



Design and implementation of a cascade control system in the heat exchange plant

Diseño e Implementación de un sistema de control cascada en la planta de intercambio térmico - PIT000

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Juan Gonzalo Álvarez Díaz¹
 Jorge Enrique Moreno Serrano²
 Edwin Fernando Ramírez Murillo³

¹ Colombian. M.Sc. National Learning Service SENA. CEAI, Cali - Colombia, Applied Research, Technological Development and Innovation Unit, UIADTI - SENA. *jgalvarez@sena.edu.co

² Colombian. M.Sc. National Learning Service SENA. CEAI, Cali - Colombia, Applied Research, Technological Development and Innovation Unit, UIADTI - SENA. jemorenos@sena.edu.co

³ Colombian. Electronic Engineer. National Learning Service SENA. ASTIN, Cali - Colombia, Investigation Unit Applied, Technological Development and Innovation, UIADTI - SENA. eramirez@sena.edu.co

Abstract

The article describes the design and implementation of the control system of the didactic thermal exchange plant - pit000, located in the center of electricity and industrial automation, CEAI - SENA, as an investigative contribution to the needs of the institutions of education and of companies, sugar mills, petrochemical, and paper mills, among others. The control system is based on a cascade strategy temperature-flow, implemented through the use of instrumentation and industrial control technology, which includes intelligent flow and temperature transmitters, programmable logic controllers and control valves with smart positioners. The design method of the control system included the development of diagrams (p & id) and strategy blocks, the definition of conditions of operation of the process, the modeling of control loops by means of transfer functions, the design of the flow and temperature controllers, the determination of the tuning parameters making use of Matlab and the final implementation of the control system. The results of the research, which are associated with the implementation of the control system, are considered satisfactory, because they are validated with the simulation and test of the control strategy in the presence of operation, as well as the control strategy complied with the purpose of improving the behavior of temperature output of the product in the process.

Keywords: Heat exchange; cascade control; PID; PIDTuning; Simulation; implementation.

Introduction

The study of cascade control strategies, based on Proportional, Integral and Derivative control actions, is a common theme in engineering control courses and

addressed by different authors, who present different implementation methodologies for this strategy in plants of thermal exchange.

Some of the results of implementation or simulation are presented in Srinivas, Prasada and Vijaya, (2012), where different control strategies are applied in a heat exchange plant using software commonly used at the academic level - LabView; in Chacón, (2013), the design of control systems for thermal exchange teaching plants is addressed, using different control techniques, which is focused on independent control loops. In Abdulbasid and Mukhtar (2014), a temperature controller is developed for the output of a heat exchanger, in which the tuning and the behavior of the controlled system were carried out and analyzed with Matlab ® SIMULINK, and in which the results focused on determining the effects of variations in sampling times on tuning parameters and behavior in the processing time. From the general review of control systems for exchangers, it can be concluded that there is a large number of articles where different control methods are exposed, from simple strategies to advanced strategies, which shows the benefits of control towards the process. Likewise, what is most reported is the use of PID strategies for the control of exchangers, this strategy being the most used at all levels in the industry (O'Dwyer, 2009).

As the hypothesis of the investigation, it is proposed "The cascade control strategy, used to improve the regulation of the control of continuous processes, can be successfully implemented in a thermal exchange plant, manufactured at a low scale of those existing in industrial companies."

Taking the hypothesis as a reference, the paper reported on the design and implementation of a cascade control strategy in a didactic thermal exchange plant, based on the use of industrial control and instrumentation technology, and applying modern methodologies and computational tools of design.

The research has a background in technological developments and other written articles on unitary operations plants carried out by the UIADTI - CEAI, which are in use in the SENA nationwide (Moreno, 2009).

Theoretical Frame

A typical scheme of the cascade control in a heat exchange plant is shown in Figure 1, where a primary

control loop established by the variable temperature and a secondary control loop established by the flow variable can be recognized. In this control system, it is sought that the exit temperature of the product fluid, $T(t)$, remains in established values through the references or desired values. The heat transfer fluid (steam), must provide the amount of energy necessary to bring the product inlet temperature - $T_i(t)$, to the desired value. The outlet temperature is controlled by manipulating the position of the valve which in turn modifies the heat transfer flow. In some processes, the heat transfer flow can be affected by changes in pipe pressure or temperature, which generates disturbances in the control system, which are not normally compensated by a simple control system. To compensate for the effects of these disturbances in the control system are implemented by the secondary flow control loop (Creus, 2010).

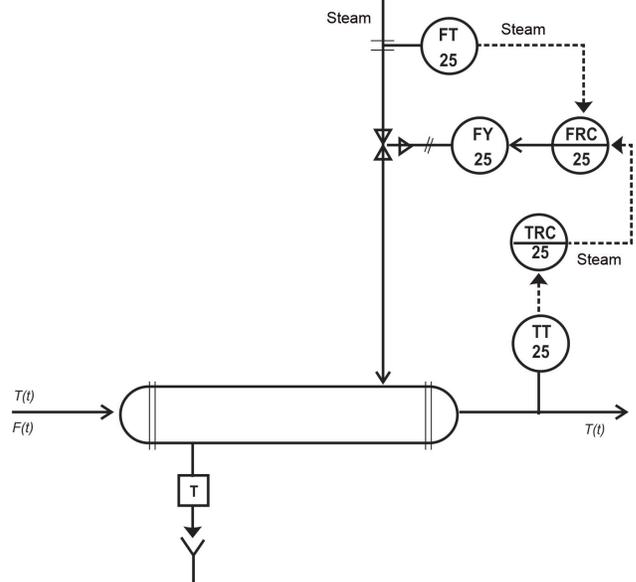


Figure 1. Scheme of Control in cascade for a heat exchanger
Source: Smith & Corripio (1991)

The design methodology of the PID control system, which contains different methods for the modeling of this type of process and subsequent design of the controller, is addressed in Moradi, and Johnson, (2005), in which the estimation method of the transfer function through nonparametric modeling. This method was taken as a reference tool in the research, in which to obtain the mathematical model of the thermal exchange process the data and dynamics of the input and output variables are taken, and by using computational tools the function is obtained transfer.

The general scheme for the design of control systems proposed by MathWorks of Matlab ® is shown in Figure 2. The procedure shows three stages: i) Design: in which the model of the process is obtained, making use of the

identification tool (Toolbox Ident), and the design of the controller, through the use of the PIDTuning tool; ii) Implementation: in which the control strategy is developed, closely associated with the technology in which the tuning parameters were implemented and tuned if necessary; iii) Verification: where the behavior of the loop is checked according to design conditions. The methodology shown in Figure 2 is the one used in the present investigation.

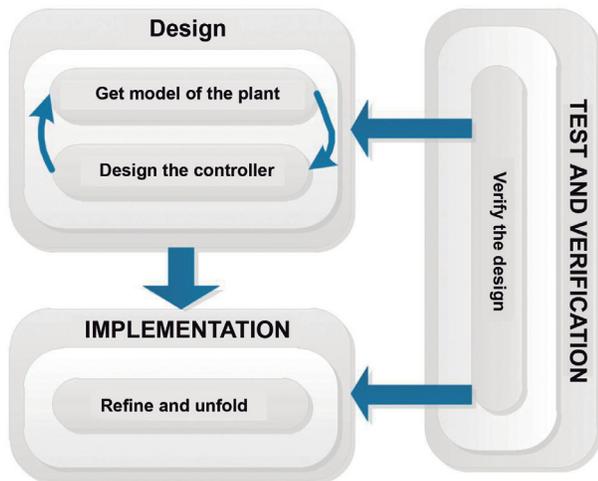


Figure 2. Stages of development of a control system
Source: MathWorks (2016)

The methodology of control system design

Process description

The pipe and instrument diagram - (P & ID) of the teaching floor, shown in Figure 3, was developed applying the ANSI / ISA S5.1 standard to represent the controlled system of the PIT000 (American National Standard, 2009). Figure 3 shows that through the heat exchanger - HE001, of the shell and tube type, two fluid streams pass: that of the product (water) that goes through the shell and that of the heat transfer fluid (hot water at 95 °C) that circulates through the tubes. The product flow enters the HE001, through the Coriolis effect flow transmitter - FIT002, the control valve - FCV001 and the temperature transmitter - TIT001. At the exit of the exchanger, the hot product meets the temperature transmitter - TIT003 and the electromagnetic flow transmitter - FIT005. The heat transfer fluid enters the HE001 through the vortex flow transmitter - FIT004, the valve FCV002, and the temperature transmitter - TIT004, and at the outlet, this flow, meet the TIT002 transmitter and the differential pressure flow transmitter - FIT003. In the plant, both the transmitters and the valves have the HART communication protocol and 4 to 20 mA communication signals.

In the process, the following variables are recognized: product flow - $Q_p(t)$, flow rate of heat transfer fluid - $Q_C(t)$, inlet temperature - TEP (t), and output TSP (t) of product and inlet temperature - TEC (t) and TSC (t) output of heat transfer fluid.

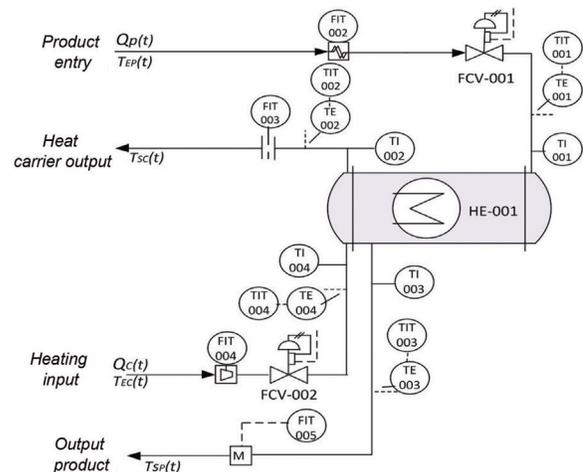


Figure 3. Diagram (P & ID) of the PIT000, with flow control cascade temperature loop
Source: authors

A platform for control and acquisition of signals

The control system was implemented in a hardware and software platform, ready for reading, processing and writing signals consisting of:

i) an AFPX reference PLC, whose configuration and programming software is FPwin Pro; both of Panasonic brand and.

ii) Kepserver software as an OPC server that allows the transfer of data through Ethernet between the PLC and the PC. The platform also has scripts made in Matlab for the storage and generation of signals, used in activities such as the definition of the point of operation, data capture for modeling the process, perform control tests and monitor the process in the plant.

Operating conditions of the process

The characterization of FCV001 and FCV002, to determine the appropriate operating points for the control system, was done by sending, through the control and acquisition platform, signals to the valves and reading the values delivered by the FIT002 and the FIT004. The characteristic curve of the FCV001 valve is shown in Figure

4, where the “y” axis is the measured flow and the “x” axis is the percentage of the opening of the valve. By performing the same procedure, the characteristic curve of the FCV002 valve is also obtained.

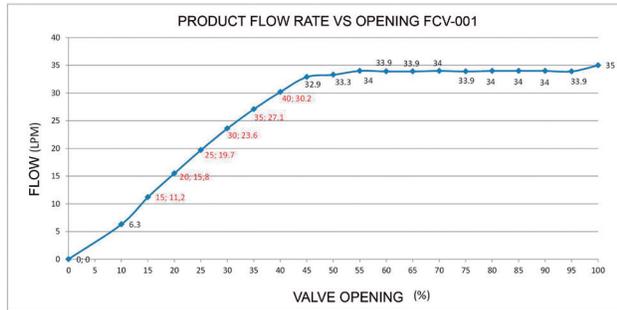


Figure 4. The characteristic curve of the FCV-001
Source: authors

Table 1 shows the main operational characteristics of the valves.

Table 1. Values characterization of the valves

Characterization valve	FCV001	FCV002
Maximum flow of operation	35	21
Minimum opening of linear operation	11.2	8
Maximum opening of linear operation	30.2	19
Suggested operation point	11.2	12.2

If the process is operated at the points suggested for the valves, a product outlet temperature is established at 43 °C, considering that the product inlet temperature is 18 °C, and the temperature of the heat transfer fluid is in the range of 90 to 95 °C.

Control strategy

The temperature-flow cascade control strategy, proposed for the thermal exchange plant, is represented by the block diagram in Figure 5, in which the controlled variable is the temperature of output of the product, $Tsp(t)$, which represents the primary control loop, and the manipulated variable of the fluid flow heat carrier which, in turn, is the controlled variable for the secondary loop, $Qc(t)$. The disturbing variables are i) the temperature of the heat transfer fluid, which varies because the heater is controlled by an ON-OFF controller in a temperature range of 90 to 95 °C, in the diagram it is identified as $d2(t)$ (t) and ii) the flow of product flow, $d1(t)$, which varies by the conditions of the process. The typical control strategy for this type of process is proposed in Smith and Corripio (1991). The $Mv(t)$ represents the opening percentage of the FCV002 valve.

Process modeling

The modeling starts with obtaining the transfer function of the flow process that was used to design the secondary control loop. In accordance with the defined operating conditions and making use of the acquisition platform, a pseudo-random signal was generated that was applied as the signal $Mv(t)$ and the flow rate $Qc(t)$ was measured, whose behavior is presented in Figure 6.

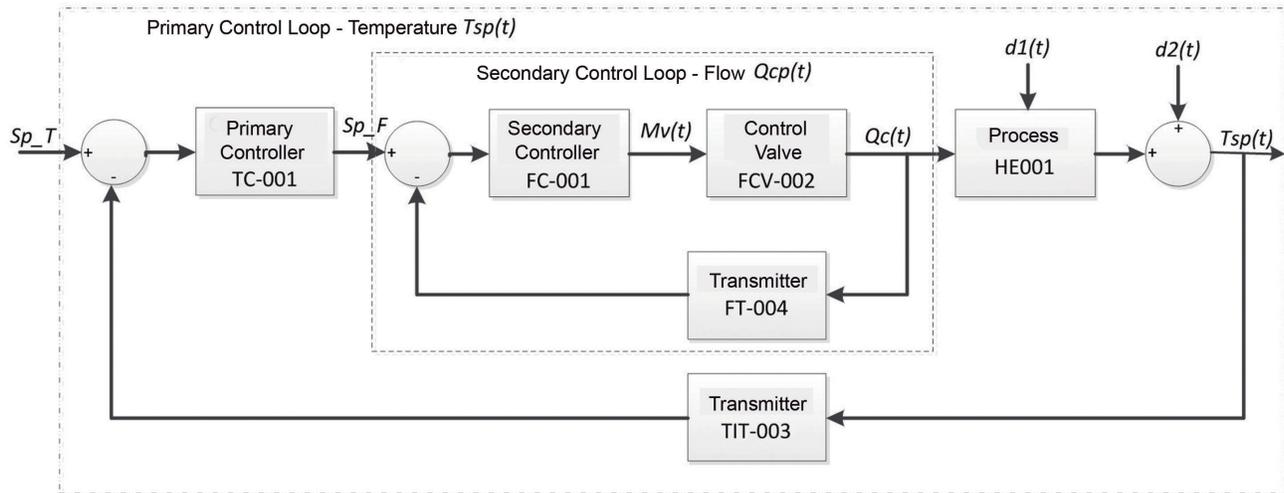


Figure 5. Block diagram of the cascade temperature - flow control
Source: the authors

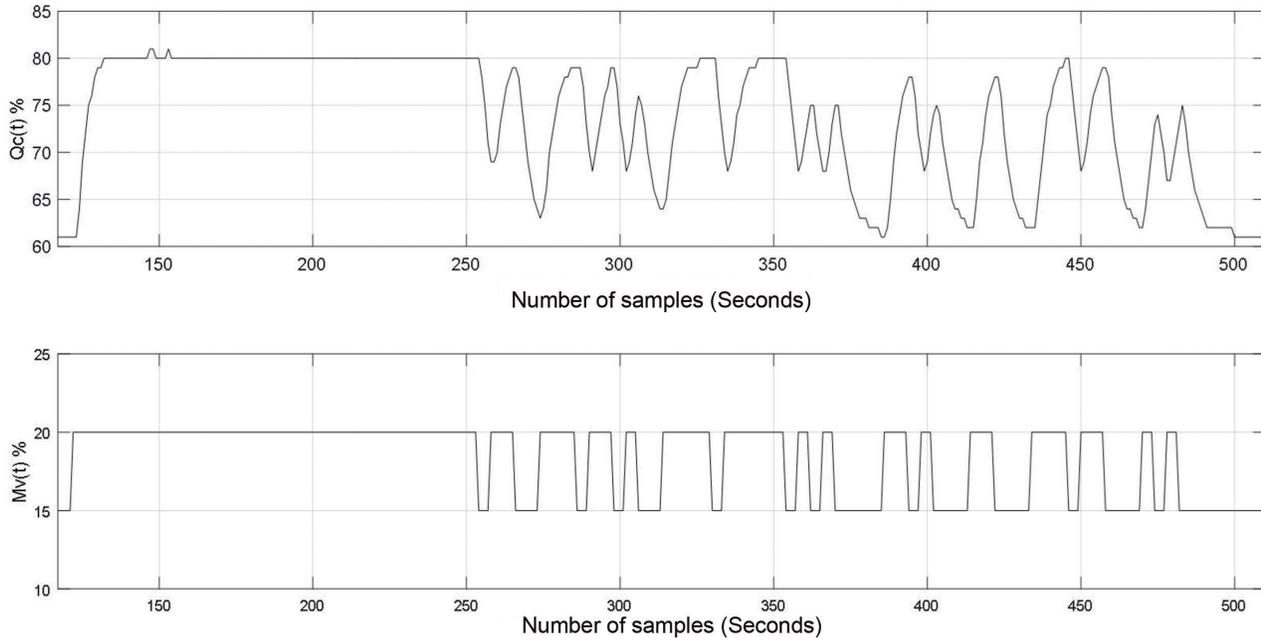


Figure 6. Signals Mv (t) and Qc (t) generated
Source: the authors

Applying the identification procedure defined in MathWorks, (2014b) and using the IDENT tool of the MATLAB, the first-order transfer function with delay was generated, which is shown in (1).

$$G_1(s) = \frac{k}{Ts + 1} e^{t_o} = \frac{3.8512}{1 + 1.65s} e^{-0.592s} \quad (1)$$

Once the mathematical model was generated, the validation was carried out through a correlation analysis between the real values and those generated by the transfer function obtained. The percentage of similarity of the model is 89.5%, as shown in Figure 7.

The same procedure was used to determine the mathematical model between Mv (t) and the temperature Tsp (t). The generated signals that were used to identify the transfer function are shown in Figure 8.

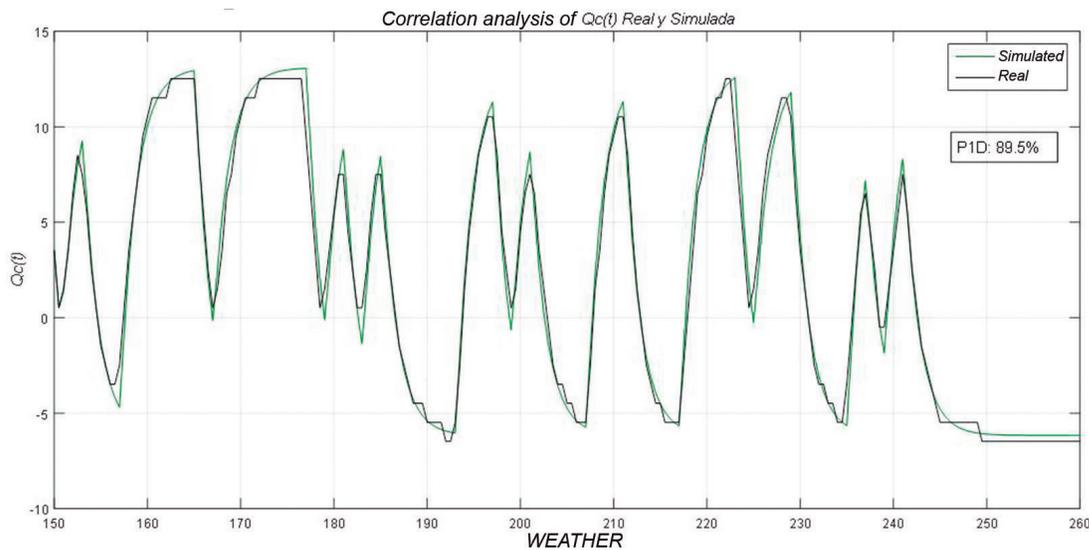


Figure 7. Correlation analysis of the transfer function for the secondary loop
Source: the authors

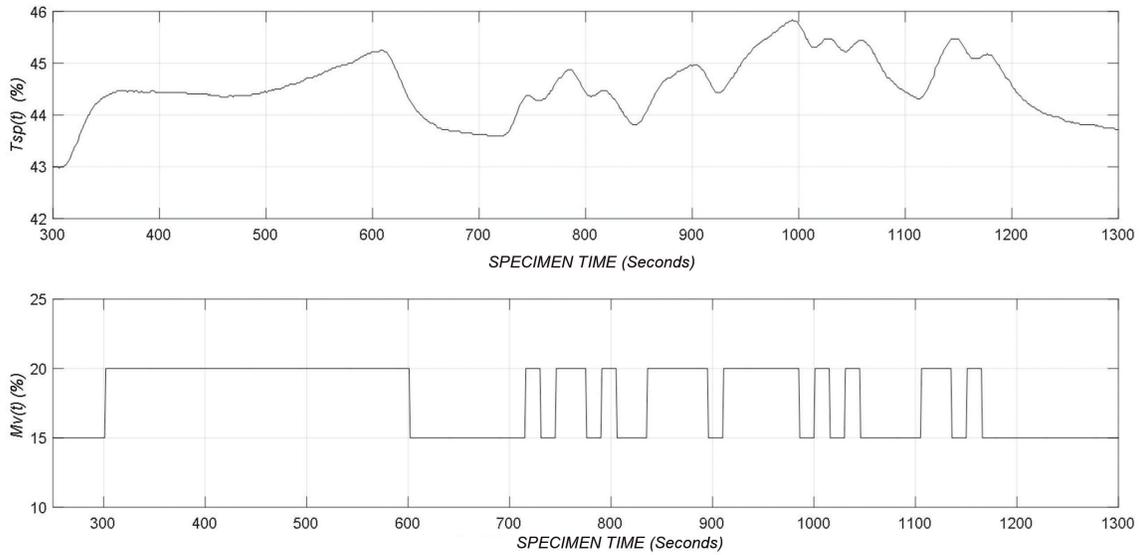


Figure 8. Signals $Mv(t)$ and $Tsp(t)$ generated
Source: the authors

The transfer function obtained for the temperature process is shown in (2).

$$G_2(s) = \frac{0.4298}{1 + 21.197s} e^{-15.942s} \quad (2)$$

The correlation analysis of the mathematical model obtained is 78 %, which is an acceptable percentage considering that the model is for control. Figure 9 shows the correlation analysis.

From equation (2) it can be seen that the process has a delay of 15.94 s. The very common characteristic in the processes related to the variable temperature.

Controllers and tuning parameters

The controllers to be designed are of the PID type. The tuning of the loops is done by obtaining the parameters of the controller: proportional gain - K_p , Integral time - T_i and Derivative time - T_d . These parameters were determined by two methodologies; the first, by means of the PIDTuner tool of Matlab and the second, according to the calculations proposed in Smith and Corripio (1991), presented in Table 2, which are calculated from the parameters of a first-order model with delays defined in (1).

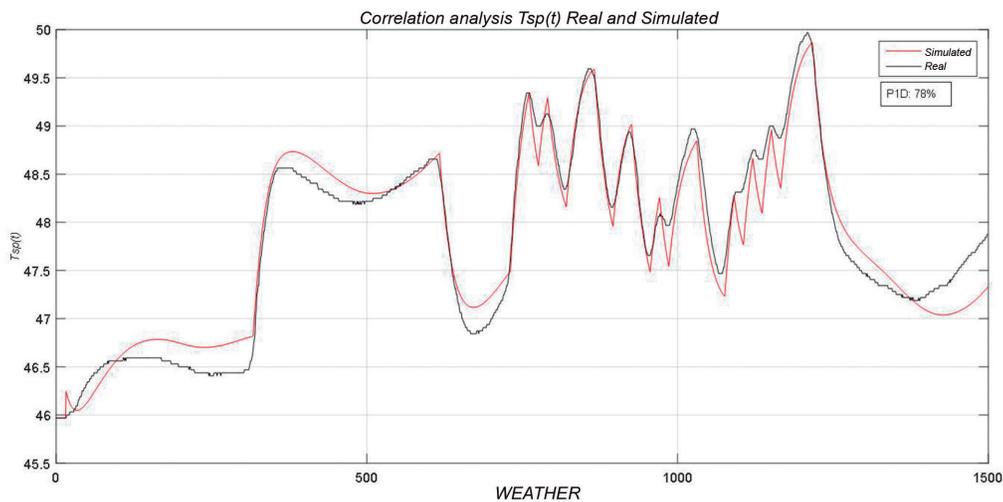


Figure 9. Correlation analysis of the transfer function for the primary loop
Source: the authors

Table 2. Methodology to determine tuning parameters

Type of controller		Proportional gain K_c	Integral time T_i	Derivative Time T_d
Proportional	P	$\frac{1}{k} \left(\frac{T}{t_o} \right)$	-	-
Proportional-integral	PI	$\frac{0.9}{k} \left(\frac{T}{t_o} \right)$	$3.3t_o$	-
Proportional-integral-Derivative	PID	$\frac{1.2}{k} \left(\frac{T}{t_o} \right)$	$2.0t_o$	$0.5t_o$

Source: Automatic process control (Smith & Corripio, 1991)

Tuning parameters of the secondary control loop controller

Lo The results obtained with the PID Tuner tool (MathWorks, 2014a), for the calculation of the tuning parameters, are shown in Figure 10, where the parameterization of the tool and the result parameters are shown. The tuning criteria are based on improving the response speed of the closed loop with respect to the open loop with an impulse of less than 15%. The controller set with the tuning parameters of Figure 10 is referred to for PID1 simulation purposes. Subsequently, the second methodology is applied. When performing the calculations defined in Table 2, the parameters are: $K_p = 0.6$, $T_i = 1.9$ and $T_d = 0$. To the adjusted controller with these values, it is called PID2. Through both methods, it is established that the controller to be implemented for the secondary loop must be of type PI. Typical for flow control.

Tuning parameters of the primary control loop controller

By developing a process similar to that performed in the secondary control loop, the tuning parameters of the primary control loop are obtained by the two methods. The result of applying the PID Tuner to the transfer function of the primary control loop is shown in Figure 11. The tuning parameters generated are: $K_p = 2.32$, $T_i = 24.45$ and $T_d = 1.84$. This controller is called PID3. The tuning parameters calculated according to Table 2 are:

$K_p = 3.7$, $T_i = 31.88$ y $T_d = 7.971$. This controller is called PID4. The parameter T_d was readjusted, by trial and error, to a value of 1.5 since the response presented an undesired behavior generated by the T_d value "large". A PID controller for temperature was implemented because it is the typical algorithm for this variable.

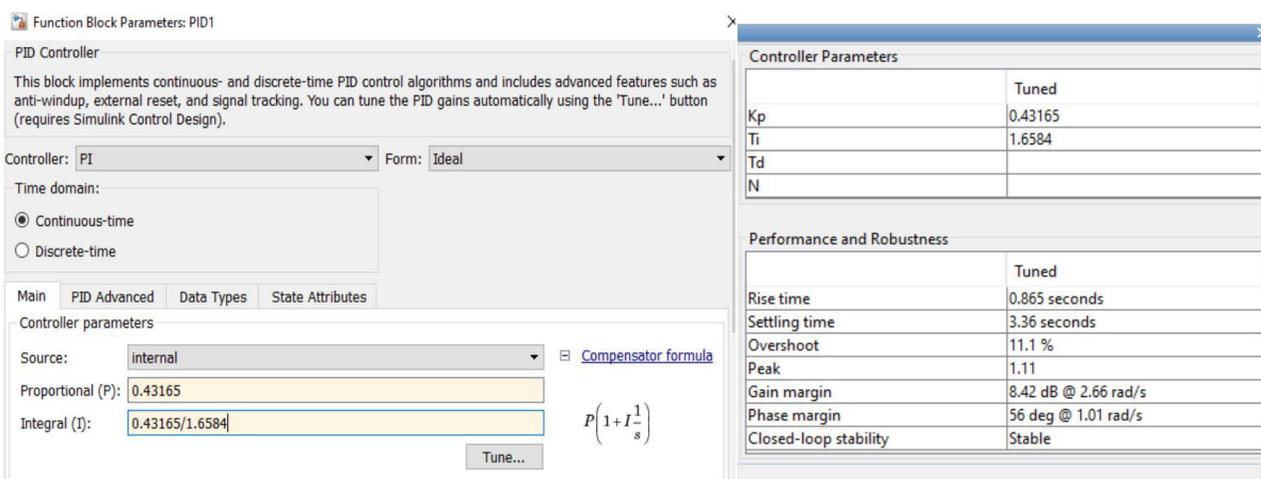


Figure 10. Tuning parameters of the secondary controller, established by the Matlab PID Tuner
Source: the authors

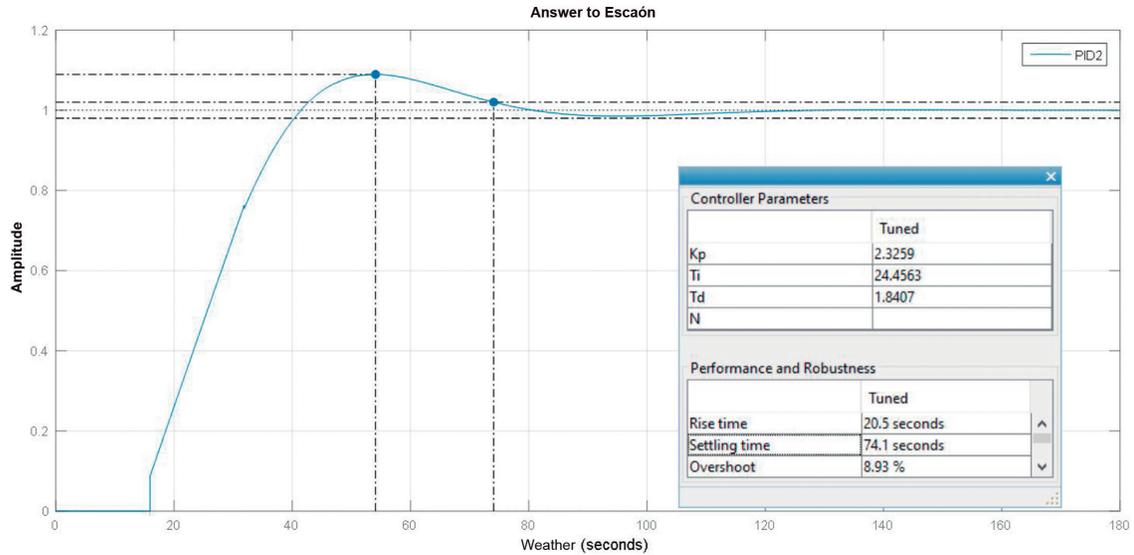


Figure 11. Tuning parameters of the primary controller, established by the Matlab PID Tuner
Source: the authors

Simulation of control loops

By means of the Matlab SIMULINK, the secondary control loop, flow loop, was simulated to evaluate the behavior in time according to the tuning parameters obtained. The block diagram of the secondary control loop implemented in the tool is shown in Figure 12, in which the simulation was observed of the two controllers PID1 and PID2.

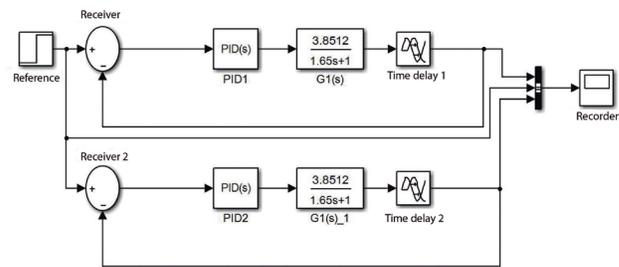


Figure 12. Simulation of PID 1 and PID2 controllers
Source: the authors

The response in a time of the two controllers is shown in Figure 13. The comparison of the two controllers

was made considering the maximum impulse, $Mp(\%)$, el establishment time, Ts (s), and steady-state error, Ess .

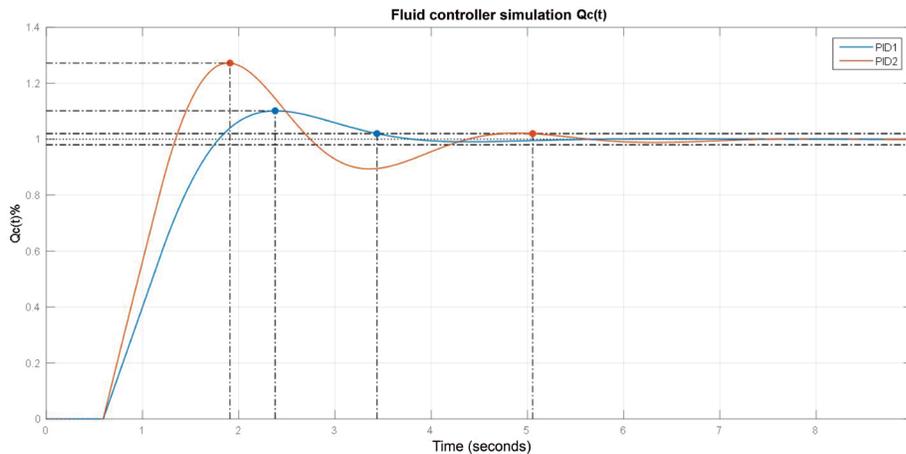


Figure 13. Simulation response of the PID1 and PID2 controllers
Source: the authors

The comparison is shown in Table 3. Considering “the best response” the one that has less overshoot and shorter establishment time, and from a simple analysis, it is concluded that the best response is that offered by the controller named PID1.

Table 3. Comparison of PID1 and PID2 controllers

Controller	Mp(%)	Ts (s)	Ess
PID1	27.2	5.05	0
PID2	11.1	3.36	0

The simulation of the primary and secondary control loops was performed, and the responses of the PID3 and PID4 controllers were compared.

The simulated response of the primary control loop with the two controllers was represented in Figure 14. Table 4 shows the comparison parameters of the two responses over time.

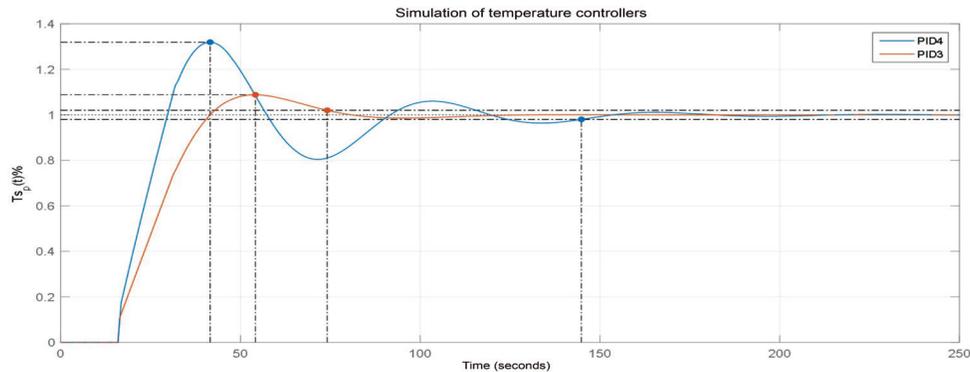


Figure 14. The controller responsible for the temperature loop
Source: the authors

Table 4. Comparison of PID3 and PID4 controller

Controller	Mp(%)	Ts (s)	Ess
PID3	34.7	149	0
PID4	11.3	80.9	0

In the comparison, it can be deduced that the best response of the primary control loop or temperature is that offered by the parameterization of the controller called

PID3. The Complete simulation of the cascade control strategy with The PID1 and PID3 controllers are shown in Figure 15, which can be displayed the capacity of the controller Flow follow the flow reference, the upper part of the figure, and the dynamic response of the temperature control loop, lower part.

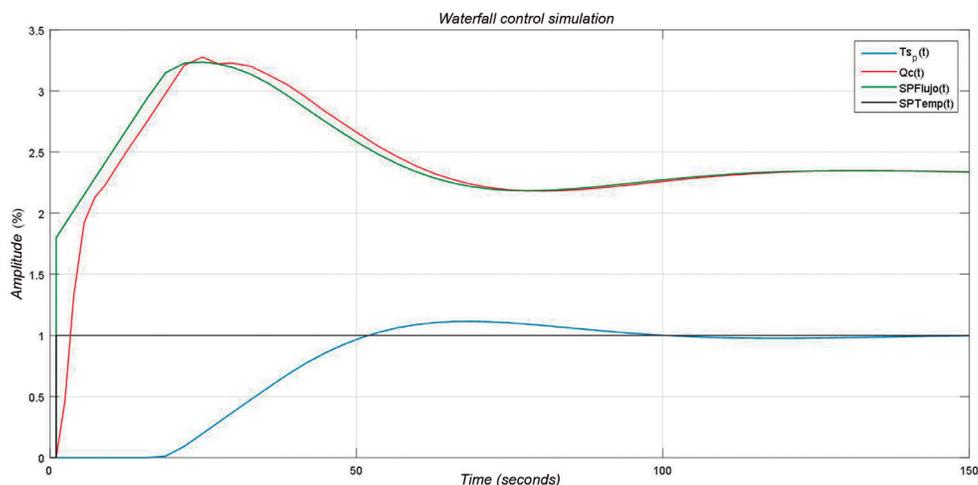


Figure 15. Cascade control loop response Flow - Temperature in Simulation
Source: the authors

Results

As a result of the research, the implementation of the temperature-flow cascade control strategy was carried out in the PIT000. The implementation involved the revision and adjustment of instruments, programming of the PLC, commissioning of the process in automatic mode, parameterization of the control loops with the obtained values and development of tests in the process in automatic mode.

In the development of tests on the implemented system, a Matlab script was established the signal SP either for flow or for temperature, according to the test performed. The data was captured through the platform and the behavior of the variables of interest was graphed. First, the flow loop was verified. The response of the flow control loop is shown in Figure 16, in which the ability of the controller to track the change of SP_F was displayed.

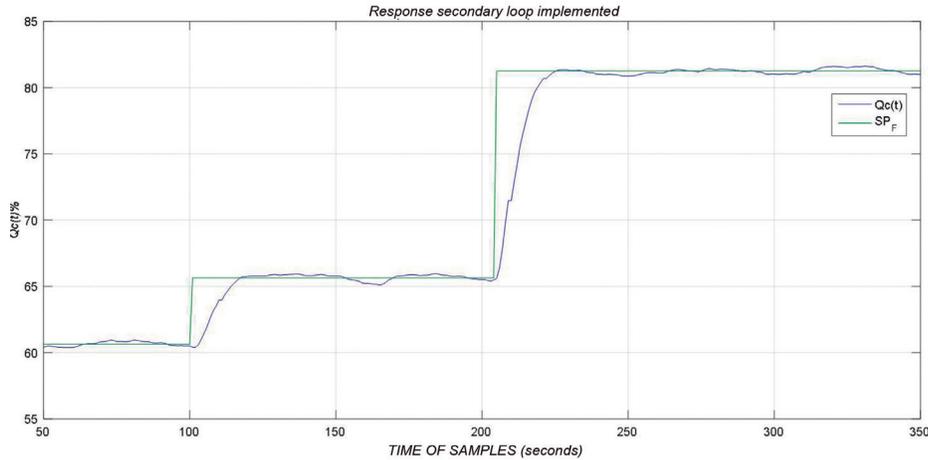


Figure 16. Test of the secondary fluid energy flow control loop
Source: the authors

The behavior of the temperature-flow cascade control loop implemented in the PIT000 is then verified. The answer is shown in Figure 17. It can be seen that the signal Tsp(t) shows a small overshoot and a good response speed, confirming that the simulation and the tuning parameters fulfill the expectations in the response of the system. The results achieved in the project validate the hypothesis,

because they show that the design and implementation of the cascade control strategy in a semi-industrial thermal exchange plant are successful. In this regard, the discussion raised by the authors is that at the academic and research level, design and implementation challenges must be addressed in industrial processes, which, in our case, is what encourages us.

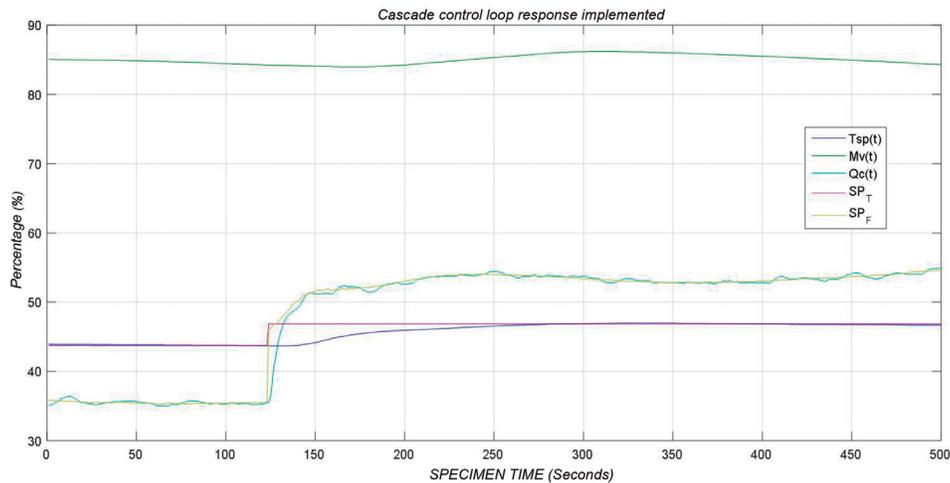


Figure 17. Cascade control loop signals Temperature - Flow
Source: the authors

Conclusions

The methodology studied and applied in the development of the research leads to satisfactory results, represented in the good performance of the control strategy, for which its relevance for the solution of problems in the companies is recognized, considering that the PIT000 plant is of industrial character due to its size and its technological endowment.

The Matlab and its applications were a fundamental tool in this work. Simulink for the simulation and comparison of controllers, Ident for identification of mathematical models through transfer functions, PID Tuner to obtain the tuning parameters of the controllers, and the OPC Tool for capturing PLC data. It is practically a tool that provides the means to solve a real control problem and that can be perfectly applied in the industry.

In the simulation, it can be observed that the closed-loop response speed has improved for both controllers in relation to the response of the open-loop systems. In the same way in both control loops, the tracking capacity of the slogans is shown, almost zero steady state error and small overshoot percentages.

The curves obtained from the implementation present general characteristics very similar to those obtained in simulation. The above shows that the proposed methodology for the design of the control loop is very practical, it can be developed in a short time and good results are obtained, with respect to the theoretical methods based on gray process models and parameter calculations through methods theoretical quantitative.

The benefits of the technology used in the implementation of the control system represent a key factor in obtaining the results and a necessary reference for its adaptation on an industrial scale.

The results obtained in the research constitute a methodological and experimental contribution of reference, to be adapted by companies that need to improve the regulation of their processes in general.

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