23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

COMPARATIVE STUDY OF PID CONTROL TUNING RULES APPLIED TO A SMALL CHAMBER REFRIGERATED BY A THERMOELECTRIC DEVICE

Fernando Augusto Araujo Pinto
Euler Assunção Costa Fonseca
Universidade Federal de Minas Gerais, Avenida Presidente Antônio Carlos 6627, Pampulha, Belo Horizonte
nando471@gmail.com
euler-costa@hotmail.com

André Romero Martins
Universidade Federal de Minas Gerais, Avenida Presidente Antônio Carlos 6627, Pampulha, Belo Horizonte
a.rmartins@hotmail.com

Ricardo Nicolau Nassar Koury
Universidade Federal de Minas Gerais, Avenida Presidente Antônio Carlos 6627, Pampulha, Belo Horizonte
koury@ufmg.br

Antônio Augusto Torres Maia
Universidade Federal de Minas Gerais, Avenida Presidente Antônio Carlos 6627, Pampulha, Belo Horizonte
aamaia@ufmg.br

Abstract. *Thermoelectric devices have been used in the refrigeration of small chambers in substitution of vapor compression refrigeration systems. One of the advantages of these systems is the direct conversion of electrical energy into heat, which facilitates the temperature control of refrigerating systems based on these devices. In this work is presented the study of the dynamic behavior of a small chamber refrigerated by a thermoelectric device. The system transfer function was identified and validated employing experimental data. This dynamic model was employed in the PID controller design. The controller tuning was performed using relations obtained from works developed by other researchers. Experimental tests were executed to evaluate the controller performance considering each tuning rule. Then, the results obtained for each method were evaluated regarding to peak time, maximum overshoot, settling time, steady state error, disturbance rejection and robustness. In conclusion, the method with the best settling time, rising time and settling time was the IMC by Skogestad. However, the method by Ziegler-Nichols presented a similar RMSE to it and the method by Vilanova presented the best RMSU.*

Keywords: *Thermoelectric devices, PID control, Tuning rule.*

1. INTRODUCTION

The necessity of creating a smaller version of every device is increasing every year. It is possible to see that the cellphone market, computational, microelectronic market and refrigeration devices market are claiming for upgrades for their products, always aiming the same functionality but easier to store and less boisterous. For example, the demand for smaller refrigeration systems is increasing because there is the necessity of creating products, as drinking fountains and small coolers that requires functionalities that the conventional vapor compression refrigeration system do not have, some of those functionalities are the small size and the silently operation.

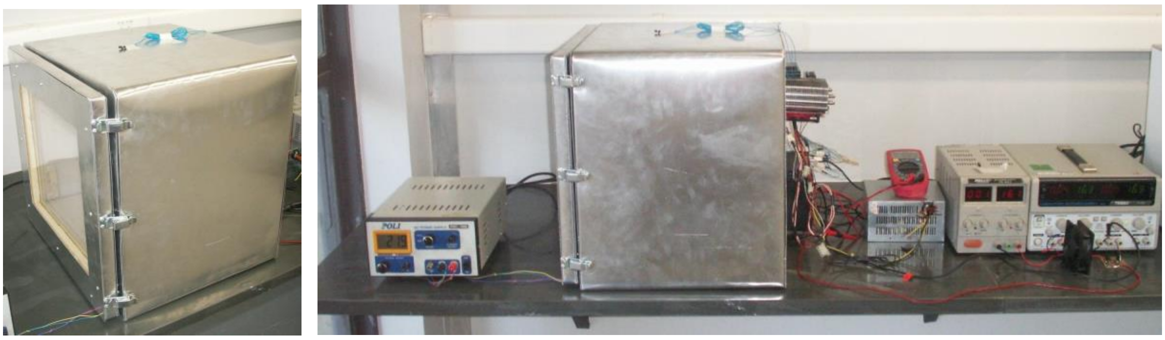
The vapor compression refrigeration system uses a compressor engine that increases the pressure of the refrigeration fluid during the cycle and it causes noise and vibration in the structure. In addition, the use of this system restricts the work directions and the space needed to implement it. The use of a thermoelectric cooling device appears as a solution for those products which the conventional refrigeration system is not suitable. Based on the Peltier effect, this device is able to convert directly electric energy into heat. In addition, it is small, do not produce noise, do not cause vibration and can be used in any direction.

Although the Peltier effect is not the most effective method to produce cold, this direct conversion of electric energy into heat makes the thermoelectric device easier to be controlled and makes it practicable in situations where the precise control of temperature is required such as coolers to transport organs. Creating an effective temperature control of a thermoelectric device has proven to be a challenge for scientists. The use of a Proportional-Integrative-Derivative (PID) controller has been shown effective because of its simplicity, however the use of this kind of controller requires an effective tuning method.

The PID controller is used in 97% of the industrial control application, because it is simple to implement as an algorithm and its simple structure are based on three parameters (Yu, 2006). However, just 32% of those applications are considered functional or excellent (Desborough & Miller, 2002), because there is not an effective method to tune its parameters accordingly to a specific system. For this reason methods were created to ensure the effectiveness and the simplicity of the PID controller. This paper explores five existing tuning methods for a PID controller applied to a physical system consisted of a thermoelectric device and a chamber. Each technique considered was evaluated through experimental tests and the results obtained were analyzed and compared accordingly to its maximum overshoot, peak time, settling time, steady state error, disturbance rejection and robustness.

2. EXPERIMENTAL APPARATUS

The chamber was projected aiming its portability, so it is big enough to be used as a small cellar and it still portable. The chamber (Fig. 1a and Fig. 1b) consists of four identically designed walls on the top, on the bottom and on the sides. The back and the front wall were modified to put the thermoelectric device and the control system. All the walls were made with an aluminum plate, polyurethane foam and a plate of nylon and the door was constructed with the same materials of the wall but with a window in the middle; this windows was made with a pair of acrylic plate with air in between and just the acrylic window enters in contact with the air inside the chamber.



(a) (b)

Figure 1 a. Frontal view of the chamber. b. Lateral view of the chamber.

The thermoelectric device used in this project was a DV-40-10 with (39.5±0.2)mm by (39.5±0.2)mm by (3.60±0.1)mm, its maximum voltage is 15.4V and its maximum current is 10A. The cold side of the device was turned to refrigerate the chamber. As specified in the datasheet, the heat transfer rate is directly related to the difference between the temperature of the hot and the cold side, so two heat exchangers with fan were installed on each side of the thermoelectric device to promote the heat conduction from hot side to the ambient and to ensure the homogeneity of the temperature inside the chamber.

The control system used during the experimentation was designed based on the CMOS FLASH-based-8bit microcontroller PIC16F877A and the temperature data acquisition was made using four calibrated LM335 temperature sensor. This microcontroller was chosen because it features 10 channels of 10-bits analogic-to-digital converter, two PWM functions, a Universal Asynchronous Receiver Transmitter (USART) and 256-bytes of EEPROM data memory. Those temperature sensors were chosen because they feature a 1ºC of initial precision, they operate from 400 µA to 5 mA and they are easily calibrated. The ambient temperature was measured with a LM335 outside the chamber and the inside temperature was measured with three LM335 inside the chamber.

The whole system was powered by a 15V DC source. The fans were connected directly to the source and the voltage sent to the thermoelectric device was regulated by the microcontroller PWM. The control system has a three-terminal voltage regulator 7805 implemented to turn the voltage given by the source from 15V to 5V.

3. METHODOLOGY

Several tests were performed varying the ambient temperature and the power given to the thermoelectric device to determine the system transfer function composed by the chamber. Those tests were divided into four sets of constant ambient temperature: 24ºC, 22ºC, 20ºC and 18ºC. For each set of temperature a step-function was defined to control the power given to the thermoelectric device. With this step-function the thermoelectric device would receive 25% of the total power, than the PWM would be increased by 25% until it get to 100% of the total source power. Each step had four hours of duration to guarantee the temperature stabilization. The transfer function chosen to represent the system response is shown in Eq.1.

$$G(s) = \frac{Ke^{-\theta s}}{\tau s+1} \quad (1)$$

The parameter K (system gain) was defined graphically as the difference between the final temperature and the initial temperature divided by the step function. The parameter θ (dead time) was defined graphically as the difference between the start time of the step and the time when the temperature starts to fall. The parameter τ (time constant) was defined recursively by an algorithm. This algorithm consisted in two parts: the first one was responsible for varying the value of τ from 1 to 5,000 and the second part was responsible for calculating the quadratic error between the real curve and the function G(s). To reduce the execution time of the algorithm, it was upgraded so instead of going through all the numbers between 1 and 5,000, this interval would be divided into two segments by an intermediate value. Three transfer functions would be created, the first one with to smallest value of τ, the second one with the intermediate value and the third one with the last value. Then the algorithm would calculate the quadratic error for each set of curves and the one with the biggest error would be deleted. A new interval would be defined between the others values. Recursively a new intermediate point would be defined and new transfer functions would be created and after calculating the quadratic errors another point would be deleted. Again a new interval would be defined and this would run until the interval converges to a single value.

4. THE TUNING METHODS

The Ziegler-Nichols (Ziegler et al., 1942) tuning rule studied was the first method considered. It is one of the most common tuning rules used in industrial control applications. Although this method guarantees a good disturbance rejection, it is not an optimal solution for all applications. The second method was based on the Internal Model Control. There are several version of the IMC tuning rule in the literature and the one utilized in this paper was made by Rivera et al. (1986). In this method the performance coefficient utilized was $\lambda = 0.8\theta$. The third method was the IMC variation made by Skogestad (Skogestad, 2003) and it is an optimization of the traditional IMC method. The fourth method was tuning rule proposed by Sree et al. (2004) and it aims the simplicity of the equations to determine the PID parameters. The last method studied was the IMC tuning rule done by Vilanova (2008). In this method the equations to determine the PID parameters follow two rules, the first one based on the time constant and robustness and the second one based on the constants of the system's transfer function. The second one was used in this paper. The Tab. 1 shows the equations for each method studied to control the temperature of the chamber.

Table 1. PID tuning rules

	PID gain		
Method	Kp	Ti	Td
4.1 Ziegler-Nichols	$\frac{1.2\tau}{K\theta}$	2θ	0.5θ
4.2 IMC by Rivera et al	$\frac{2\tau+\theta}{K(\lambda+\theta)}$	$\tau+\frac{\theta}{2}$	$\frac{2\theta}{2\tau+\theta}$
4.3 IMC by Skogestad	$\frac{2\tau+\theta}{3\theta K}$	The minimum value between $\tau+\frac{\theta}{2}$ or 8θ	$\frac{\tau\theta}{2\tau+\theta}$
4.4 Sree et al	$\frac{\tau/\theta+0.5}{K}$	$\tau+0.5\theta$	$\frac{0.5\theta(\tau+0.1667\theta)}{\tau+0.5\theta}$
4.5 Vilanova	$\frac{Ti}{2.65K\theta}$	$\tau+0.03\theta$	$1.72\theta N$ and $N=\frac{\tau}{Ti}-1$

5. DEFINING THE SYSTEM MODEL

The temperature's behavior inside the chamber during the tests defines the transfer function parameters. The Fig. 2 shows the tests performed with the ambient temperature of 18ºC, 20ºC, 22ºC and 24ºC respectively.

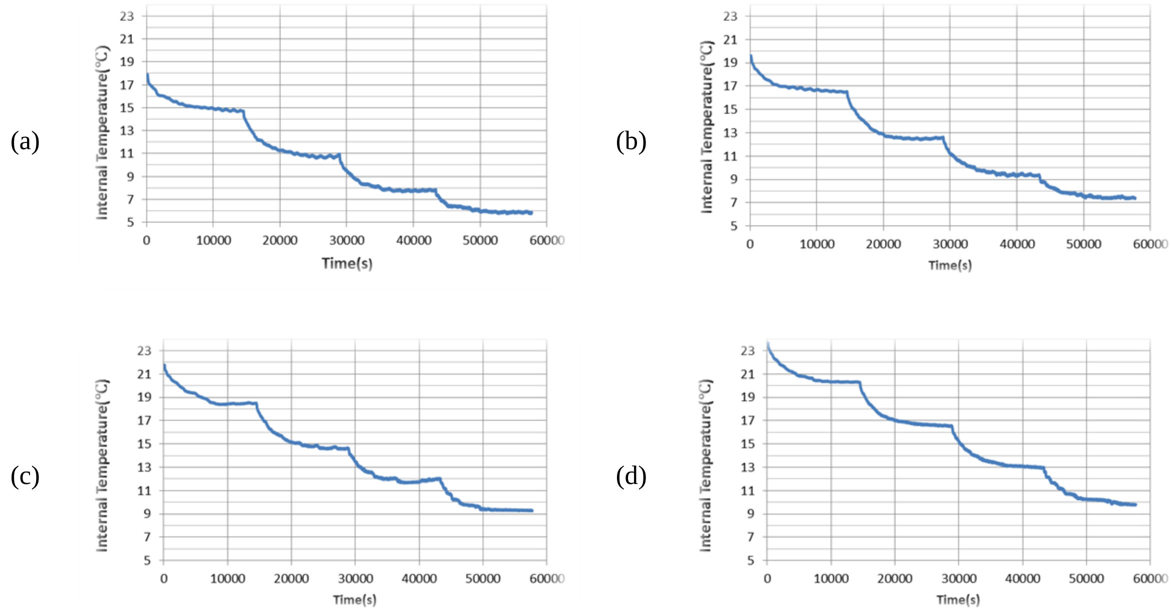


Figure 2. Graphic time versus internal temperature during a test with four steps of 25%, 50%, 75% and 100% of the total power with ambient temperature of a. 18ºC, b. 20ºC, c. 22ºC and d. 24ºC

The Fig. 3 shows the real curve and its mathematical model of G(s) that is written in Eq. 2 for an ambient temperature of 20ºC. The mathematical model G(s) was made using the real curve for the ambient temperature of 20ºC

$$G(s) = \frac{-12.28e^{-30s}}{2306s+1} \tag{2}$$

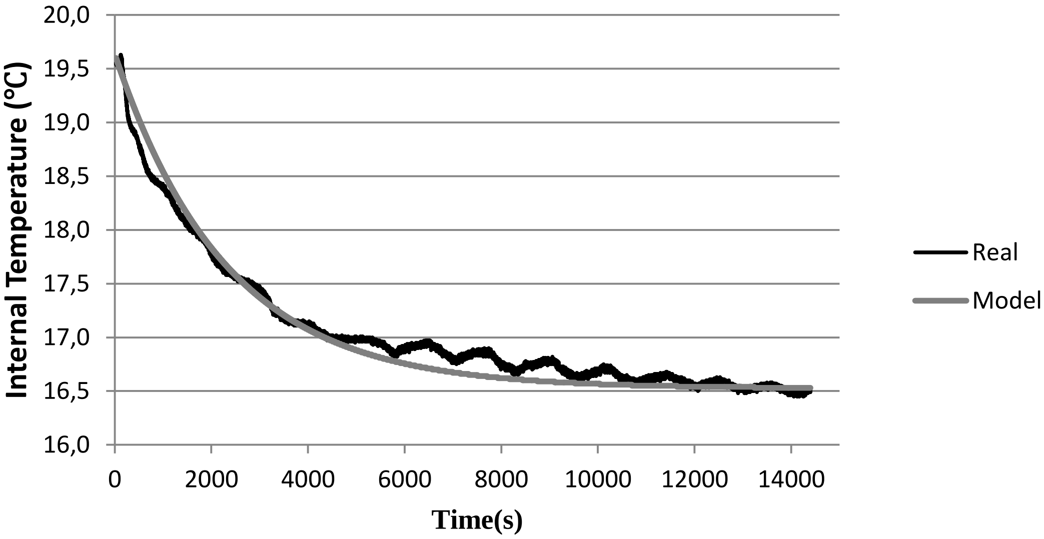


Figure 3. Experimental Results for the tuning Methods

After determining the system transfer function, the PID gains were calculated utilizing the tuning methods mentioned in Tab 1. The Tab. 2 shows the value for the gain Kp, Ki and Kd for each method utilizing the parameters of the transfer function.

Table 2. Values for Kp, Ki and Kd for each tuning method.

	Methods				
PID gain	4.1	4.2	4.3	4.4	4.5
Kp	7.511	4.846	4.200	6.300	2.363
Ki	0.125	0.002	0.017	0.003	0.001
Kd	112.671	72.225	62.595	94.096	0.047

A experimental test was performed with a set point of 17ºC and an ambient temperature of 20ºC for each tuning rule. The system response was evaluated regarding to peak time, maximum overshoot, settling time, steady state error, disturbance rejection and robustness to determine which one controlled better the temperature. The robustness of a tuning method was characterized by the ability of controlling the temperature with the standard model and with a modified model. For each method a new experimentation using a modified model with values of gain increased by 20% were done. So the new experimentation results for each tuning rule is evaluated with the same characteristics mentioned before; to be considered robust, a tuning rule needs to show small variation in its control performance. The Fig. 4 shows the chamber's internal temperature behavior during the experimentation for each tuning method and the Fig. 5 shows the robustness experimentation for each method studied.

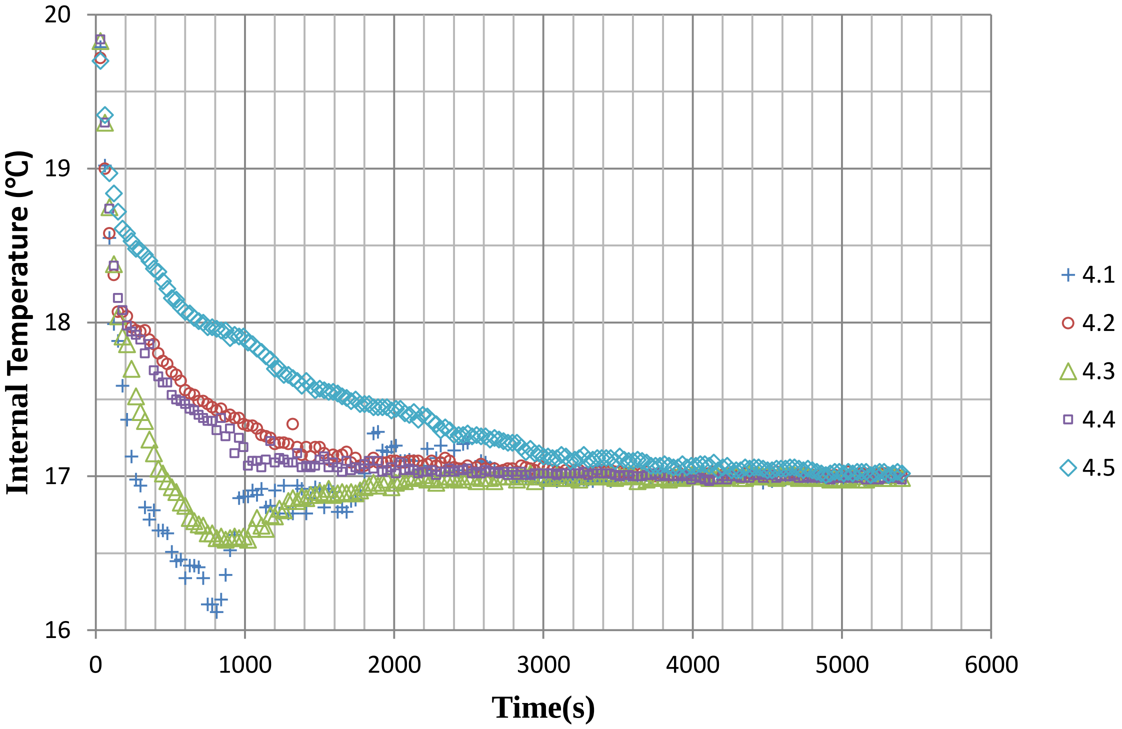


Figure 4. Chamber's internal temperature response using different PID tuning methods.

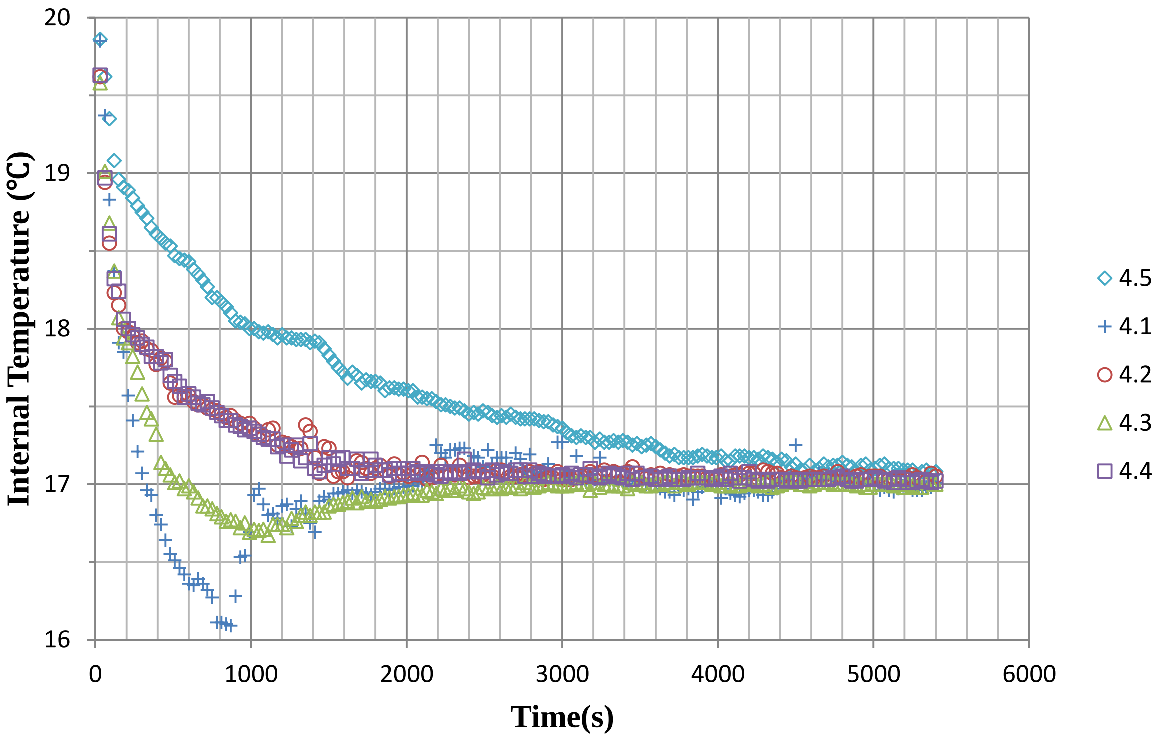


Figure 5. Chamber internal temperature response during robustness experimentation.

The value of the parameters employed in the evaluation of the controller robustness is shown in the Tab. 3. And the comparison between each method is shown in Tab. 4. The Root Mean Square Error (RMSE) and Root Mean Square Control Effort (RMSU) were calculated using the Eq. 3 and Eq. 4 in accordance to Maia (2014).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\Delta T_{S\,i} - \Delta T_{S\,Set})^2}{n}} \tag{3}$$

$$RMSU = \sqrt{\frac{\sum_{i=1}^{n}(\theta_i - \theta_{i-1})^2}{n}} \tag{4}$$

Table 3. Comparison between the standard model and modified model regarding to RMSE and RMSU

	Standard model		Modified model	
Method	RMSE	RMSU	RMSE	RMSU
4.1 Ziegler-Nichols	0.3964	0.0114	0.444	0.0144
4.2 IMC by Rivera et al	0.4445	0.005	0.4353	0.0039
4.3 IMC by Skogestad	0.3968	0.0023	0.3816	0.0001
4.4 Sree et al	0.4307	0.0022	0.4401	0.0012
4.5 Vilanova	0.6764	0	0.8301	0

Each tuning rule was analyzed considering the system response overshoot, rising time, peak time, settling time, RMSE and RMSU in the standard model. The robustness was characterized by the variation in the system response between the standard and the modified model. By analyzing Tab. 4, it is possible to conclude that the method 4.2, 4.4 and 4.5 had no overshoot. However, the method proposed by Ziegler-Nichols had an overshoot of 0.92°C. When analyzing the rising time, the method 4.1 was the best method, with 256s, while the method 4.5 was the worst, with 4882s of rising time. The peak time is considered just for the methods with overshoot and the method with the best result was the Ziegler-Nichols, with 778s before reaching the set point.

Table 4. Comparison between the standard model and modified model

	Standard model				Modified model			
Method	Overshoot	Rising time	Peak time	Settling time	Overshoot	Rising time	Peak time	Settling time
4.1 Ziegler-Nichols	0.92	256	778	2604	0.93	303	794	4520
4.2 IMC by Rivera et al	-	3291	-	2172	-	5573	-	2604
4.3 IMC by Skogestad	0.43	453	919	1434	0.36	513	1073	1717
4.4 Sree et al	-	2457	-	1435	-	4365	-	2371
4.5 Vilanova	-	4882	-	3274	-	7302	-	4460

The settling time defines how fast the system output reaches the set point with a maximum deviation of ∓1%. The method with the faster control was the method proposed by Skogestad (4.3), and the worst method was the method proposed by Vilanova (4.5). The RMSE is a measure of the difference between the temperature and the set point. The method that provides the lowest RMSE is the more efficient the method. With the Tab. 3, it is possible to conclude that the tuning method by Ziegler-Nichols and the IMC by Skogestad had the smallest value of RMSE.

The RMSU is a measure of the control effort. The method that provides the lowest RMSU is the one that requires the lowest effort from the thermoelectric device. The tuning method by Vilanova had the best RMSU from all the methods, followed by the IMC by Rivera.

6. CONCLUSION

This paper compared five tuning methods for a PID controller applied in the temperature control of a chamber cooled by a thermoelectric device. All the methods were evaluated by its overshoot, rising time, peak time, settling time, RMSU and RMSE. Some of the methods studied presented overshoot of 0.93°C and 0.43°C, while the others had no overshoot. The comparison of the methods showed that there is not a method with good performance in all the parameters.

Although the method IMC by Skogestad was one of the methods with the best settling time and rising time performance, the tuning method proposed by Ziegler-Nichols had a similar RMSE. The tuning method presented by Vilanova had a better RMSU performance. In general, all the methods could control the temperature well, but the overall evaluation of a method requires a specification about the real function of the chamber. If its function is to work as a small cellar, the best tuning method is the one with the smallest RMSU, where the small control effort is required. However, if its function is to work as a container for organ transport, for example, it is required a method with a small RMSE, because it is important to have a precise temperature control.

7. REFERENCES

Maia, A. A., Horta-Gutierrez, J. C., Koury, R. N., & Machado, L., 2014, "Superheating Control Using an Adaptive PID Controller", Taylor & Francis Online.

Rivera, D. E., Morari, M., & Skogestad, S., 1986, "Internal Model Control, 4. PID Controller Design", Ind. Eng. Chem. Process Des. Dev., 252-265.

Skogestad, S., 2003, "Simple analytic rules for model reduction and PID controller tuning", Journal of Process Control 13, 291-309.

Sree, R. P., Srinivas, M. N., & Chidambaram, M., 2004, "A simple method of tuning PID controllers for stable and unstable FOPDT sytems", Computers and Chemical Engineering, 28, 2201–2218.

Vilanova, R., 2008, "IMC based Robust PID design: Tuning guidelines and automatic tuning", Journal of Process Control 18, 61-70.

Ziegler, J., & Nichols, N., 1942, "Optimum Settings for Automatic Controllers", Transactions of ASME, 759-768

Ho, W., Hang, C., Cao, L.,1995, "Tuning of PID Controllers Based on Gain and Phase Margin Specification", Automatica, 005-1098

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.