AUTOCLAVE'S CONTROL USING A SMITH PREDICTOR

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ABSTRACT

This article is about an autoclave´s pressure and temperature control, using a Smith predictor as predictive controller. The first step was to obtain a mathematical model for these variables through a data acquisition device and a Labview platform programmed software, which was designed to communicate the process and the computer. Once obtained the process dynamic, the control algorithms were designed, starting with the PI controller by poles assignment and then with the Smith Predictor, which compensate the delay effect in feedback loop. Finally the control algorithm's simulations were made, resulting a successful pressure and temperature control as well as valid sterilization process parameters.

Keywords: *pressure, temperature, autoclave, sterilization.*

RESUMEN

Este artículo presenta el control de las variables presión y temperatura al interior de una autoclave, usando un compensador de tiempo muerto denominado Predictor de Smith. Inicialmente se obtiene el modelo matemático de las variables por medio de un dispositivo de adquisición de datos y un software programado en la plataforma Labview, diseñado con el fin de comunicar el proceso y el computador. Una vez obtenida la dinámica de la planta se procede al diseño de los algoritmos de control, iniciando con el controlador PI por Asignación de Polos y luego con el Predictor de Smith, el cual tiene como fin compensar el efecto del retardo en el lazo de realimentación del control. Finalmente se realizan las simulaciones de los algoritmos de control, resultando exitoso el control de las variables, y a su vez, cumpliendo con los parámetros de un proceso de esterilización.

Palabras clave: presión, temperatura, autoclave, esterilización.

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1. INTRODUCTION

This article shows some results of a research conducted between Politécnico Colombiano Jaime Isaza Cadavid and Universidad de Antioquia; this work was done to compare performances among several control algorithms [1].

One of the main problems in conventional controllers, like PID controller, is its low performance in plant control with a considerable delay [2]. The delay presence in the system makes its control harder to implement, due to disturbances entering the process are detected after a significant time. Furthermore the control action taken based on the last measurement is inadequate because it will try to regulate a situation which has already happened one time back [2].

In general, one way to solve this problem is to reduce the controller gain with the purpose of waiting the actuation outcome after delay. If you tune a controller for a plant with and without delay the parameters will be completely different. Lose-loop performance of the process without delay will be higher than equivalent plant with delay. So, a question appears: ¿Is it possible to design a controller so that the plant has the same performance with and without delay? The answer is yes, but it isn't possible to compensate the delay because it is intrinsic to the process but one can compensate its effect on the feedback [3].

2. OBTAINING THE DINAMIC BEHAVIOR OF THE PRESSURE AND TEMPERATURE VARIABLES INSIDE AUTOCLAVE

2.1 Prior knowledge from autoclave used.

An autoclave is a tool designed to sterilize food and medical or laboratory equipment, using steam at high temperature and high pressure. Autoclaves work allowing the entry of steam but restricting its output, until it get an internal pressure of 29.7 PSIA, which allows the inside temperature reaches 121 ℃.

Sterilization is the destruction or disposal of any type of microbial life from inanimate objects, including spore forms or fungi and bacteria. Sterilization can be performed using physical or chemical agents [4].

In order to get more efficiency in the sterilization process, the autoclave was equipped with the instruments necessary to control and monitor the main variables involved in this process: temperature, pressure and water level. To control the process PI controllers were implemented initially with fixed parameters designed by pole assignment method, afterwards it was used the algorithm for the Smith Predictor because of the process high delay.

The autoclave used is a vertical container tightly closed which puts up with high pressures to achieve temperatures higher than obtained in boiling [5].

The reached temperature inside autoclave should range between 121℃ and 131℃ with pressures between 29.7 PSIA and 41.3 PSIA respectively; values obtained from the steam tables, where it is possible to visualize the relationship between boiling temperature and pressure inside autoclave. To achieve a sterilizing effect, temperature and pressure mentioned above must be maintained for about 20-30 minutes, after this period, autoclave must be cooled until the internal pressure reaches atmospheric pressure value [6].

• The autoclave's technical specifications are:

Autoclave type:	Vertical
Capacity:	40 liters
Autoclave shape:	Cylindrical
Steam source:	External
Maximum flow of steam:	44 lb/h
Working temperature:	130ºC (Max.)
Internal pressure:	55 PSIA (Max.)
Pressure from jacket:	120 PSIA (Máx.)
Material:	Stainless steel
Thermal insulation:	In warm area
Cover:	Tilt.
Load method:	Top.

Figure 1 shows the instrumentation implemented in autoclave to generate the control of the variables inside it.

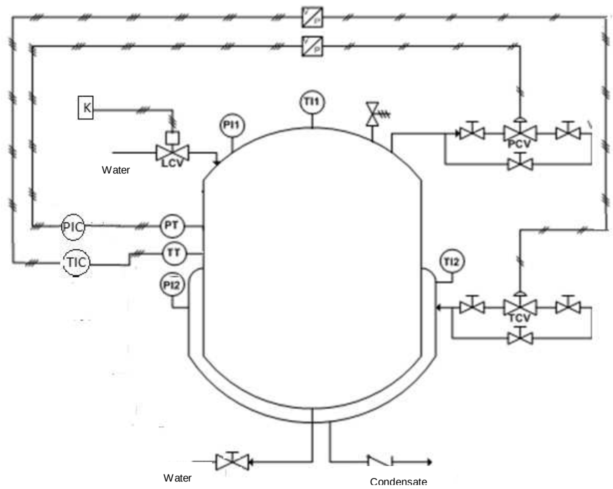

Figure 1.Autoclave instrumentation diagram.

2.2 Identification pressure and temperature variables.

Data collected for identification were obtained through data acquisition board NI-6221, made by National Instruments, pioneer and leading company in virtual instrumentation technology. This board is inside the PC assigned to the autoclave. Also it was used a software in Labview platform for data acquisition. Although the process is nonlinear, its dynamic was approximated to first-order model with delay and it worked on the area required to achieve adequate sterilization, as shown below. To get temperature and pressure plants identification, these were approximated to first-order model with delay, as it was mentioned above, and it was used the reaction curve's nonparametric graphic method.

Figures 2 and 3 represent the variable responses pressure and temperature inside autoclave after applying an input signal of step-shape to the steam flow control valve. To achieve that, the valve was moved from fully closed to fully open, generating a step amplitude of 100%. The temperature sensor was calibrated from 0 to 200℃ and pressure transmitter from 0 to 30PSIA.

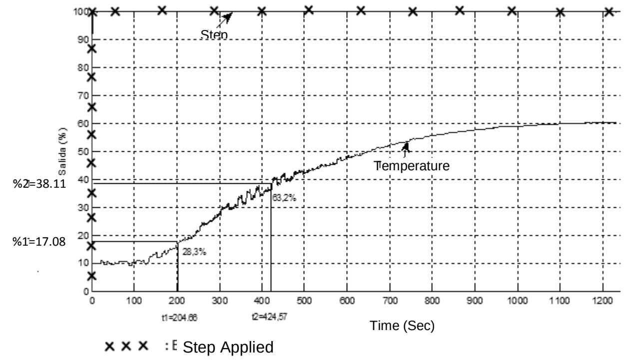

Figure 2.Temperature response for step applied (Output displayed in %).

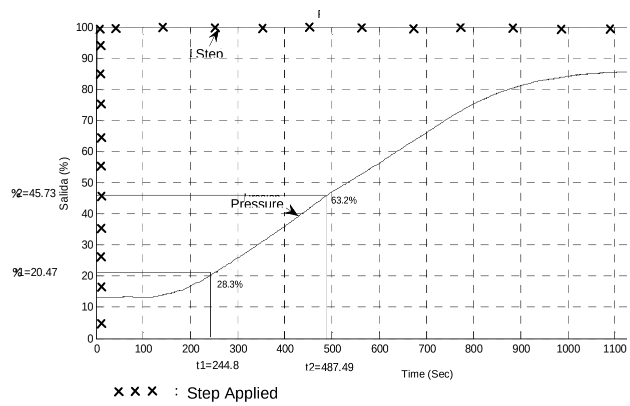

Figure 3.Pressure response for step applied (Output displayed in %).

Using the two points' method corresponding to 28.3% and 63.2% of the total change of the variable for step applied, the following process models were obtained:

Temperature:

$$G_p(S) = \frac{0.603e^{-94.71S}}{329.85S + 1} \qquad (1)$$

Pressure:

$$G_p(S) = \frac{0.7236\, e^{-123.45S}}{364.03S + 1} \qquad (2)$$

3. CONTROL SEQUENCE

Complete sterilization cycle comprises the following steps:

Automatic filling of sterilization chamber: this is done with water until it reaches the desired level.

Air expulsion from the chamber: this is done by heating up to 80℃ without pressurize the chamber but controlling the rate of temperature increase.

Heating: this is performed by controlling the pressure and temperature above 80℃.

Sterilization: this is performed during the set time at the selected temperature.

Cooling: when sterilization process finishes the autoclave is allowed to cool up to it reaches the environmental temperature.

Discharge: automatic output of water and steam from sterilization chamber.

End of process: Notice completion of the sterilization cycle.

4. DESIGN OF CONTROLLERS USING SMITH PREDICTOR

Figure 4 shows the basic configuration of a control system using Smith Predictor. The controller R corresponds to calculated regulator for the plant without delay. The Smith Predictor Compensator is shown in the system outlined by the dashed line. With this structure it is possible to design a regulator for a plant without delay keeping its performance when the delay is included [2].

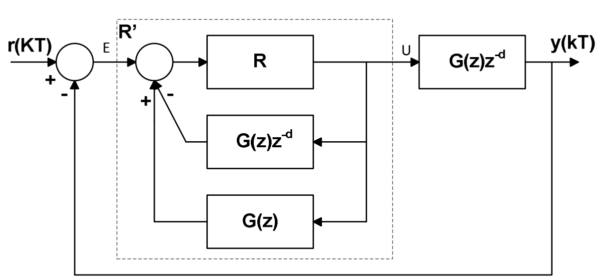

Figure 4. Smith Predictor.

After defining the new regulator R', as the inset in figure 4 and using block diagram algebra, its transfer function is:

$$R'(z) = \frac{U(z)}{E(z)} = \frac{R(z)}{1 + (1 - z^{-d})R(z)G(z)} \qquad (3)$$

4.1 Controller using pole assignment

With the purpose of design a digital controller using pole assignment method, it proceeds as follows [7]:

- The system characteristic equation is formed including the controller to design.

$$1 + R(z)G(z) \qquad (4)$$

- The desired characteristic equation is formed selecting poles inside the unit circle, according to specified design requirements. This equation must have the same order than plant-controller system.

$$(z + p_1)(z + p_2)\cdots(z + p_n) = 0 \qquad (5)$$

Where $p_1, p_2 \cdots p_n$ are the desired poles for the closed loop system. Then the equal exponent coefficients in z are compared one by one in equations 4 and 5, from this comparison are obtained n simultaneous equations whose solution generates the controller parameters.

PI controller has the following way:

$$R(z) = \frac{q_o z + q_1}{z - 1} = \frac{q_o + q_1 z^{-1}}{1 - z^{-1}} \qquad (6)$$

4.2 PI control for Temperature.

Returning to equation (1) from temperature first order model with delay and making their respective discretization with T=40s, there were obtained the following equations for the plant with and without delay respectively:

$$G(z)z^{-d} = \frac{0.0445 z^{-1} + 0.0243 z^{-2}}{1 - 0.8858 z^{-1}} * z^{-2} \qquad (7)$$

$$G(z) = \frac{0.0445 z^{-1} + 0.0243 z^{-2}}{1 - 0.8858 z^{-1}} \qquad (8)$$

The sample period is calculated according to the criterion $0.2\tau eq \leq T \leq 0.6\tau eq$, where τeq is the time constant of the closed-loop continuous system.

The characteristic equation plant-controller excluding delay is:

$$1 + \frac{q_0 + q_1 z^{-1}}{1 - z^{-1}} * \frac{0.0445\,z^{-1} + 0.0243\,z^{-2}}{1 - 0.8858\,z^{-1}} = 0 \qquad (9)$$

$$\begin{aligned} &1 - (1.8858 - 0.0445q_0)z^{-1} \\ &+(0.8858 + 0.02243q_0 + 0.0445q_1)z^{-2} \\ &+0.0243q_1 z^{-3} = 0 \end{aligned} \qquad (10)$$

To calculate the desired poles from the closed loop system is assumed a settling time equal to $t_s = 573\ s$ and a damping coefficient equal to $\xi = 0.8$, in order to improve the speed of system response. As shown from equation 1, the settling time of the open loop system is 4τ, i.e. 1319 sec, finally to make faster the system response the chosen value is mentioned above.

With this conditions the poles are located on $z = 0.7396 \pm j0.1572$. As the characteristic equation of system plan-controller is a third order one, it is necessary to add a new pole to the desired characteristic equation:

$$(z - 0.7396 - j0.1572)(z - 0.7396 + j0.1572)(z - a) = 0 \qquad (11)$$

$$\begin{aligned} &1 - (1.4794 + a)z^{-1} + (0.5718 + 1.4794a)z^{-2} \\ &+0.5718a\,z^{-3} = 0 \end{aligned} \qquad (12)$$

Comparing term by term the equations (10) and (12) and solving the resulting equations it is found that:

$$a = -0.1744 \qquad q_0 = 5.2177 \qquad q_1 = -4.1072$$

Then, the PI controller obtained is

$$R_T(z) = \frac{5.2177z - 4.1072}{z - 1} \qquad (13)$$

Figure 5 shows the temperature system response with the PI controller estimated using pole assignment method.

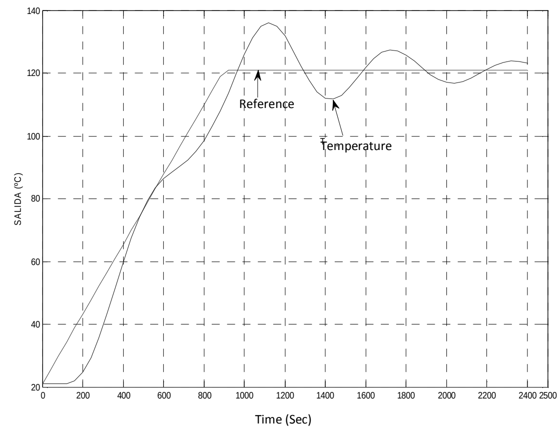

Figure 5.Temperature response applying controller PI by pole assignment method (Output displayed in ℃).

4.3 PI control for pressure.

Returning to equation (2) from pressure first order model with delay and making their respective discretization with T=50s, there were obtained the following equations for the plant with and without delay respectively:

$$G(z)z^{-d} = \frac{0.0508\,z^{-1} + 0.0419\,z^{-2}}{1 - 0.8716\,z^{-1}} * z^{-2} \qquad (14)$$

$$G(z) = \frac{0.0508\,z^{-1} + 0.0419\,z^{-2}}{1 - 0.8716\,z^{-1}} \qquad (15)$$

The sample period is calculated according to the criterion $0.2\tau eq \leq T \leq 0.6\tau eq$, where τeq is the time constant of the closed-loop continuous system.

The characteristic equation plant-controller excluding delay is:

$$1 + \frac{q_0 + q_1 z^{-1}}{1 - z^{-1}} * \frac{0.0508z^{-1} + 0.0419\,z^{-2}}{1 - 0.8716\,z^{-1}} = 0 \quad (16)$$

$$\begin{aligned} &1 - (1.8716 - 0.0508q_0)z^{-1} \\ &+(0.8716 + 0.0419q_0 + 0.0508q_1)z^{-2} \\ &+0.0419\,q_1 z^{-3} = 0 \end{aligned} \qquad (17)$$

To calculate the desired poles from the closed loop system is assumed a settling time equal to $t_s = 716.24\ s$ and a damping coefficient equal to $\xi = 0.8$, in order to improve the speed of system response. As shown from equation 2, the settling time of the open loop system is 4τ, i.e. 1456 sec, finally to make faster the system response the chosen value is mentioned above.

With this conditions the poles are located on $z = 0.7396 \pm j0.1572$. As characteristic equation of system plant-controller is a third order one, it is necessary to add a new pole to the desired characteristic equation:

$$(z\text{-}0.7396\text{-}j0.1572)(z\text{-}0.7396\text{+}j0.1572)(z\text{-}a)=0 \quad (18)$$

$$1-(a+1.4794)z^{-1}+(0.5718+1.4794a)z^{-2} +0.5718a\,z^{-3}=0 \quad (19)$$

Comparing term by term the equations (17) and (19) and solving the resulting equations it is found that:

$a = -0.2077 \qquad q_o = 3.6278 \qquad q_1 = -2.8362$

Then, the PI controller obtained is

$$R_T(z) = \frac{3.6278z - 2.8362}{z-1} \quad (20)$$

Figure 6 shows the pressure system response with the PI controller estimated using pole assignment method.

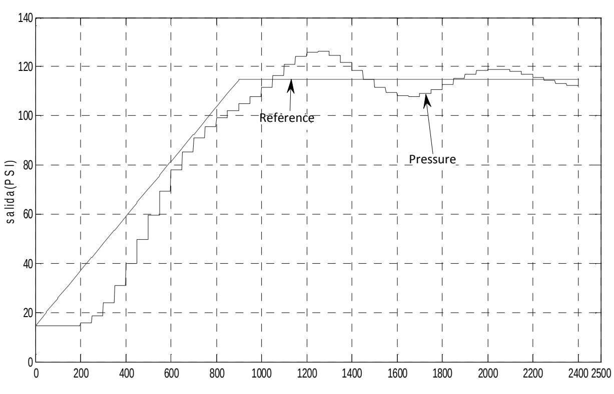

Figure 6.Pressure response applying controller PI by pole assignment method (Output displayed in PSI).

4.4 Smith Predictor

4.4.1 Temperature control using Smith Predictor:

Taking equation 3 (Controller type Smith Predictor), the transfer function from temperature plant without delay and the transfer function from PI temperature controller by pole assignment method, it is found that:

$$R^{'}(z) = \frac{\frac{5.2177z - 4.1072}{z-1}}{1+(1-z^{-2})\frac{5.2177z-4.1072}{z-1} * \frac{0.0445z+0.0243z}{z^2-0.8858z}} \quad (21)$$

Simplifying:

$$R^{'}(z) = \frac{5.2177z^5 - 8.729z^4 + 3.6381z^3}{z^5 - 1.6536z^4 + 0.8298z^3 - 0.3319z^2 + 0.0559z + 0.0998} \quad (22)$$

It was obtained the difference equation from previous equation in order to present the control law:

$$u(k) = 5.2177e(k) - 8.729e(k-1) + 3.6381e(k-2) + 1.6536u(k-1) - 0.8298u(k-2) + 0.3319u(k-3) - 0.0559u(k-4) - 0.0998u(k-5) \quad (23)$$

Figure 7 shows the temperature system response using Smith Predictor.

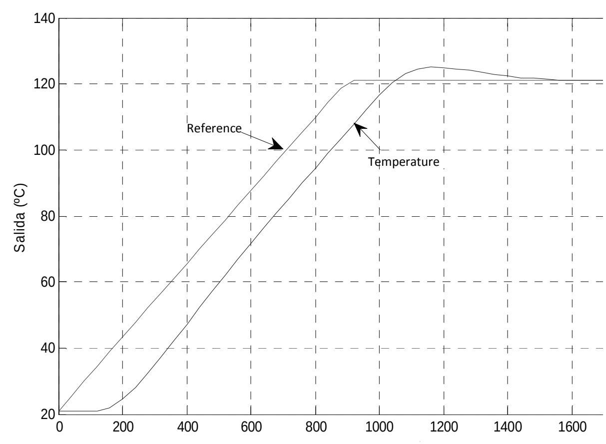

Figure 7.Temperature response applying Smith Predictor with PI by pole assignment method (Output displayed in ℃).

4.4.2 Pressure control using Smith Predictor:

Taking equation 3 (Controller type Smith Predictor), the transfer function from pressure plant without delay and the transfer function from PI pressure controller by pole assignment method, it is found that:

$$R^{'}(z) = \frac{\frac{3.626z - 2.8362}{z-1}}{1+(1-z^{-2})\frac{3.626z-2.8362}{z-1} * \frac{0.0508z^{-1}+0.0419z^{-2}}{1-0.8716z^{-1}}} \quad (24)$$

Simplifying:

$$R'(z) = \frac{3.626z^5 - 5.9966z^4 + 2.472z^3}{z^5 - 1.6873z^4 + 0.8794z^3 - 0.303z^2 - 0.078z + 0.1188} \quad (25)$$

It was obtained the difference equation from previous equation in order to present the control law:

$$u(k) = 3.626e(k) - 5.9966e(k-1) + 2.472e(k-2) + 1.6873u(k-1) - 0.8794u(k-2) + 0.303u(k-3) + 0.0078u(k-4) - 0.1188u(k-5) \quad (26)$$

Figure 8 shows the pressure system response using Smith Predictor.

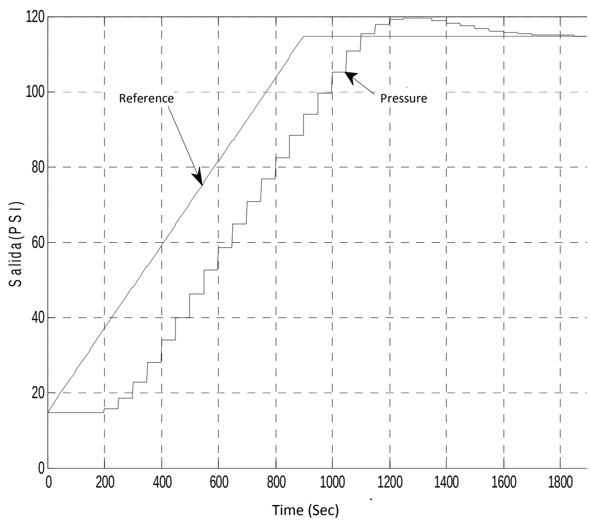

Figure 8.Pressure response applying Smith Predictor with PI by pole assignment method (Output displayed in PSI).

Finally, It was executed the process control on Labview platform, implementing the control algorithms from equations 13, 20, 23 and 26, the results are shown in figures 9 and 10:

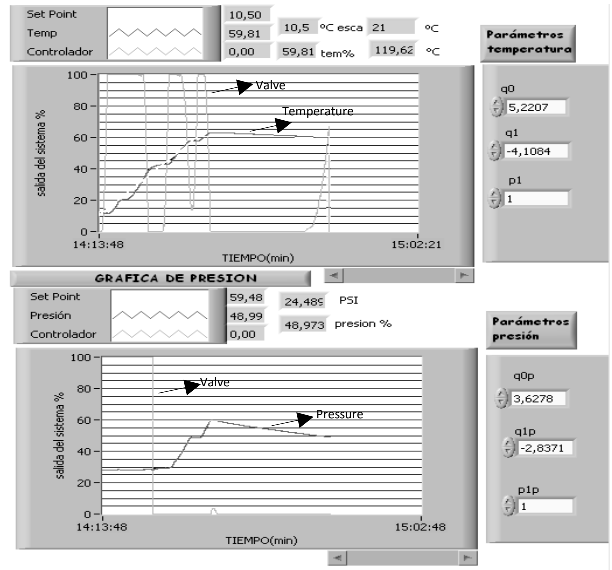

Figure 9. Control software main display type PI for temperature and pressure variables (Output displayed in %).

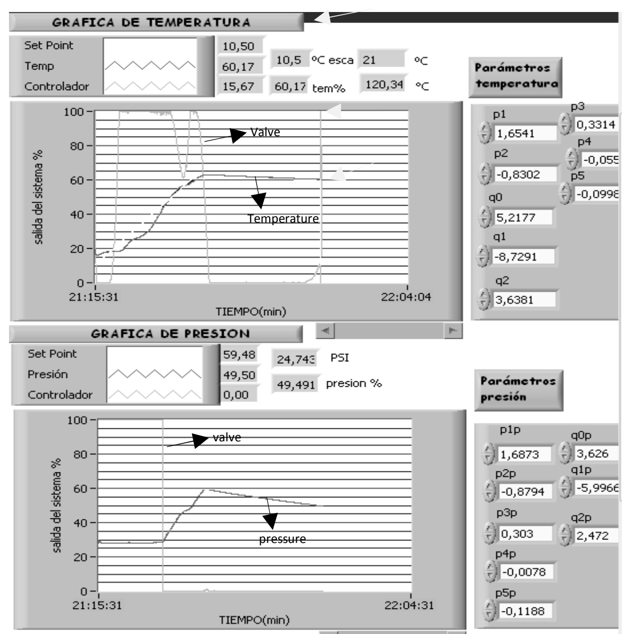

Figure 10. Control software main display type Smith Predictor for temperature and pressure variables (Output displayed in %).

To analyze the controller performances in autoclave´s variables regulation is enough to compare figures 5 and 7, 6 and 8 in theory and figures 9 and 10 at a practical level, where Smith Predictor performance is better than the conventional PI controller, then, as shown in these graphs, the delay effects has been reduced considerably, this can be seen in the oscillation reductions in the system response, although delay was kept as it was mentioned at the beginning, the output signal was stabilized faster, with less overshoot and zero error, i.e. the Smith Predictor satisfies the stability conditions, speed, response and system accuracy.

5. CONCLUSIONS

- Through implementation of Smith Predictor type control algorithm it was verified experimentally the good performance of this algorithm in the processes with significant dead time; this characteristic was initially seen on MatLab simulations. With this controller type it was achieved that temperature and pressure responses reach and follow their respective references up to complete the sterilization cycle.

- To calculate the Smith Predictor it was used conventional PI controllers calculated by the pole assignment method, which was made to find the controller to provide the best process response, and because Smith Predictor theory suggests designing a conventional controller that doesn't include the delay of the plant [3].

- When a PI controller is used the control effort on the valve is quite oscillatory and with variability that covers practically the entire range of valve opening (0-100%). Then, when the Smith Predictor was used the control effort on the valve was much smaller than the one generated by PI controller, these differences can be seen in figures 9 and 10, which show the two algorithms performance implemented both in the real process and on Labview Platform.

6. REFERENCES

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