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DESIGN OF A PID CONTROLLER TO REGULATE THE HOT WATER TEMPERATURE OF A HEAT PUMP OPERATING WITH CO_2 AND A SOLAR EVAPORATOR

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Abstract. *Recently, the interest of industries and the scientific community for natural fluids as a substitute for the traditional CFCs and HCFCs has been increased. The CO_2 has shown itself as one of the most promising alternatives, especially in heat pumps for the heating of residential water, due to its high efficiency and reduced size of the systems that operate with this fluid. The utilization of CO_2 as a refrigerant combined with solar assisted evaporators is a strategy that is being used to increase the COP of heat pump systems. A solar evaporator, however, will not behave predictably due to the fact that the water coming out of it will change its temperature as a result of the natural variation of the available energy from the sun. That being said, this paper presents the study and the project of a control algorithm for the water outlet temperature of the heat pump. A PID (Proportional-Integral-Derivative) controller was developed and tuned using methods described in the literature. The developed controller was evaluated through computational simulations in order to determine its robustness, disturb rejection, stabilization time and error in a steady state. Using different performance rates, the best tuning method was determined as being the ITAE - servo method. The controller tuned by this method turned out to be the best as to control the outlet temperature of the water, with a steady state error of $3.6 \cdot 10^{-4}$ °C and a settling time of 225 s.*

Keywords: *Heat pump, control system, water temperature.*

1. INTRODUCTION

Brazil is one of the countries with the biggest hydroelectric potential in the world. The energy obtained from such source, however, may not be enough especially during periods of drought. In October 2012, nearly all of the thermal power stations in Brazil were activated on full load due to the low levels on the reservoirs, leading to an emission of millions of tons of CO_2 and an increase in the electricity fees paid by consumers. This shows that the Brazilian economic development, in the long run, depends on diversifying its energy matrix and finding short-term solutions for consuming less energy or improving the processes used to generate it.

One of the singularities in Brazil's energy consumption is the high share of energy spent on domestic water heating. According to the data from the EPE [Empresa de Pesquisa Energética – *Energy Research Company*] report (EPE, 2012), 73 out of each 100 Brazilian houses had at least one electric shower as of 2011.

Due to the Brazilian domestic energy consumption characteristics, the study of alternative solutions for heating water in a more efficient way that may contribute to the reduction of domestic energy consumption is justified. One of the most promising alternatives for that is using a heat pump as a substitute to the electric shower.

As the name itself says, a heat pump is a device that transfers heat (thermal energy) from a source at a low temperature to another at a higher temperature. The high temperature source is represented by the hot water and the low temperature is, usually, ambient air. The ambient that surrounds us represents a huge energy reservoir, which is at the same time our energetic referential. In order to reach any condition above or below ambient temperature, work must be applied. With the intent of using the energy available in the ambient, the heat pump transfers this energy to the water, through a vapor-compression cycle. This vapor-compression cycle usually presents a Coefficient of Performance (COP) greater than 3 (KONG (2011), STARKE (2013)), which means that, for each unit of energy spent on the system, the water will receive 3 units of energy in the form of heat. In the best-case scenario, the COP for an electric shower is 1.

In order to further improve the efficiency of the heat pumps, some researchers have been using a solar evaporator on their heat pumps in order to use solar energy and, with that, make them even more power efficient. The utilization of such system makes the efficiency of the heat pump dependent on the climatic conditions on the region it is installed. This way, water might get too hot for bathing when there are no clouds in the sky and it might not reach the desired temperature in a cloudy day.

2. PROTOTYPE DESCRIPTION

The heat pump used in this study was designed to heat water to temperatures suited for bathing and to work with a transcritical cycle with CO_2 as its refrigerant. Fig. 1 presents a photograph of the heat pump used in this study. Construction details regarding this heat pump can be found in Faria (2013), Oliveira, (2013) and Castilla Alvarez (2015):

Figure 1. Heat pump used in this study.

The heat pump is basically made of an evaporator, a gas cooler and a hermetic compressor. The evaporator is made of a copper tube with a diameter of 6 mm and a length of 16.3 m, shaped as a coil on top of an aluminum plate with an area of 1.57 m². The gas cooler is made of a countercurrent concentric tube heat exchanger coiled in the outer part of the water reservoir, which has a capacity of 0.27 m^3. The tube in which the CO_2 flows is a copper tube with an internal diameter of 6 mm and an external diameter of 7.58 mm. Water flows in the countercurrent through the annular section, and the outer tube has an internal diameter of 12 mm and an external diameter of 12.70 mm. The total length of the tubing is 24.3 m. The compressor used in the heat pump is a hermetic compressor, with a low power and high starting torque made by EMBRACO (model EK6210CD), designed to work exclusively with CO_2 as its fluid. The expansion valve is a needle valve with a diameter of 1.6 mm, model SS-31RS4 made by SWAGELOK. The control of the refrigerant flow is done manually. A manual needle valve is used for controlling the flow of water entering the system. An electromagnetic flow measurer from INCONTROL, model VMS PRO, is used for determining the water flow.

The heat pump has 7 thermocouples of the T type (copper-constantan), with a diameter of 1.5 mm and a 10 cm long sheath, from manufacturer ECIL. The thermocouples were obtained along with a calibration certificate and installed in the inlet and outlet of each component of the heat pump, as depicted in Fig. 2.

In the prototype there are also two solar radiation sensors. One of them is responsible for measuring the incident radiation on the evaporator plane, which has an inclination of 30º from the horizontal, and the other one measures it in the horizontal plane. These sensors are manufactured by BLACK & WHITE PYRANOMETER, model 8-48.

All of the data generated by the different sensors here presented are received and treated by a data acquisition system. This system is made of basically a module for the conditioning of signals from the thermocouples, the flow measurer and the radiation sensors. For the thermocouples an acquisition board of the model USB-9162 (24 bits) is used; for the water flow and solar radiation, a USB-6211 model board is used, both manufactured by National Instruments and installed on a PC computer. The LabVIEW® software was used in order to process the collected data.

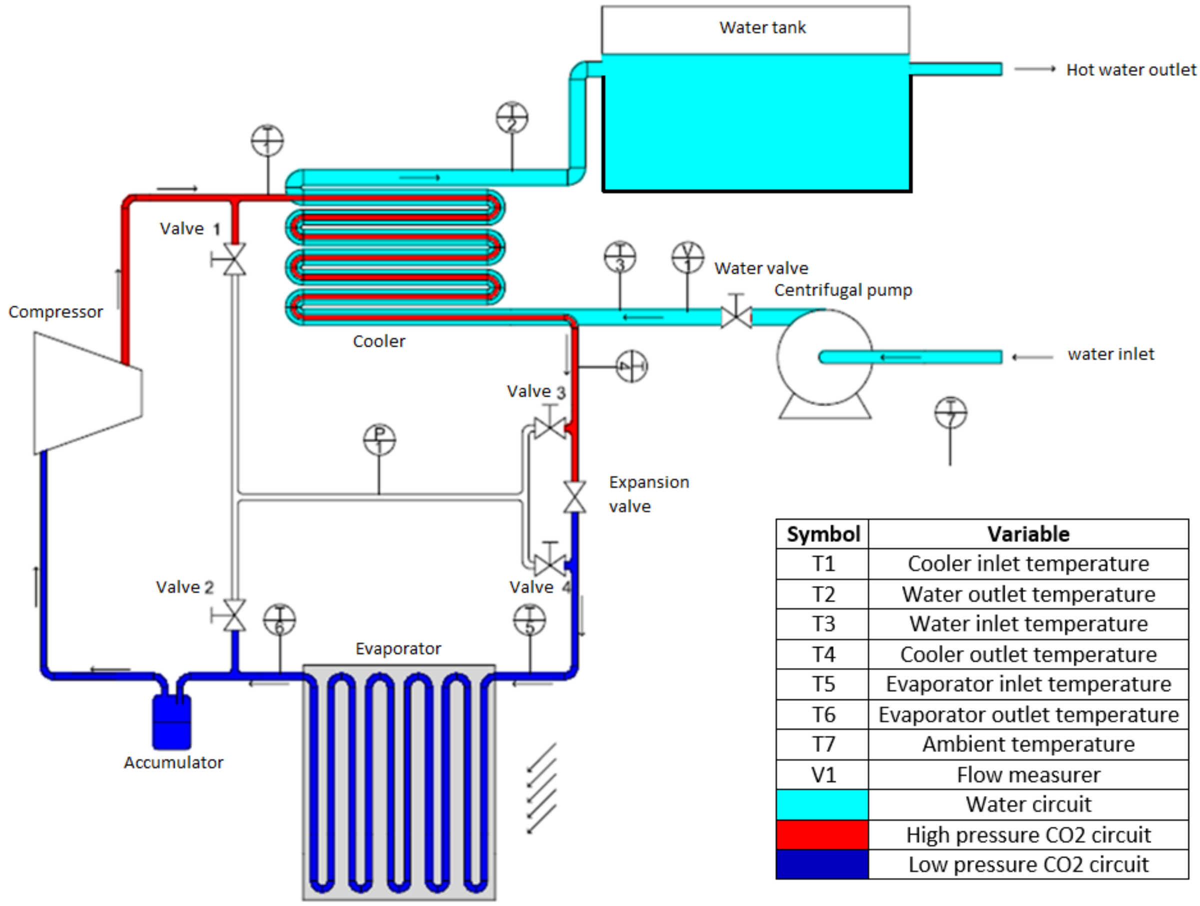

Figure 2. Schematic drawing of the heat pump.

The transfer function that represents the dynamic behavior of the water temperature as a function of the water flow entering the heat pump system, when it is working with the income of solar energy in its solar evaporator, has already been identified in a previous study (Castilla Alvarez, 2015). This system was developed as a first order system plus dead time (FOPDT), as seen on (Eq. 1), with its constants depicted in Table. 1.

$$G_{(s)} = \frac{K_p}{\tau\, s+1} e^{-\theta\, s} \tag{1}$$

Table 1. System identification results

K_p	τ	θ
7,6403	196,5600	111,4080

3. METHODOLOGY

In this study, the temperature of the water exiting the system was controlled with the implementation of a parallel PID controller responsible for defining the magnitude of the changes in the water flow entering the cooler. The transfer function for this controller can be seen on (Eq. 2).

$$G_c(s) = K_c\left(1 + \frac{1}{\tau_I s} + \tau_D s\right) \tag{2}$$

In which K_c represents the proportional constant, τ_I the integrative constant and τ_D the derivative constant. Relations extracted from the literature were used in order to determine these parameters. Among the methods suggested to this day, the most used ones are the ones that present adjustment rules based on an approximate model of the process, usually represented by a first order plus dead time transfer function. These methods are known as methods that are based on K_p, τ and θ. The first order plus dead time transfer function is simple enough and provides a satisfying quality in the approximation of real systems that behave as first order systems. Because of that, this class of methods have been specially developed for the tuning of PID controllers with a gain K_p, a dead time of θ and a time constant τ. With the intent of tuning the controller in the best way possible, seven (7) tuning methods were extracted from the literature. They are presented in Table 2.

Table 2. Tuning rules for parallel PID controllers

Method	K_c	τ_I	τ_D
Ziegler & Nichols (1942)	$\frac{1,2}{K_p} \cdot \frac{\tau}{\theta}$	$2 \cdot \theta$	$0,5 \cdot \theta$
Chien, Hrones & Reswick– 0% (1952)	$\frac{0,6}{K_p} \cdot \frac{\tau}{\theta}$	τ	$0,5 \cdot \theta$
Chien, Hrones & Reswick– 20%(1952)	$\frac{0,95}{K_p} \cdot \frac{\tau}{\theta}$	$1,357 \cdot \tau$	$0,474 \cdot \theta$
Cohen & Coon (1953)	$\frac{1}{K_p} \cdot \left(0,25 + 1,35 \cdot \frac{\tau}{\theta}\right)$	$\theta \cdot \left(\frac{1,35 + 0,25 \cdot \frac{\theta}{\tau}}{0,54 + 0,33 \cdot \frac{\theta}{\tau}}\right)$	$\frac{0,5 \cdot \theta}{1,35 + 0,25 \cdot \frac{\theta}{\tau}}$
ITAE – servo Lopez *et al.* (1969)	$\frac{0,965}{K_p} \cdot \left(\frac{\tau}{\theta}\right)^{0,85}$	$\frac{\tau}{0,796 - 0,1465 \cdot \frac{\theta}{\tau}}$	$0,308 \cdot \tau \cdot \left(\frac{\theta}{\tau}\right)^{0,929}$
ITAE – regulatory Lopez *et al.* (1969)	$\frac{1,357}{K_p} \cdot \left(\frac{\tau}{\theta}\right)^{0,947}$	$\frac{\tau}{0,842} \cdot \left(\frac{\theta}{\tau}\right)^{0,738}$	$0,381 \cdot \tau \cdot \left(\frac{\theta}{\tau}\right)^{0,995}$
IMC Garcia and Morari (1982)	$\frac{2 \cdot \tau + \theta}{2,6 \cdot K_p \cdot \theta}$	$\tau + \frac{\theta}{2}$	$\frac{\tau \cdot \theta}{2 \cdot \tau + \theta}$

Due to the existence of several controller parameterizations and of a great number of methods for tuning such parameters, it is important to define means of quantifying the quality of the dynamic behavior of the control system's performance. It is highly desirable that the controller behaves such as, when the system is operating, it responds with values within the expected range for such quality parameters. Restrictions for the manipulated variable, however, cannot be violated, and it is also necessary that the structure of the controller available for the control system be respected. According to Cordero (2004), the quality parameters must be reliable for a given class of systems, easy to be applied and at the same time selective, so that the resultant system is clearly a good one. In order to evaluate the quality of the response produced by the designed controllers, the Steady State Error (Eq. 3), the Integral of the Absolute Error (IAE) (Eq. 4), the Integral of the Time-weighted Absolute Error (ITAE) (Eq. 5), the Root Mean Square of the Control Effort (RMSU) (Eq. 6), besides other classic parameters such as the Settling Time (5%) (t_S), the Rise Time (t_R) and the Maximum Deviation (MD) were calculated. (Maia et al., 2014; Ogata et al., 2003)

$$e_\infty = y_0 - y_{sp} \tag{3}$$

$$IAE = \int_0^\infty \left|e_{(t)}\right| dt \tag{4}$$

$$ITAE = \int_0^\infty t \cdot \left|e_{(t)}\right| dt \tag{5}$$

$$RMSU = \sqrt{\frac{\sum_{i=1}^{n}(a_i - a_{i-1})^2}{n}} \tag{6}$$

4. RESULTS

The transfer function parameters for a PID controller can be calculated with the help of the constants suggested by the authors presented in Table. 2. These calculations are done by a programmed routine in the software Matlab®, which calculates the controller constants from the FOPDT transfer function (Eq. 1) based on the constants in Table 1. The values calculated for these parameters are presented in Table 3.

Table 3. Parameters for the PID controller calculated from the identified system

Method	K_c	$K_I = K_c/\tau_I$	$K_D = K_c \cdot \tau_D$
Ziegler & Nichols (1942)	0,2771	0,0012	15,4360
Chien, Hrones & Reswick– 0% (1952)	0,1386	$7{,}04 \times 10^{-4}$	7,7180
Chien, Hrones & Reswick– 20%(1952)	0,2194	$5{,}19 \times 10^{-4}$	7,3167
Cohen & Coon (1953)	0,1316	$5{,}85 \times 10^{-4}$	4,8345
ITAE – servo Lopez *et al.* (1969)	0,2046	$7{,}42 \times 10^{-4}$	7,3111
ITAE – regulatory Lopez *et al.* (1969)	0,3041	0,0020	12,9436
IMC Garcia and Morari (1982)	0,2280	$9{,}03 \times 10^{-4}$	9,8949

In order to evaluate each of the calculated control systems, a simulation diagram in closed loop was created with the help of the Simulink® software as indicated by Fig. 3. The performance of the controllers was tested for changes in the set-point going from 43 °C to 40 °C when 1000 seconds had passed (to ensure the system had reached equilibrium) and also for when a disturbance of 0.5 L/min in the water flow is applied to the controller exit at 2500 seconds. At the controller's exit, a saturator block was added in order to limit its action and make it closer to the real values for the water flow in the prototype. For these simulations, the saturator's lowest limit was set to zero and its maximum limit was set to 4 L/min. Since the sensor's dynamic is much faster than the plant's dynamic, the transfer function for the sensor was considered as being an unitary gain in the simulations.

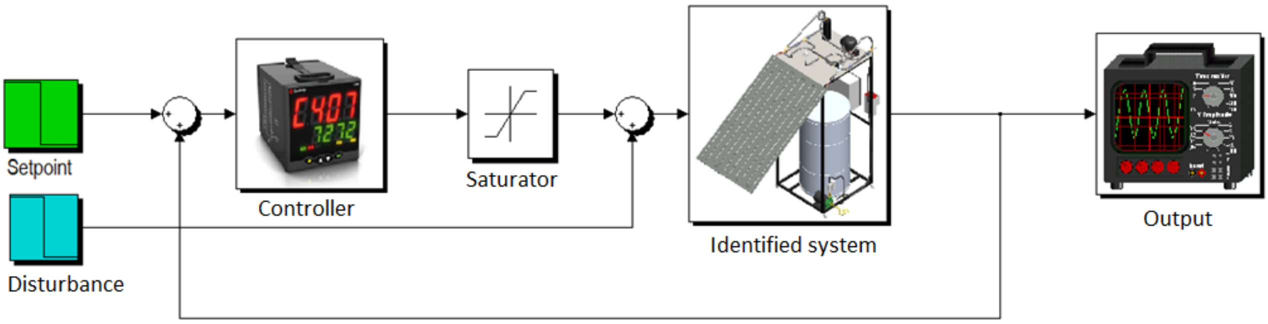

Figure 3. Implemented control loop for testing the controllers

Figure 4 presents the identified plant's response for an evaporation temperature of 13.12 °C for each of the designed controllers. This graph presents the predicted behavior for the water outlet temperature using the different controllers. The controllers tuned by the Ziegler & Nichols and the ITAE – regulatory method presented the most variable responses and were the ones with the greatest peak overshoots. All seven controllers, however, managed to stabilize and keep the water temperature at the desired levels.

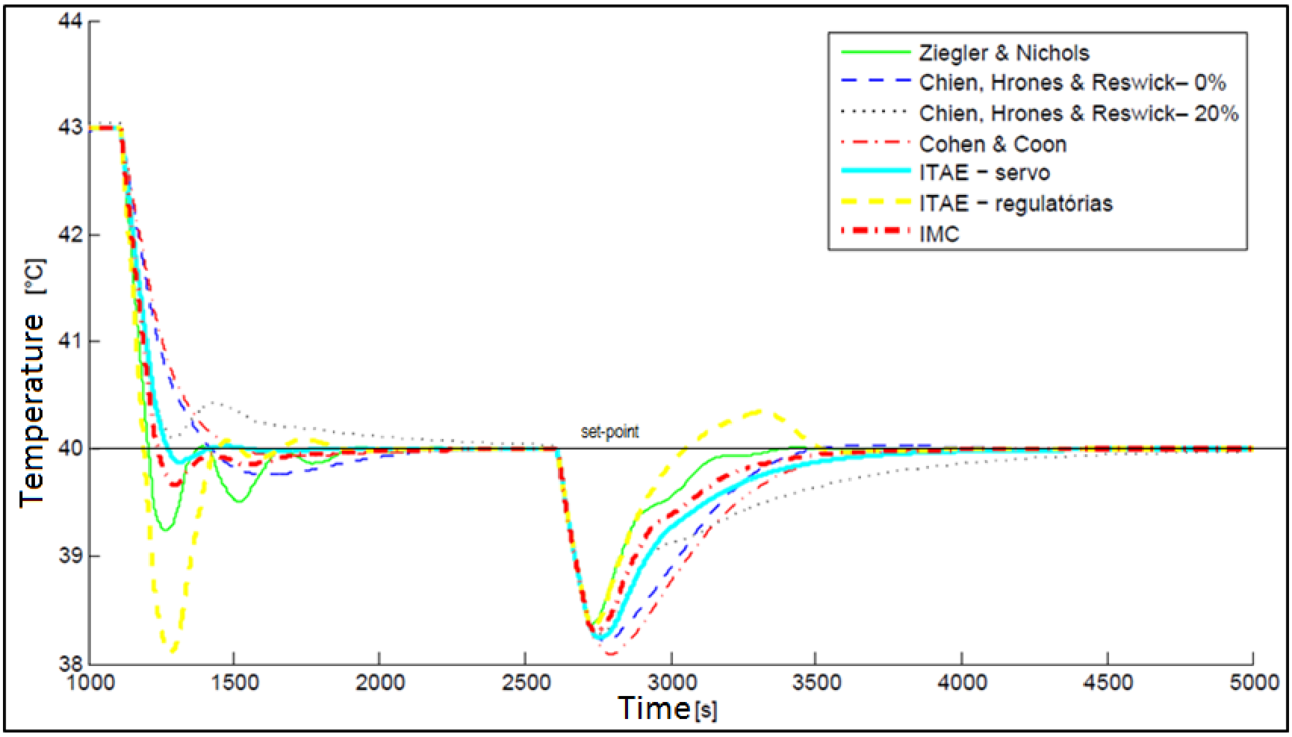

Figure 4. Plant's temperature response for a set-point change and, later, a disturbance in the control signal

Figure 4 shows how the fastest controllers are also the ones that present the biggest overshoot (Ziegler & Nichols, ITAE – regulatory and IMC), while the controllers that present slower responses are also the most stable ones (Chien, Hrones & Reswick– 0%, Chien, Hrones & Reswick– 20% and Cohen & Coon).

Figure 5 shows the behavior of the control signal generated by the different controllers in order to keep the system within the boundaries set by the set-point.

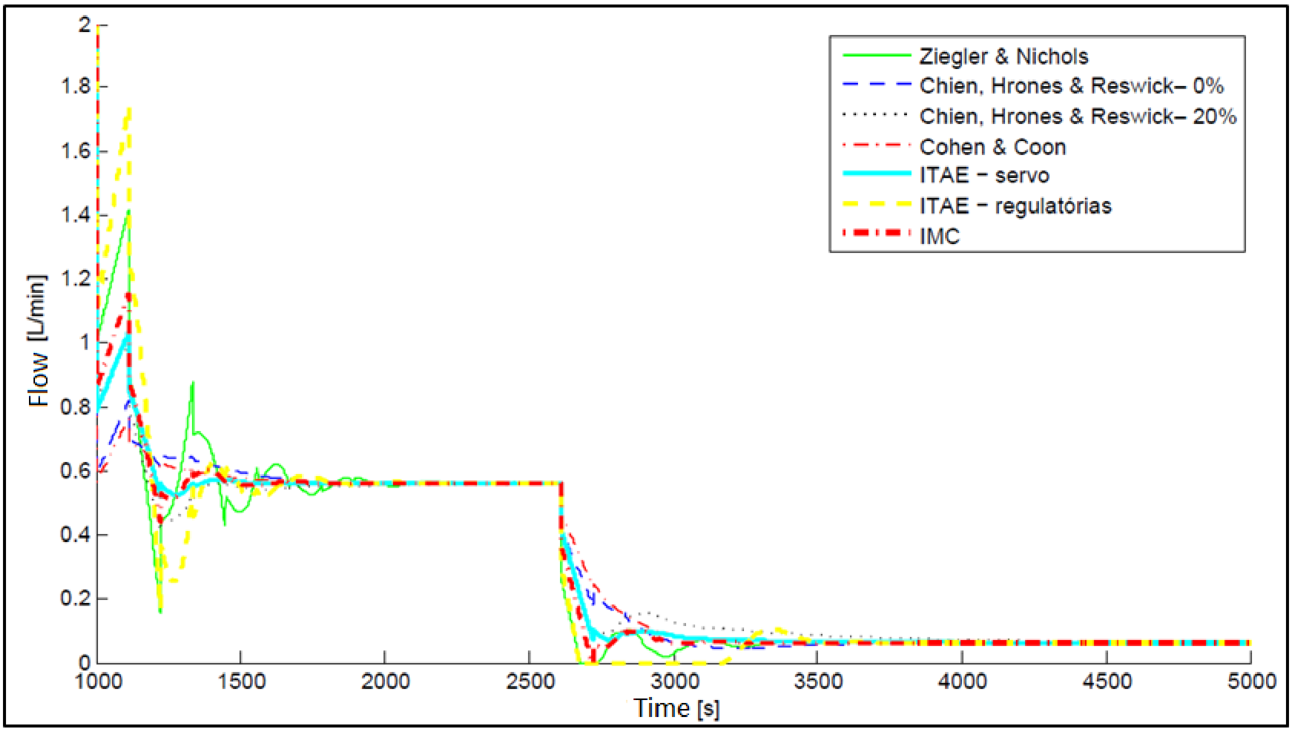

Figure 5. Generated control signal in response of a set-point change and, later, a disturbance in the control signal

It is possible to notice, in Figure 4, an irregular behavior in the water flow after the disturbance caused at t=2500 s for the systems tuned by the Ziegler & Nichols and the ITAE – regulatory methods. This irregular shape is due to the action of the saturator, which prevents the signal from assuming values lower than zero.

The parameters evaluated in order to determine the best controller were calculated and presented in Tab. 4. This table summarizes the data obtained through the use of a routine written on Matlab® that was based on the behavior of each of the tested controllers in the control system depicted in Fig 4.

Table 4. Quality parameters for each of the methods when the set-point is changed

Method	**e∞**	**IAE**	**ITAE**	t_S	t_R	**MD**	**RMSU**
Ziegler & Nichols	$-3{,}9\text{x}10^{-3}$	643,4	$1{,}1\text{x}10^{5}$	313	77	1,9	19,85
Chien, Hrones & Reswick– 0%	$-5{,}6\ \text{x}10^{-3}$	765,0	$1{,}6\text{x}10^{5}$	304	215	0,6	20,53
Chien, Hrones & Reswick– 20%	$46{,}2\ \text{x}10^{-3}$	758,8	$2{,}0\text{x}10^{5}$	227	221	0	20,12
Cohen & Coon	$2{,}6\ \text{x}10^{-3}$	728,1	$1{,}2\text{x}10^{5}$	325	241	0,15	20,56
ITAE - servo	$3{,}6\ \text{x}10^{-4}$	556,2	$5{,}9\text{x}10^{4}$	225	116	0,3	20,19
ITAE - regulatory	$-5.2\text{x}10^{-6}$	750,2	$1{,}3\text{x}10^{5}$	389	65	4,7	19,69
IMC	$1{,}4\ \text{x}10^{-3}$	588,4	$8{,}6\text{x}10^{4}$	211	96	0,8	20,07

5. CONCLUSIONS

According to Fig. 4, Fig. 5 and Tab. 4, the controller that presented the best response for the heat pump system when changes were made to its set-point was the controller tuned according to the ITAE – servo method. It presents the best characteristics when changes are made to the set-point, and those are going to be the most frequently made changes. One of the most important contributions of this study was showing that it is possible to control the water outlet temperature in the heat pump by controlling the water flow. This control will increase the efficiency of the system as well as bring more comfort to the user, since it allows for the heating of water to bathing temperatures under different climatic conditions. After analyzing the quality parameters for each of the seven studied controllers it is possible to state that, for this system, when the set-point temperature is changed, the controlling method, from best to worse, can be listed like this: ITAE – servo, IMC, Ziegler & Nichols, ITAE – regulatory, Cohen & Coon, Chien, Hrones & Reswick– 20% and, lastly, Chien, Hrones & Reswick– 0%. At first sight, comparing the RMSU parameter with the graphic depicting the generated control signal (Fig. 5), it may seem like there’s a contradiction, but the explanation is that, during the first seconds following the disturbance, the systems tuned by the Ziegler & Nichols and the ITAE – regulatory methods (which in Fig. 4 are clearly oscillatory and in Tab. 4 present a lower RMSU) generate a small response (in magnitude) when compared to the controllers tuned by the other methods. Since the RMSU parameter emphasizes big errors (in magnitude) instead of small, constant errors over time, those two methods ended up having a lower RMSU parameter than the others. The implementation of the controllers made it possible to reduce the settling time of the system. This fact can be seen when you compare the results of the tests presented in Castilla Alvarez (2015), where it would take approximately 1000 seconds to lower 3 °C in the temperature. With the system controlled by a controller tuned according to the ITAE – servo method, it is possible to reduce this time to approximately 166 seconds, as can be seen on Fig. 4. Also, when the prototype heat pump is working under constant climatic conditions, the refrigeration cycle’s temperatures are not significantly affected by the step variations made in the water flow entering the gas cooler.

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7. RESPONSIBILITY NOTICE

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