $S_{in} = 138$ g/l	$t_r = 2.1$ h	45	$t_r = 4.15$ h	45
	$t_p = 13.6$ h	49.76	$t_p = 10$ h	48.5
	$t_s = 27.7$ h	47.53	$t_s = 10{,}3$ h	44.1
	$O_s = 10.58$%		$O_s = 7{,}78$ %	
	$e_{ss} = 4{,}26$%		$e_{ss} = 0$%	
	$BT = 47.53 – 49.47$		$BT = 44.1 – 45.9$	

Source: Authors.

IV. Conclusions

The results obtained coincide with the related experimental results in the references. It is observed that the lower the Dilution rate (D), the concentration of cells decreases and the concentration of the product tends to increase, but at the same time it takes longer to enter the steady state region, increasing the error.

Productivity, being inversely proportional to the dilution rate, is also affected when the dilution rate increases or decreases.

Better dynamic behavior can be observed in the case of using the Fuzyy controller.

It is proposed to evaluate the effect of mechanical variables, such as agitation speed, on the growth of microorganisms and product formation, and to determine the effect of pH and carbon dioxide on biomass and product formation.

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