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Cost effective control strategy for small applications and pilot plants: on–off valves with temporized PID controller

Alexandre Restrepo, Andres González, Sergio Orduz*

Biotechnology and Biological Control Unit, Corporación Para Investigaciones Biológicas, Apartado Aéreo 7378, Medellín, Colombia

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Abstract

Hardware investment for process control represents an important part of the global cost of a small-scale project and low cost solutions do not respond as well as robust systems. Combining the low cost of the on–off actuators with the robustness of classical controllers could produce good results in variable control. Three strategies were used in order to obtain temperature control in fermentation runs of *Bacillus thuringiensis*. The first was control on–off, which is the simplest method to achieve variable control by using on–off valves. The second is a modified on–off with waiting time, which allows the system a pause before sensing the variable value; therefore, the size of the variable overlaps are reduced. Finally, a combination of on–off valves with a temporized virtual-PID controller (PIDt) was developed and implemented, and accurate control of temperature during the fermentation process was obtained. This last variable control strategy uses an algorithm which may be easily implemented by a non-specialized computer programmer. An additional advantage of the results obtained include an 82% reduction in the cost of valves by the use of non-conventional techniques and programming tools.

Keywords: On–off values; Temporized PID controller; Pilot plants

1. Introduction

Process control systems are classified according to the type of control they may exert on a given procedure [5]. One of the limitations in developing a control system is the cost of actuators, and in general terms, the more complex the control system, the higher investment required in hardware.

In small-scale applications, where initial investment costs are of great importance, it is fundamental to find effective and low cost solutions. Generally in biotechnology, variations from one fermentation to another do not allow the development of mathematical models in a relative short time [7], so model based controllers cannot be implemented as fast as they are needed. Therefore, classical control with small modifications is used; furthermore, predictive systems, like artificial intelligence (AI) applications, are under development or being tested [1], only a few industrial applications are controlled by AI and non-critical aspects of a process are assigned to intelligent controllers because of the complexity of the processes [8]. A type of controller using fuzzy logic systems is employed by the industry [3], with good results, but mostly in electronics and robotics.

However, to implement a robust control system it is necessary to invest in expensive continuous elements and actuators that are commonly used by PID controllers, and their cost is around 2000 USD each. The cost of controllers or a PLC plus the cost of the network system to interconnect the different controllers must be added in any of the systems.

On the other hand, a low cost control system uses on–off elements and the actuator cost is around 150 USD each. The disadvantage is their poor performance in maintaining the variable at the required set point and a non-adequate response to system disturbances. By combining the low cost of on–off actuators with the smoothness and robustness of PID controllers, a practical control system, with good results in variable control, at an acceptable cost may be obtained. In the past, a similar technique using on–off actuators, called dual mode control was employed to improve a control system, but this effort was abandoned because it did not produce accurate results for commercial use [5]. The strategy proposed in this work could mean saving a considerable amount of money in actuators, while performing an adequate control. Temporized on–off and PID controllers were designed and compared to a classical on–off controller. The resulting design presents an efficient and economic control system consisting of a virtually temporized PID with programming tools and on–off valves that may replace expensive propor-

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* Corresponding author.
E-mail address: sorduz@cib.org.co (S. Orduz).

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Nomenclature

e	error
f0	on–off controller output
k_c	proportional constant
lpm	liter per minute
on–off-t	on–off temporized controller with constant period
PC	personal computer
PID	proportional integral derivative controller
PIDt	denomination for the temporized PID controller
PLC	programmable logical controller
PWM	pulse with modulation
rpm	revolutions per minute
s0	PID output signal
t0	event period
t1	characteristic process time
t2	clock
t3	valve opening time of the on–off-t controller mode
t4	event period of the on–off-t controller algorithm
vvm	air volume per minute (lpm) per initial volume of culture medium (l)
y	variable value
y_i	maximum value of variable y in the overlap i
y_i^*	variable value with respect to its set point
y_{sp}	set point value of variable y

Greek symbols

ξ	decay ratio
τ_D	derivative time constant
τ_I	integral time constant
τ_P	plant time constant

tional valves and controllers, while obtaining an efficient, robust and easy to program controller.

2. Materials and methods

The microorganisms used were the autoaglutinating strain 162-2422 of *Bacillus thuringiensis*, *B. thuringiensis* subsp. *medellin* strain 163-0131 and *B. thuringiensis* subsp. *kurstaki* strain 172-0451 deposited in the Biotechnological and Biological Control Unit Culture Collection. Bacteria were grown in 55% of the total volume of the fermentors; culture medium CIB-2 [2,6] was inoculated with 10% of a previous culture, the 20-l fermentor was inoculated with 1-l of a 13 h culture and the 200-l fermentor with a 5 h 11-l fermentation performed in the 20-l fermentor. Agitation speed varied between 200 and 700 rpm and aeration rate varied between 0.18 and 2 vvm. Temperature set point was fixed at 30 °C, and 70 fermentations were performed in the 20-l fermentor and 13 in the 200-l.

The 20 and 200-l fermentors were designed and locally built. Each fermentor has a PT-100 type resistance temperature detector (RTD), four Danfos multifluid solenoid valves (EVSIS10), two Fluid Automation Systems solenoid air valves (6-311EB02-30). For data traffic, one ADAM-5000 module (network device), one ADAM-5017 module (8 analog input), two ADAM-5060 modules (6 relay), one ADAM-4520 module (RS485/232 converter), one PC with Intel® Pentium® II 233 MHz processor, 196 Mb RAM memory, and software Genie® 3.02 from Advantech were used.

Each sensor sends the signal to a transmitter that standardizes it to 4–20 mA. Then, the signal passes to a data acquisition module and translates it to a RS-485 signal, which must pass through an RS-485/232 converter so the PC can receive it (Fig. 1).

In this project, three strategies defined below were implemented and tested. The pure on–off control, the temporized on–off (on–off-t) and the designed temporized PIDt controller. The first type is a pure on–off controller, which opens or closes valves depending on variable positions or states. To control the temperature during fermentations, two controllers of each kind were used, one to cool the system and another one to heat it.

The second algorithm used was the on–off-t controller, designed as follows:

```
Begin
  If f0=1 then
    {
      t2=t2+1;
      If t2<=t3 then
        {Open valve};
      Else
        {Close valve};
      If t2>t4 then
        {t2=0};
    }
End;
```

t3 and t4 are user-defined times.

The on–off-t controller was tuned in such a way that the slope of the temperature curve was not too marked to avoid large variations in the *B. thuringiensis* culture temperature. This was done by implementing a delay time in the algorithm, and in this case, the delay time for the subsequent control action (t4) was 60 s. This delay time was chosen after three tests, evaluating times between 50 and 70 s, and the value was determined by its proximity to the response time of the system.

The last controller tested consists of a modified PID output using the algorithm shown below. The designed virtual-PID software controller uses two parameters to temporize its output. These parameters are used to determine the opening and closing of valves and the event duration, which is based

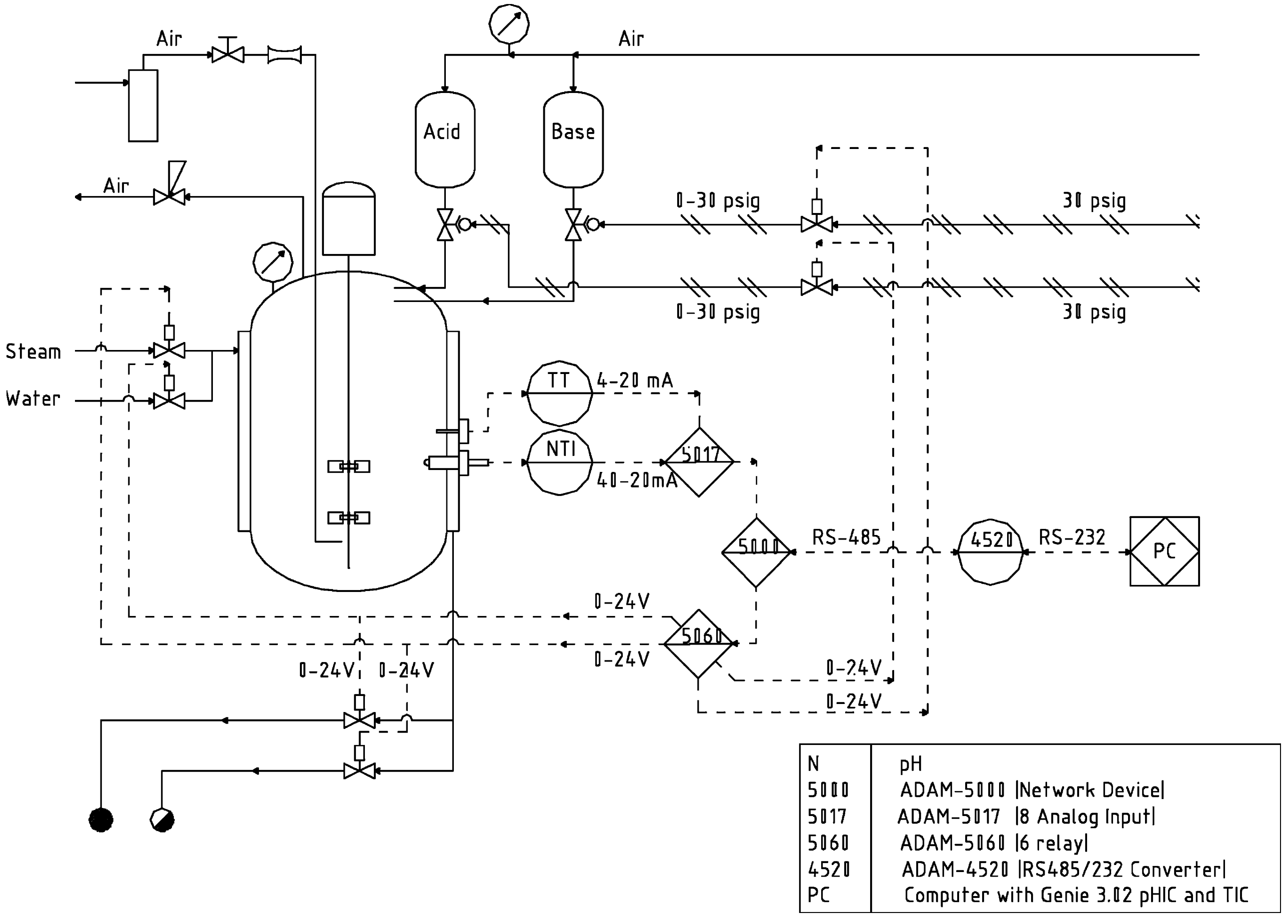

Fig. 1. Pipe and instrumentation diagram of the 20 and the 200-l fermentor used to test the three types of controllers.

on a user-predefined time (t1). It depends on the nature of the process and the kind of equipment used. In this case, an event consists of two commands: open and close valve.

The algorithm developed to improve the PIDt controller is as follows:

```
Begin
   If s0>0 then
      {
         t2=t2+1;
         If t2<=s0 then
            {Open valve};
         Else
            {Close valve};
         t0=t1/s0;
         If t2>t0 then
            {t2=0};
      }
End;
```

Thus, variable opening and waiting times are obtained, which means that this controller is a PWM with variable period (Fig. 2). Examples of calculations of opening and waiting times are shown in Table 1.

In the algorithm, t0 acts like a line that limits the region where the counter t2 can move, which is the period of the PWM (Fig. 3). In this graph, it is observed how the counter t2 behaves as a saw like function with variable amplitude, which corresponds to the modulation period. Having defined s0 as the opening time of the valve, and being part of the equation defining the PWM period, the valve modulation with variable period is then obtained. These actions are translated into the behavior described by the opening and closing curves of the valves (Fig. 4).

As the PID is a function of the error in the temperature value, its output varies according to this error. The greater the error, the greater will be its s0; therefore the PWM period is smaller, and as a result, the valve opening time (s0) is greater and the delay time ($t0 - s0$) is lower. These lead to a greater flow of control fluid, steam in case the system needs to be warmed up or water in the opposite situation.

When the temperature error is small or zero, s0 is also small or zero. This means that t0 becomes large and the opening time of the valves turns smaller or none. Therefore, the control actions are few or none. In case the error is zero, a mathematical singularity will be observed in this algorithm, specifically, when the value of s0 is zero, t0 becomes infinite,

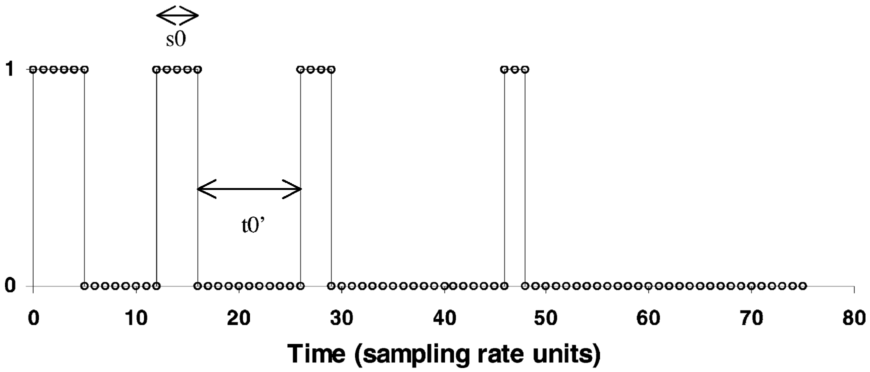

Fig. 2. Action diagram of the temporized PID; where 1 is equivalent to an open valve and 0 to a closed valve. When error decreases, s0 is smaller, while t0 and waiting time t0′ increase. The algorithm can be represented by the expression $t0' = t0 - s0$.

since s0 is in the denominator of the function. This can be avoided redefining the rank of the PID controller output, a minimum value as ±0.1, could be a good option (Figs. 3 and 5).

Tuning the PIDt was initially performed with algorithms proposed in the literature [5], but waving responses by the PIDt controller were obtained due to the additional parameters included (t1) and the clamp rate output of the PIDt virtual controller. For this reason, the tuning of the PIDt controller was performed through trial and error. Each controller was tested by inducing a step change in temperature (6–8 °C below the set point) in order to compare the different responses and to determine the best controller to be used with this type of actuators. PIDt response curve was compared to a theoretical response curve of a PID with continuous actuators [4,5,9]. Finally, the PIDt was tested during batch fermentations in the 20 and 200-l fermentors.

3. Results and discussion

In order to test the efficacy of the temperature control systems, a decrease between 6 and 8 °C below the set point was induced. Comparing the results obtained with the proposed PIDt algorithm that controls on–off valves with the results of a classical PID controlling proportional valves [4], an equivalent response to a step change in the input error was observed. The resulting response curve of the three different types of controllers to the induced step change in temperature is shown in Fig. 6; where the pure on–off made a first large overlap and kept oscillating during the rest of the control time (1.4 h); the on–off-t did not make a significant first overlap, as compared to the other controllers tested, but it had a long response time and kept oscillating during the evaluation period (1.4 h); and finally, the PIDt made a small overlap and kept the temperature closer to the set point than the two other controllers tested.

Tuning the PIDt controller was successful and this controller showed a decay ratio (ξ) of 0.27 (Eq. (1)), which is close to the recommended value of 0.25 [5,9], whereas the pure on–off showed $\xi = 0.2$ and the on–off-t $\xi = 1$. The decay ratio term expresses the proportion between the first and the second overlap of the variable carried out by the controller:

$$\xi = \frac{y_2^*}{y_1^*}, \quad \text{where} \quad y_i^* = y_i - y_{\mathrm{sp}} \tag{1}$$

Table 1
Opening and closing times of the valves for temperature control during *B. thuringiensis* fermentations determined by the designed PIDt controller

Virtual PID in Genie 3.02		Calculations of the programmed algorithm with pseudocode in Genie 3.02 (PIDt)		
PID output s0 (range 0–5)	t1	Opening time: s0 valve open (s)	Closing time: (t1/s0) – s0 valve closed (s)	Total period time: (t1/s0) (s)
0.1	60	0	600[a]	600[a]
1	60	1	59	60
2	60	2	28	30
3	60	3	17	20
4	60	4	11	15
5	60	5	7	12
0.1	25	0	250[a]	250[a]
1	25	1	24	25
2	25	2	10.50	12.50
3	25	3	5.33	8.33
4	25	4	2.25	6.25
5	25	5	0	5

[a] These values are considered as infinite compared to the times used in the algorithm.

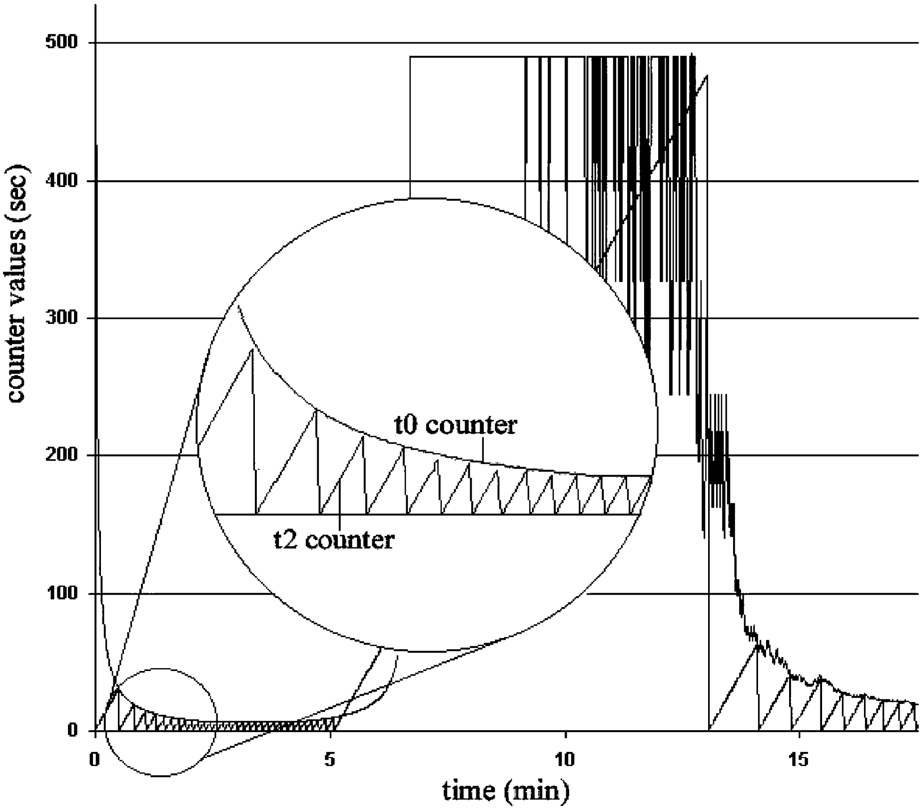

Fig. 3. Behavior of the counters used for the modified PWM. The t0 counter limits the values of the t2 counter. The oscillations observed in the t0 counter are a consequence of the PID output, which depends on the temperature error value.

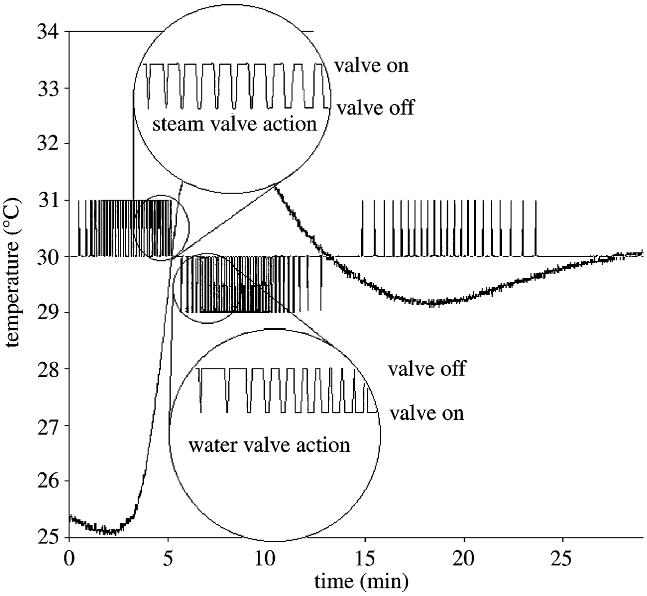

Fig. 4. Valve action during temperature control. The changes observed in opening and closing times of the valves reflect the behavior of the counters described in Fig. 3, where the different period values of the PWM, which depend on the temperature error, are observed. The uses of the required control fluid, depending on the system needs are also indicated.

In addition, this result is less waving than the pure on–off and the on–off-t controllers, and the temperature was kept closer to the set point and response times and overlaps were shorter than in the other control systems tested (Fig. 6).

The PIDt controller contains action restrictions within the control program; therefore, a variable state must be defined, and in this case, the temperature can be above or below the set point. A given controller must be used depending on the temperature value. Steam is used when error is negative and cooling water when it is positive (Fig. 5), and to define it, the actual value of the variable and the set point must be used (Eq. (2)):

$$e = y - y_{\mathrm{sp}} \tag{2}$$

The high efficiency of the PIDt is explained by the use of the modified PWM, which simulates the response of the classical PID control system. In physical terms, the total volume of the fluid (steam or cooling water) that passes through the fermentor jacket at a given period of time, and depending on the error value, must be the same in both cases, either using a classical PID control system or using the PIDt. This means that the heat removed or added to the fermentor is the same in both control systems.

Besides the classical parameters in the PID control system (k_c, τ_I, τ_D), additional parameters such as t1, and range

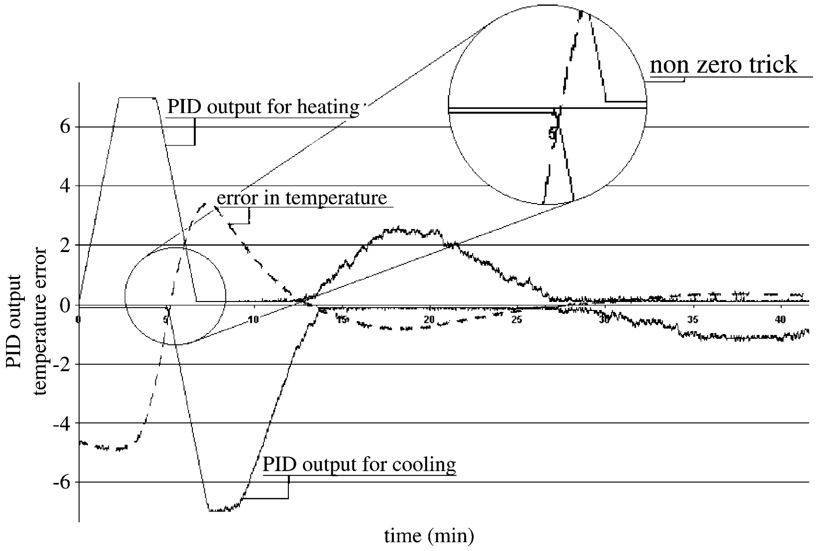

Fig. 5. Behavior of the virtual-PID controllers as a function of the error in the temperature (Eq. (2)). The PID values are used to calculate the t0 counter values, and therefore, t2 (Fig. 3); thus, the modified PWM is obtained. The non-zero trick that avoids the calculation error can be observed in detail; in this way, the PID output will never reach zero.

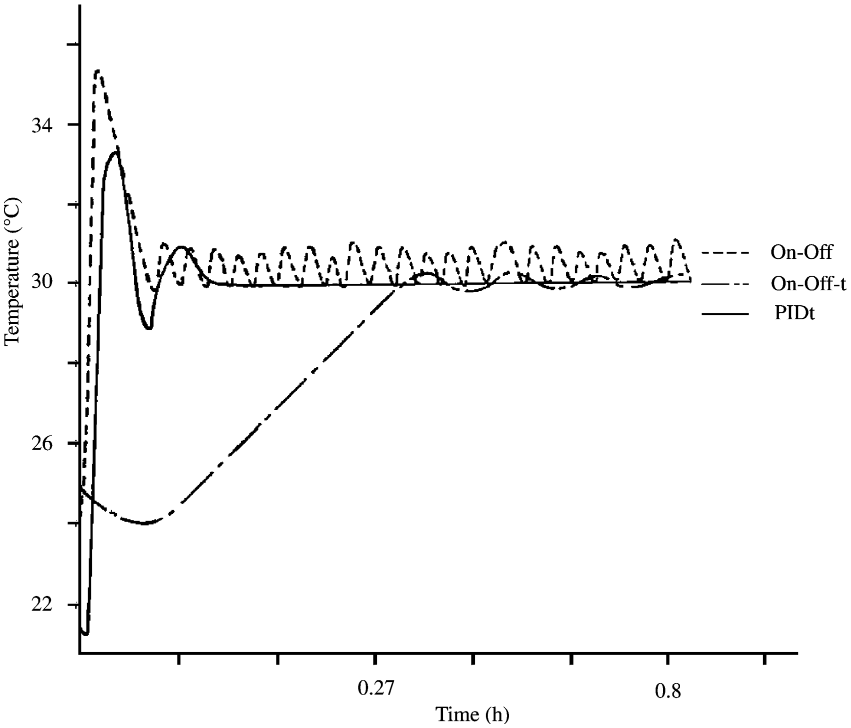

Fig. 6. Temperature response curve obtained with the already evaluated controllers. The objective was to keep temperature at 30 °C, starting from an important error (6–8 °C). The temporized PID proved more efficient in raising up and maintaining the temperature at its set point, although it was not as fast as the pure on–off controller. However, it showed an improved performance in maintaining the temperature closer to its set point than the temporized on–off controller, and resulted in more stable temperature values, with a maximum error of ±0.2 °C during the fermentation runs.

and rate of change in the output signal of the virtual PID, are also essential for a smooth handling of the variables and contribute to a better management of the overlaps, since they function as filters, avoiding controller instability. The exchange rate of the PID output signal is the maximum slope allowed for the PID output signal change in time. A recommended value for t1 is 70% of τ_P and for the exchange rate of the PID output is 120% of the total range of output by unit of sampling time. With these values, a precise temperature control was obtained at the CIB pilot plant during fermentations of *B. thuringiensis* strains 162-2422, 163-0131 and 172-0451, reaching a maximum error of 0.2 °C.

It is possible to use advanced controllers with on–off valves to obtain adequate temperature control, as in the case of fuzzy logic strategies; however, this approach demands sophisticated programming ability or a high software investment, and in both cases, programming the system is a time-consuming task. Although it is possible to acquire advanced low cost commercial temperature control systems using fuzzy logics (http://www.temp-inc.com), the output signal of these systems requires the use of expensive proportional valves.

There are two main advantages of the temperature control system proposed: (1) does not require advanced trained personnel in computer programming to implement the algorithm; (2) an accurate temperature control is achieved, with a low investment in final control elements, such as on–off valves.

4. Conclusions

Among the evaluated temperature control strategies, PIDt was the best, and temperature control with this PIDt system was as efficient and robust as classical PID with continuous actuators.

Combining on–off control elements, a PIDt controller for each state of the variable, and by manipulating the virtual-PID signal, variable opening and closing times of valves were obtained. The designed controller responds in a similar way and with the same reliability of a classical PID control system.

During the operation of the PIDt, a sampling period of 1 s was used, which restricts the opening time of the valve to this value. This PIDt gives adequate control of low sensitive variables due to the restriction in the sampling rate; for this reason, a sampling rate of 0.2 s is recommended to control high sensitive variables.

With the designed PIDt, an inexpensive control system could be obtained and in the construction of the CIB pilot fermentation plant, the global saving was 11.7% using on–off valves to control temperature; considering only the valve cost, a total saving of 82% was achieved. The use of a PC allows the implementation of non-conventional, modular, and flexible algorithms, and the use of logical rules may avoid the need of expensive expert programs.

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References

[1] D.R. Daughman, Y.A. Liu, Neural Networks in Bioprocessing and Chemical Engineering, Academic Press, New York, 1995.

[2] W.M. Liu, R.K. Bajpai, A modified growth medium for *Bacillus thuringiensis*, Biotechnol. Prog. 11 (1995) 589–591.

[3] A. Nürnberger, D. Nauck, R. Kruse, Neuro-fuzzy control based on the NEFCON-model: recent developments, Soft Comput. 2 (1999) 168–182.

[4] A. Quintero, Sistemas Unitarios de Control, Medellin-Colombia, Editorial U.P.B., 1993.

[5] F.G. Shinskey, Process Control Systems, McGraw-Hill, New York, 1996.

[6] F. Vallejo, A. Gonzalez, A. Posada, A. Restrepo, S. Orduz, Production of *Bacillus thuringiensis* subsp. *medellin* by batch and fed-batch culture, Biotechnol. Tech. 13 (1999) 279–281.

[7] H.J.L. Van Can, H.A.B. te Braake, C. Hellinga, K.C.A.M. Luyben, J.J. Heijnen, An efficient development strategy for bioprocesses based on neural networks in macroscopic balances, Biotechnol. Bioeng. 54 (1997) 549–566.

[8] T.K. Radhakrishnan, S. Sundaram, M. Chidambaram, Non-linear control of continuous bioreactors, Bioprocess. Eng. 20 (1999) 173–178.

[9] C. Smith, Process engineers: take control, Chem. Eng. Prog. 19 (2000) 19–29.