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Design and Implementation of a Digital PID Temperature Controller for Neonatal Incubator ESVIN

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Abstract: The project has as its aim the design and implementation of the control of temperature in the cockpit of the prototype of neonatal life support equipment ESVIN based on the international standard IEC 60601-2-19 concerning the basic security and operation of the neonatal incubators. The prototype has been developed and is important because the cockpit is a new concept of medical equipment of neonatal life support. There was a modeling of the system of heating of the incubator using the concepts of system identification with the purpose of finding a mathematical model that describes the dynamic behavior of the system. Then, design and implement the strategy of feedback control with digital PID (proportional-integral-derivative) algorithm. The model allowed the design and implementation of a digital PID controller that meets in a satisfactory manner with the requirements, in accordance with the international standard. The control system implemented in the neonatal incubator ESVIN improved the effectiveness of the neonatal life support equipment in regard to temperature controller of the cockpit.

Key words: Neonatal incubator, IEC 60601-2-19, digital PID algorithm, temperature controller.

1. Introduction

The group GIDEMS (Grupo de Investigación y Desarrollo de Equipos Médicos y Sistemas) of the Pontifical Catholic University of Peru has developed new concepts relating to support equipment for infants in critical condition. ESVIN is a prototype based on a pending patent, designed to provide the newborn a reliable and secure environment, which requires the variable temperature control; such as established in the studies [1] who noted that the preterm infants of less than 1.5 kg sample had a mortality rate significantly high.

Subsequent studies established the importance of the thermal environment on the survival of the newborn. This work aims to develop a system of temperature control in the cockpit of the ESVIN prototype as shown in Fig. 1, based on the IEC 60601-2-19 [2] concerning the safety and performance of incubators.

To meet the stated objective, it was necessary to get through identification of a mathematical model system of the process of temperature variation in the cockpit, which describes with an appropriate level of accuracy the dynamic behavior of the process and then design and implementation of digital PID (proportional-integral-derivative) control.

The paper is organized as follow: Section 2 is methodology; Section 3 presents the results; and Section 4 gives conclusions.

2. Methodology

The design and development of system considered the control system, the modelling system and the algorithm of control. The control system considered the sensing module, driving module, control module and the plant.

2.1 The Control System

The Sensing Module is a thermistor whose electrical resistance varies as a function of temperature (10,000 ohms is equivalent to 25 °C), with a measuring range of

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0 to 70 °C and accuracy of 0.2 °C.

For control purposes the range was 25 to 43 °C. Therefore, the thermistor could vary its electrical resistance in the range of 10 K to 4.3 K ohms respectively, according to the temperature in the cockpit.

A data acquisition module allows you to translate the electrical signal of the thermistor as the unit of electrical resistance to electrical signal of voltage or electrical voltage in the range of 0 to 10 VDC, to be able to be read by an analog input channel of the data acquisition card.

The actuator module allows you to translate the control signal PWM (pulse width modulation) of 3.3 VDC to 20 mA that comes out of a digital port of the controller to the electrical signal of 220 VAC at 2 A to energize the actuator. The heater is a metal resistor of 370 Watts, used to generate heat in the cockpit. The heat energy delivered to the cockpit is changed by varying the electrical energy is supplied to the heater element.

The control module is a computer embedded (ARM9 model TS-7350) of 200 MHz multi-use, it allows the development of multiple built-in functions through its peripheral interfaces that includes: RAM (random-access memory), Ethernet, USB (universal serial bus), serial port, input and output channels digital and analog. In this handler you implement digital PID control.

The operating system uses Linux-Debian. A data acquisition card (Model TS-ADC16) has 16 analog input channels of 16 bit resolution and able to acquire 100 samples per second. It is used to read the signal from the temperature sensor using one of their analog inputs and convert it to digital signal so that it can be read by the driver.

Plant module is the prototype ESVIN, place of accommodation of the neonate.

2.2 Modeling of the System

Considering that the temperature in the passenger compartment of the prototype ESVIN constitutes the controlled variable (PV) and that the electrical power to the heater represents the MV (manipulated variable), the mathematical model will be the temperature in the cockpit as output variable and to the electrical power to the heater as input variable.

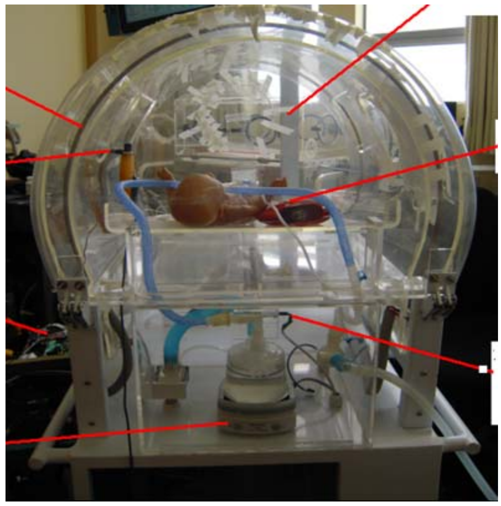

Fig. 1 Prototype of neonatal incubator ESVIN.

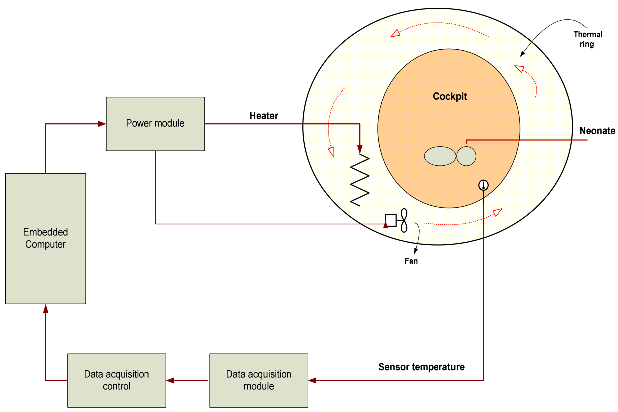

Fig. 2 Control system of temperature ESVIN.

If it is assumed that the system can be modeled as causal system, linear and time invariant, then the model can be expressed as a transfer function [3]. In Fig. 2, there is a conceptual diagram of the system.

Once established, the experimental conditions, you proceeded to carry out the test of static gain, to know the region of operation in which the system can be considered as a linear system. It was determined that for an input signal type step 60% PWM applied to the heater zones there are reasonably linear, which covers the entire range of control. The results of this test are shown in Fig. 3.

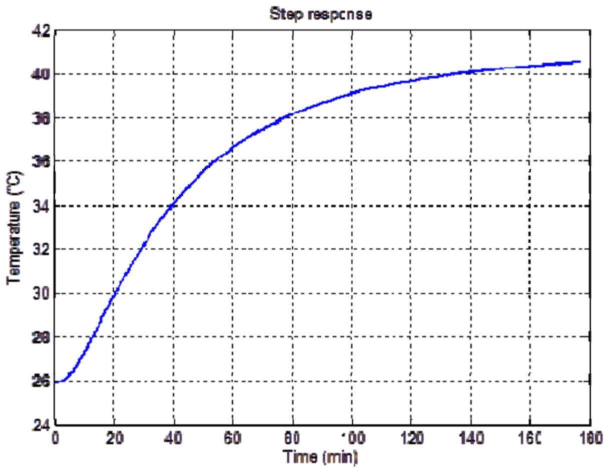

Fig. 3 Step response (60% PWM) heater.

It is noted that with the entrance step in open loop is covered almost all the regions of linear dynamic behavior of the temperature in the cockpit. It can also be seen that the slope more no-shows at the beginning of the response, but the time after; this form of response allows to establish that the response of the system corresponds to a second-order system, critically damped or over damping [4].

Then, the dynamic behavior of the temperature in the cockpit of the prototype ESVIN is represented by the transfer function:

$$G(s) = K\frac{W_n^{\,2}}{S^2 + 2W_n^{\,2}\xi S + W_n^{\,2}} \qquad (1)$$

where: $G(s)$ is a function of transfer, K is gain, W_n is natural frequency and ξ is damping factor. From Fig. 3 and as in Res. [3-5], it is estimated the parameters of the transfer function: K = 24.55, W_n = 0,055 and ξ = 1.3.

By replacing in Eq. (1), the model is obtained.

$$G(s) = 24.55\frac{0.003039}{S^2 + 0.143S + 0.003} \qquad (2)$$

To validate the model obtained [6], it will implement the program in Simulink as shown in Fig. 4.

Plant responses and the model are shown in Fig. 5.

It is noted that both responses are approximated by what it is concluded that the model obtained is representative for the purposes of control.

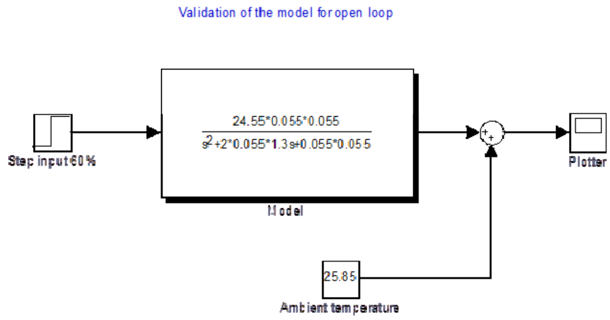

Fig. 4 Diagram of control in Simulink.

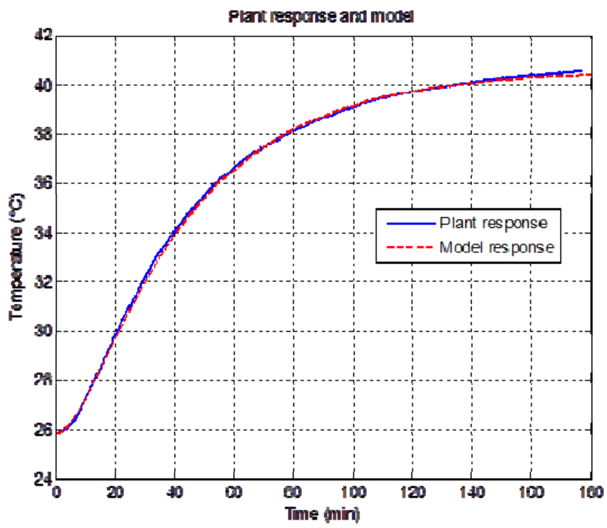

Fig. 5 Response of data observed and modeled.

2.3 PID Control Algorithm

It was designed the digital control strategy on the basis of the obtained model, initially at the level of simulation to get the parameters of the PID (tuning) and subsequently was implemented in the controller.

Design conditions were established according to the international standard IEC 60601-2-19 dealing with the basic safety and operation of the neonatal incubators.

The methodology consists of designing a PID algorithm time continuous and then to obtain the expression in discrete time through evolution. The PID algorithm continuous time series is selected with the variant derived from filtered [7] whose equation as transfer function is shown in Eq. (3).

$$\frac{U(s)}{E(s)} = K_p^{\,2}\left[1 + \frac{1}{T_i S}\right]\left[1 + \frac{T_d S}{\alpha T_d S + 1}\right] \qquad (3)$$

For write Eq. (3) using the method of approximation rectangular as in Refs. [7, 8]:

$$\frac{U(z)}{E(z)} = K_t\left(\frac{z - z_1}{z - 1}\right)\left(\frac{z - z_2}{z - p_1}\right) \quad (4)$$

$$K_t = K_p \frac{(1 + T/T_i)(T_d(\alpha + 1) + T)}{\alpha T_d + T} \quad (5)$$

$$z_1 = \frac{T_i}{T_i + T} \quad (6)$$

$$z_2 = \frac{T_d(\alpha + 1)}{T_d(\alpha + 1) + T} \quad (7)$$

$$p_1 = \frac{\alpha T_d}{\alpha T_d + T} \quad (8)$$

Taking into account the following considerations:

$$K_t = \frac{K}{(1 - z_1)(1 - z_2)} \quad (9)$$

$$p_1 = 0 \quad (10)$$

By replacing Eqs. (9) and (10) in Eq. (4) and re-arranging, you have:

$$\frac{U(z)}{E(z)} = \frac{K}{1 - (z_1 + z_2) + z_1 z_2}\left(\frac{1 - (z_1 + z_2)z^{-1} + z_1 z_2 z^{-2}}{1 - z^{-1}}\right) \quad (11)$$

Eq. (11) represents the transfer function of the PID algorithm (sampled) linear. The digital PID algorithm to be implemented in the controller, such as equation expressed in differences and reordering is obtained from Eq. (11).

$$U(k) = U(k-1) + K_t[E(k) - (z_1 + z_2)E(k-1) + z_1 z_2 E(k-2)] \quad (12)$$

where, K, z_1 and z_2 are the tuning parameters. In Eqs. (5)-(7), you have:

$$K_p = \sqrt{\frac{K_t}{[(T_i + T)/T_i][T_d + T/T]}} \quad (13)$$

$$T_i = \frac{z_1 T}{1 - z_1} \quad (14)$$

$$T_d = \frac{z_2 T}{1 - z_2} \quad (15)$$

Eqs. (14) and (15) provide that the tuning parameters z1 and z2 in discrete time are related to the parameters integrative time (T_i) and derivative time (T_d), respectively in continuous time; also, the values of z_1 and z_2 must be greater than zero but less than unity.

The control system was implemented in Simulink as shown in Fig. 6.

Also Matlab™ allowed the implementation of the PID algorithm discrete from Eq. (11), the model of the plant obtained in Eq. (2) and initializes in Simulink the constants, and displays the results.

2.4. Implementation of the Control System.

Finally, implement the system considering the hardware shown in Fig. 7.

For the execution of the program use the development environment with operating system Linux-Ubuntu, the NetBeans IDE, cross-compiler for ARM architectures, GCC and source code of the programs.

The main program is the development in "C" language, then using the cross compiler creates the executable to be able to download the driver and finally run the program implemented.

The developed program follows the flow diagram shown in Fig. 8.

3. Results

The results that are achieved by running the main program implemented in the controller.

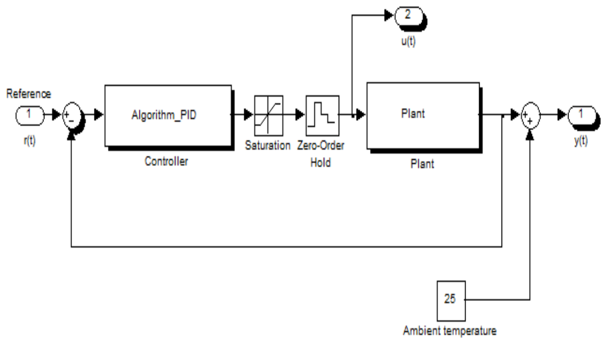

Fig. 6 Diagram of the temperature control.

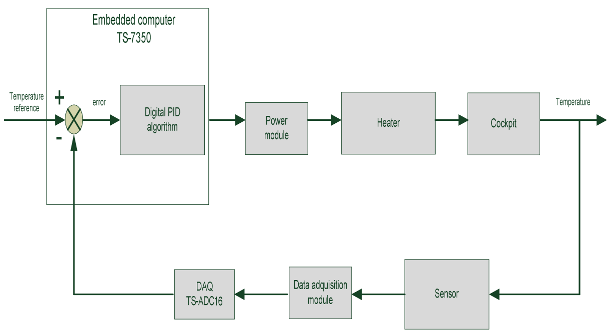

Fig. 7 Control system of the prototype ESVIN.

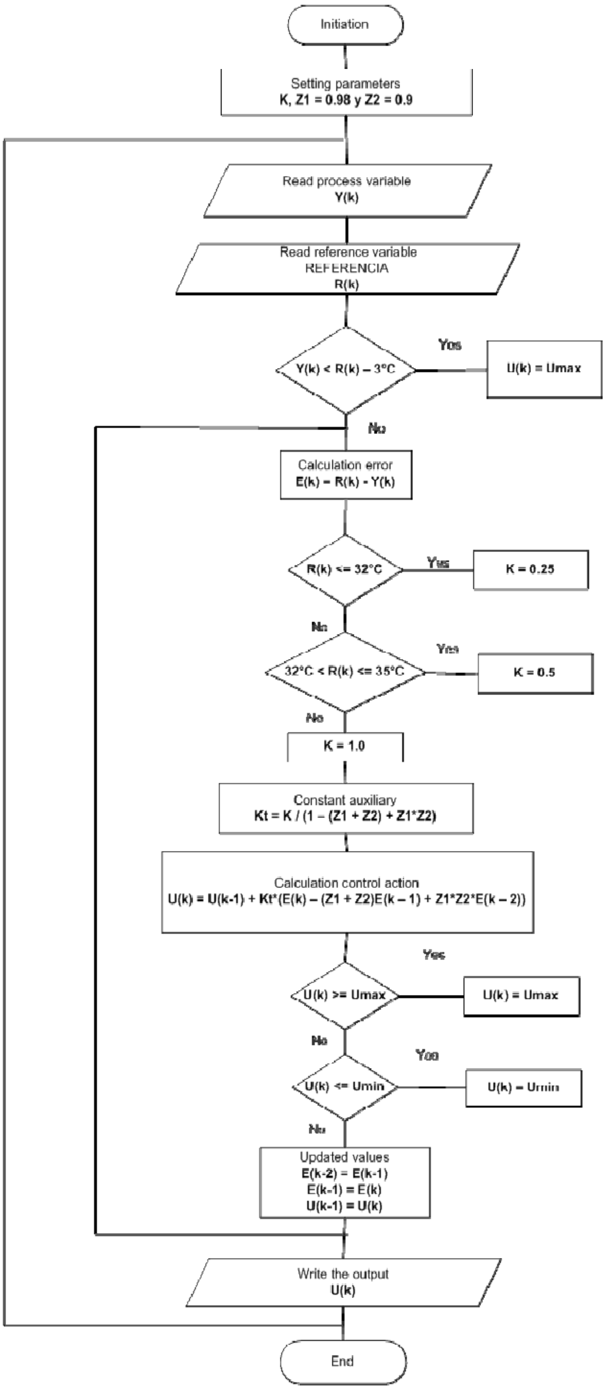

Fig. 8 Flow diagram of the digital PID algorithm.

The parameters of the tuned PID controller are digital: $z_1 = 0.98$, $z_2 = 0.9$, $K_1 = 0.25$, 0.5 or 1.0 (setpoint). This value of K is automatically updated in the main program. For warm-up time, according the standard IEC 60601-2-19, these results are shown in Fig. 9.

To obtain the status of thermal stability, according to international standard IEC 60601-2-19, they implement a test whose results are shown in Figs. 10 and 11.

To obtain the overshoot, according to international standard IEC 60601-2-19, they implement a test whose result is shown in Fig. 12.

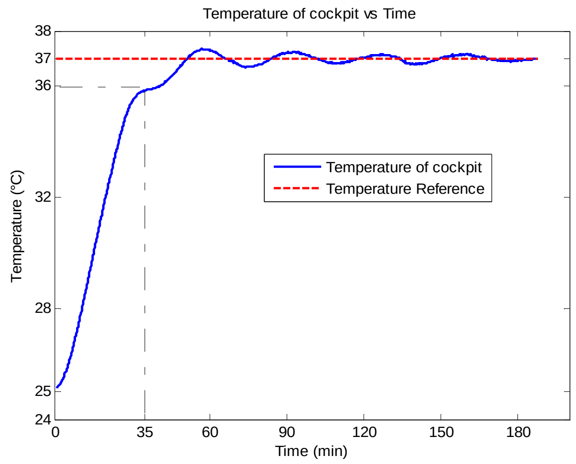

Fig. 9 Warm-up time according IEC.

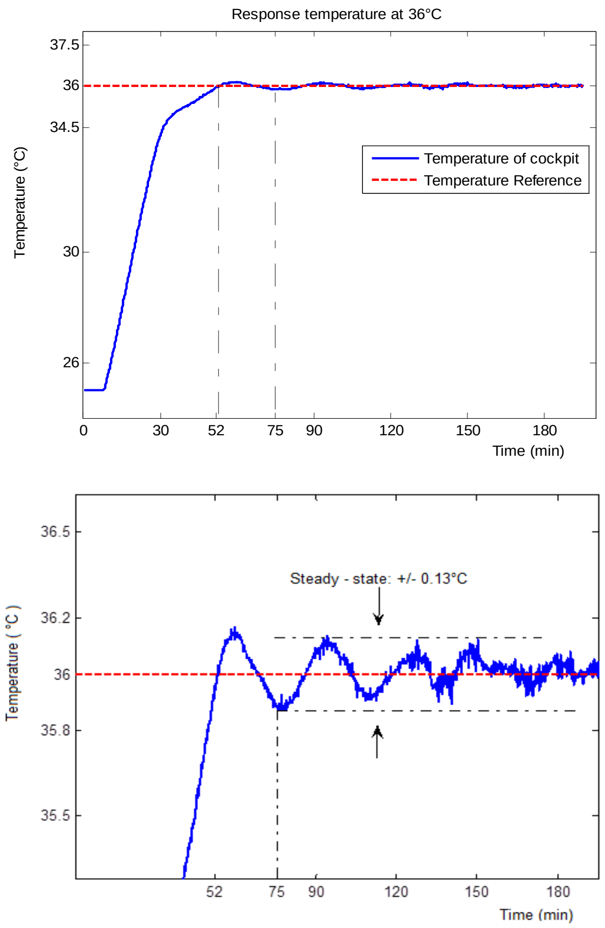

Fig. 10 Steady-state error at 36 ºC.

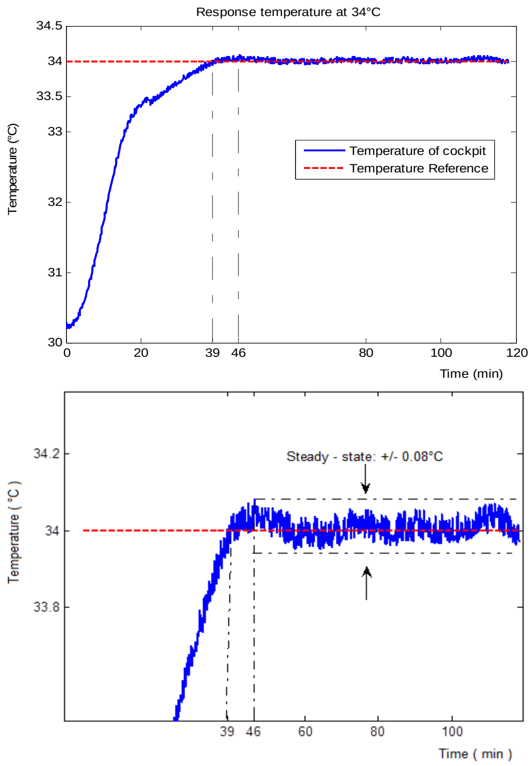

Fig. 11 Steady-state error at 34 °C.

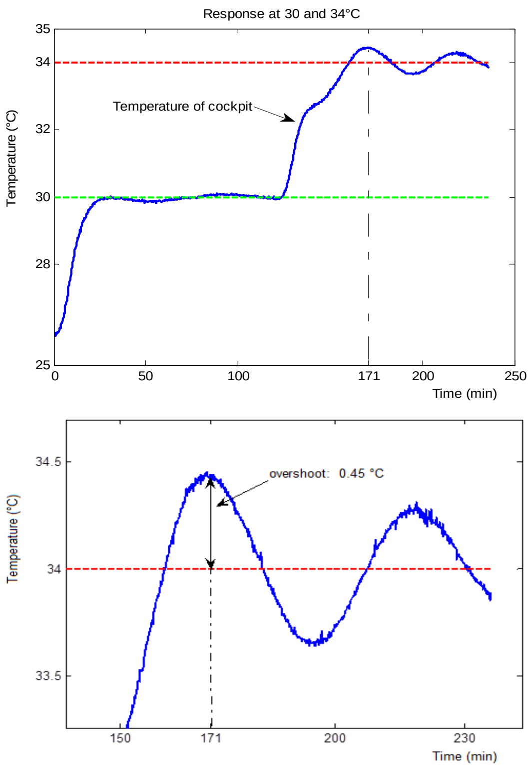

Fig. 12 Response to overshoot.

4. Conclusions

The mathematical model obtained describes the dynamic behavior of the temperature in the passenger compartment in a satisfactory manner.

The validation results show that the obtained model describes with high accuracy the process object of study, by what is considered suitable for control purposes.

The programs implemented allowed us to obtain the tuning parameters using the simulation. The considerations set out in Eqs. (9) and (10) were of great help for the tuning of the PID algorithm.

The digital PID controller allowed to control the temperature in the cockpit of the prototype in a satisfactory manner, in accordance with the conditions established in the standard IEC 60601-2-19 concerning the basic security and operation of medical equipment, obtaining:

A warm-up time of 35 min, a steady-state error of 0.13 °C, over the provisions of norm (0.5 °C) and an overshoot of 0.45 °C exceeding established in the norm (2 °C).

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