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DIGITAL EQUIPMENT FOR THE TEMPERATURE CONTROL INSIDE AN ENCLOSURE. THE SYSTEM MODELING

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Abstract **– The fast design flow for the temperature control inside a thermal enclosure includes some identification elements, modeling and simulations for the digital control algorithms in different forms and a preparation of the real-time algorithm using an appropriate programming language for the hardware implementation. The solution, after this short but holistic approach, is a ready to use form for the computing relations associated to the control algorithm and the optimum values for the tuning parameters. In this stage, many hardware options and constraints must be considered so that the models and simulations could reproduce the real operating conditions of the experimental platform (that will be presented in a subsequent paper). For a small thermal enclosure designed and realized both for educational and scientific purposes, the first step is to identify a transfer function based on IN / OUT experimental data. Using this result, several models were analyzed, considering different external conditions, various operation modes and several control algorithms: by commutation (On / Off, with hysteresis band), proportional (P), PI (continuous and digital forms). A careful design of the models was tuned so that all the basic processing for the simulations should as closed as possible with the real-time operation of a target microcontroller, with its specific hardware / software constraints.**

Keywords: *Temperature control, models and simulations, control algorithms, microcontroller*

1. INTRODUCTION

A very “classic” problem like the temperature control remains always very important not only because the variety of applications but also because it is always open to new solutions related to the design flow, the control algorithm, the performance criterions and the features of the experimental platform. There are many approaches for controlling the temperature with conventional or unconventional algorithms. The paper [6] makes a comparison between PID and fuzzy control solutions. An embedded solution for pedagogical purposes is presented in [3] and such an experimental platform was very inspiring for this study. The complexity of the involved theoretical support and the hardware structures depend on the application type. For buildings it is important to compensate the potentially disturbing factors and to organize a decentralized control and communication structure – [5], within the modern concept of pervasive sensing and computing - [10]. When the precision of the controlled temperature becomes an essential factor, as for semiconductor manufacturing enclosures, many theoretical tools become very complex (predictive and adaptive algorithms) and the best hardware elements (beginning with the sensors) must be selected – [10]. The importance of the sensors could lead to very new solutions, like a self verifying sensor – [4], more accurate and reliable than the classic type. More and more studies and solutions concern the combination of several unconventional control strategies in the soft-computing domain called also “the intelligent control” and this approach is important especially for non-linear and stochastic systems, having a fast dynamic and without a (reliable) mathematical model – [10]. The fuzzy control technique belongs to a promising tool set of the artificial intelligence approach; the author obtained good results implementing such algorithms – [2] and for nonlinear models with uncertain parameters and disturbances, an adaptive fuzzy controller could deliver good solutions – [9]. It is important to mention, however, that some drawbacks of this kind of solutions (lack of some analytical support for proving the solution quality, an infinite tuning parameters) must be considered.

In this paper, although the design is associated with a flexible structure for the software and the hardware support, conventional control algorithm will be taken into account. The replacement of the control task in the final program is feasible.

The literature offers a growing flow of books, articles and Internet publications in this domain; most of the materials exhibit theoretical analysis, other give mainly the experimental results and not a few authors share principles or statements. Although all these are valuable sources, the author considers that a practical design flow for all components of the problem is more suitable for many readers. The design stage means, in the general context of “an information rich world” – [8] and, particularly, for the involved objective:

a. the identification of the main characteristics for the thermal enclosure, including the temperature sensor;

b. the control algorithm design;

c. the modeling and simulation of the system with an universal programming platform, like Matlab / Simulink (rich in Toolboxes and applications) and the tuning of the controller so that the results could have the expected (or better) results, in different forms: an initial quasi-continuous one, another using samplers / quantifiers and the characteristics of the future hardware devices;
d. the computation of some program data for the real-time control, so that the previous simulations could offer reliable results;
e. the choice of a programming support for the real–time control and the program design in accordance with the target platform.
f. the hardware configuration, by pre-fabricated modules, including or not new own boards (drivers, interfaces, conditioning modules, power supply devices, connection elements);
g. the program transfer into the microcontroller;
h. the on-line experiments and the improvement of the program and data.

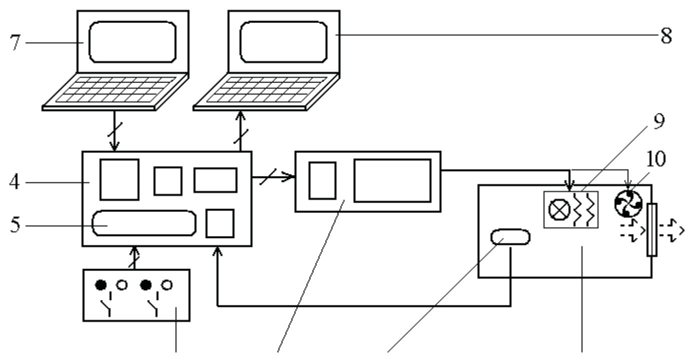
In this design flow, many returns to previous stages are possible and useful to optimize the partial and the global results. This paper concerns the steps a-d and a subsequent paper will presents the steps e-h, as well as the real-time results.

2. THE GLOBAL SYSTEM AND AN IDENTIFICATION OF THE ENCLOSURE

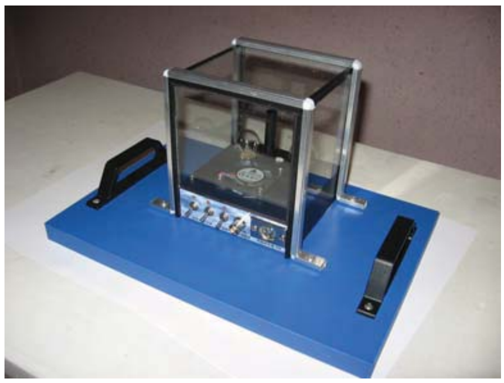
Fig. 1 presents the system configuration - 1a and the image of the thermal enclosure - 1b (manufactured in the Digital Control laboratory of the Faculty for Engineering in Electromechanics, Environment and Industrial Informatics). This extended structure (development system type) remains with only the essential elements after all the development and tuning. The enclosure 1 is heated with 1 or 2 bulbs 12 V DC / 21 W. The temperature sensor 2 closes the loop. The control equipment 4 must have an extended displaying area – 5 and several operator controls (6). The driver 3 must be able to transfer both analog and PWM controls. The computer 7 is for developing and transferring the program and the on-line data. An extra computer hosts a logic analyzer for debugging and evaluations.

For the identification of a transfer function of the enclosure, an analytical approach is not productive because the enclosure has many different materials with unknown quantitative characteristics. A simple identification method based on experimental points IN-OUT will be proceedded. This aquisition data (like from fig. 1c and 1d) from several experiments for heating and cooling in different conditions show that the enclosure with all components seems having a 1st order behavior, so its transfer function is adopted as:

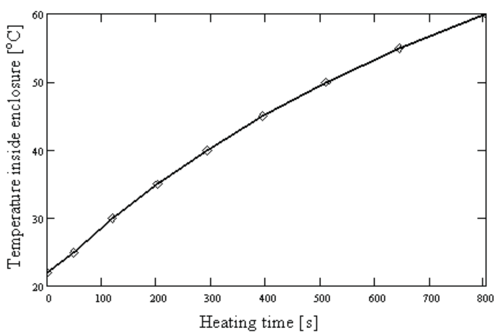
$$G_{encl.}(s) = \frac{k_{encl.}}{1+s \cdot T_{encl.}} \quad (1)$$



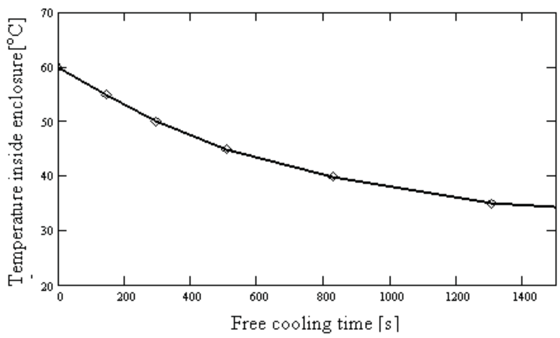
a.



b.



c.



d.

Figure 1: The main elements of the system and some data for the identification.

$k_{encl.}$ [^oC / V] was evaluated computing the average value for all heating / cooling experiments, upon the ratio between the voltage / current controls and the steady-state temperatures. A rougly image for the $T_{encl.}$ is obtained considering the duration of the transient regimes. As a supplementary confirmation, $T_{encl.}$ was also computed by solving an exponential equation for different operation regions, points X and regimes, as function of the initial and final (steady-state) points:

$$T_{encl.} = t_X \;/\; \ln\frac{\tau_{steady\_st} - \tau_{in}}{\tau_{steady\_st.} - \tau_X} \qquad (2)$$

The previous considerations and relations gave as reliable (despite some values dispertion): $k_{encl.}$= 7.33 and $T_{encl.}$= 833 s. Any deviation from this model (especially during the cooling regimes, when the thermal transfer conditions are different) could be interpreteted as a parametric perturbation that the control algorithm must be able to manage. A better estimation could be done by a neuro-fuzzy model, obtained by means of more experimental IN-OUT data.

2. MODELS AND SIMULATIONS FOR THE THERMAL SYSTEM

An important design step is the computer simulation of the closed - loop system so that the control algorithm could be evalueted and optimized. A high quality model must not only take into account all the elements with their characteristics but to consider the operating regimes as close as possible to the conditions in real-time – [1]. One first model – fig. 2 considers, besides the transfer function of the enclosure, two additional elements: a first order filter one, having the role to model the sensor inertia; and another with a similar role for the heating element. Their time constants (estimated) have an essential role for the later parameter tuning of a PI control algorithm:

$$G_{PI}(s) = k_p \cdot (1 + \frac{1}{s \cdot T_i}) \text{ - form a)} \qquad (3)$$

or

$$G_{PI}(s) = \frac{1 + s \cdot T_r}{s \cdot T_i} \text{ - form b)} \qquad (4)$$

Now, the global enclosure has the transfer function:

$$G_f(s) = \frac{k_f}{(1 + s \cdot T_f) \cdot (1 + s \cdot T_\Sigma)} \qquad (5)$$

$k_f = k_{encl.}$, $T_f = T_{encl.}$ (f - from ”fixed” part) and T_Σ is the sum of the small time factors. An optimum tunning (modulus criterion, Kessler variant) is given by:

$$T_r = T_{encl}\,;\; T_i = 2\, k_{encl} \,.\, T_\Sigma \qquad (6)$$

The model from fig. 2 is considered as an ideal one because the next reasons:

- there is no sampling for the signals / variables;
- many elements and phenomenons are ignored (like the free or forced cooling);
- no real-time constraint is taken into account (associated to a control processsor, with its harware / software features).

However, this model is useful beacuse can give reliance to a control structure, proves that the control algorithm is able to manage the steady-state and the dynamic regimes and allows the algorithm tunning. The controller has a final saturation element so that the control variable could be compatible with the voltage range of the power part.

The results from fig. 3 confim the model validity. The set-point tempearture is reached exactly (the steady-state error is less than 0.001 ^oC) after 200 s. The temperature has a quasi-exponential behavior; it would be pure exponential for a step voltage delivered by the controller, but this doesn’t happen because the controller operates properly. The zoomed windows of the main variables from the fig. 3b prove a good quality of the loop, with smooth variation not only for the temperature but also for the controller variables.

A next model – fig. 4, is much more realistic. The thermal model is more complex, considering the

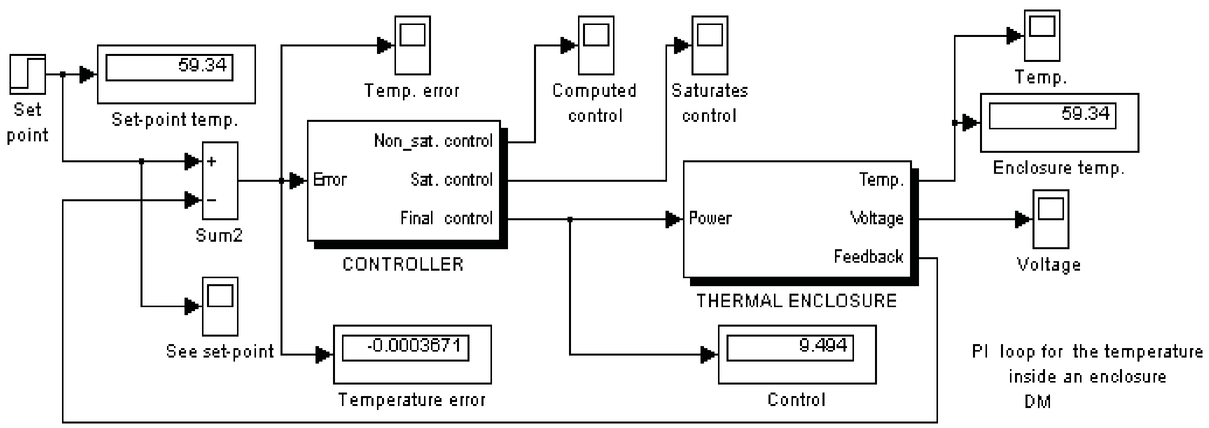


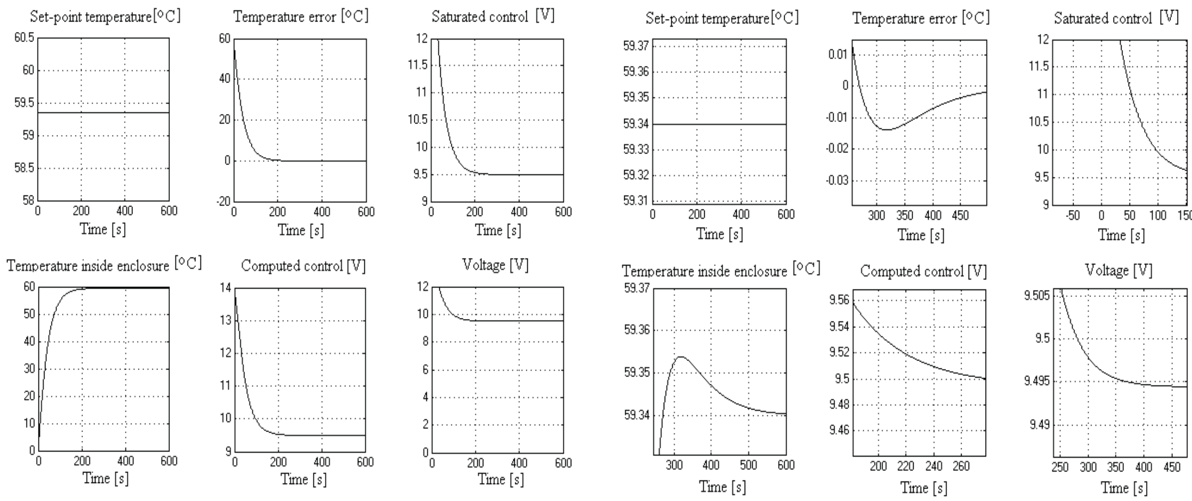
Figure 2: An ideal and simple model for the system.

environment temperature, the natural (free) and forced (by a fan) cooling conditions. The samplers inserted as well as the computations inside the controller block involve the sampling period – T. For emulating the real-time operationg conditions, other elements were considered too: the arithmetic format of the target processor, the numbers quantification.

Fig. 5 reveals the results for a hysteresis control algorithm with a reference temperature of 65 ^{o}C and a complex operating cycle that includes the intervention of the fan and a manual ”off” switching for the control equipment. The algorithm is able to remove with difficulties the effect of an additional cooling by the external perturbation. The zoomed views reflect the commutations inside the hysteresis band. The strong solicitations of the power supply as well as of the heating elements are the main drawbacks of this method. The temperature ringing during the steady-state regime, although adjustable, is limited by the commutation frequency. The advantage for a real-time implementtation is given by the simple and fast on-line computations. The results prove a good quality of the model.

The same model with a digital PI controller generates the results from fig. 6 and 7 (this last one, with strong external perturbations). With standard notations (ε: the temperature error; u: the controller output; k_P and T_i: tuning parameters of the algorithm), the specific on-line computing relations are:

$$u_k = u_{k-1} + k_P \cdot \left(\frac{T}{T_i} + 1 \right) \cdot \varepsilon_k - k_P \cdot \varepsilon_{k-1} \qquad (7)$$



a. b

Figure 3: The results for an ideal PI control algorithm.

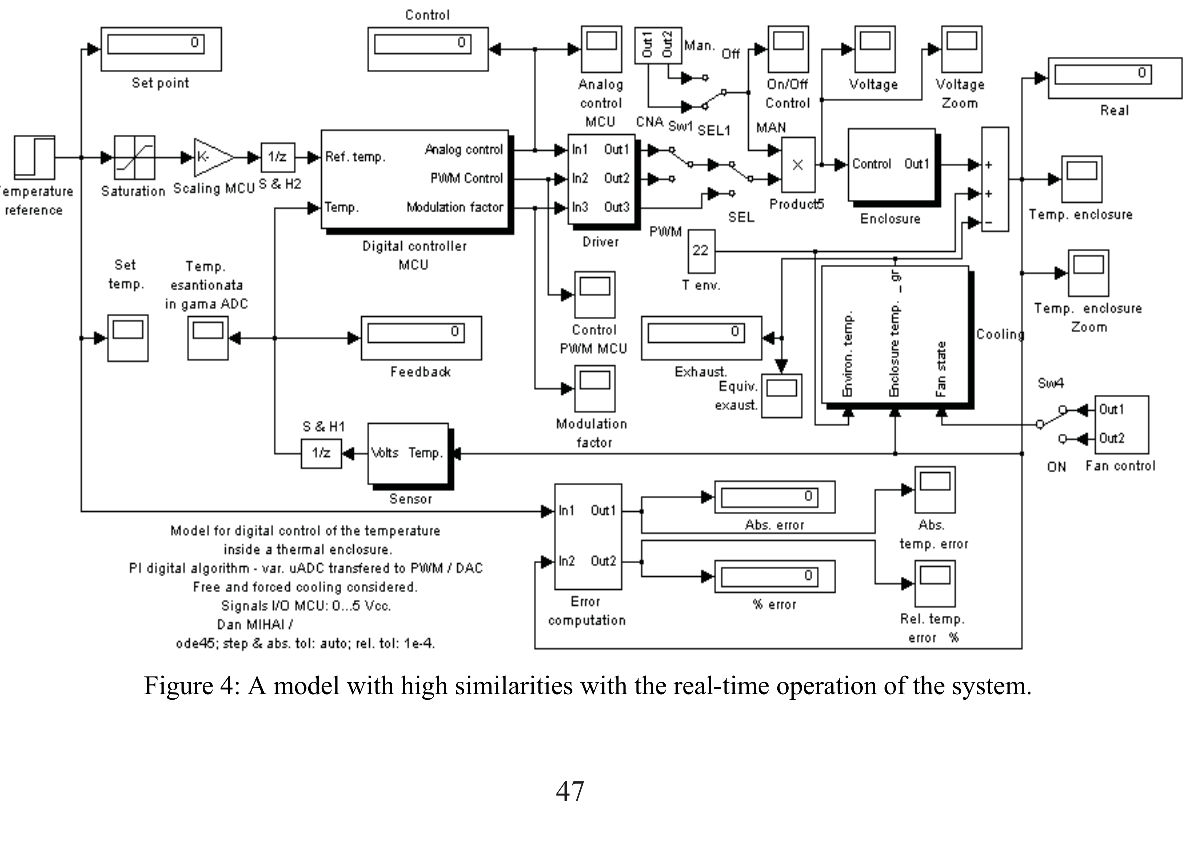


Figure 4: A model with high similarities with the real-time operation of the system.

$$u_k = u_{k-1} + k_p \cdot (\varepsilon_k - \varepsilon_{k-1}) + \frac{k_p \cdot T}{T_i} \cdot \varepsilon_k \qquad (8)$$

The form (8) is operational when T is big enough so that the error variation could be identifiable (at least 1 LSB). For $T << T_i$, a simple PI (degenerated) form is:

$$u_k = u_{k-1} + k_p \cdot (\varepsilon_k - \varepsilon_{k-1}) \qquad (9)$$

For the controller modeling, a special care was given to the order for performing the artihmetic operatins in order to avoid lost of small terms (it is useful to mention the importance of the integral term, although its minor weight) by truncation to integer numbers - as by the subsequent real-time arithmetic of the microcontroller. The steady-state error is less than 1 % (lower ringing of the temperature) and the actions of the controller are more nuanced. Even when the temperature is affected by a strong perturbation (the fan activated) - fig. 7, the controller is able to ensure a right operation of the loop (following the imposed cycle) and good quality both for the steady-state and the dynamic regimes.

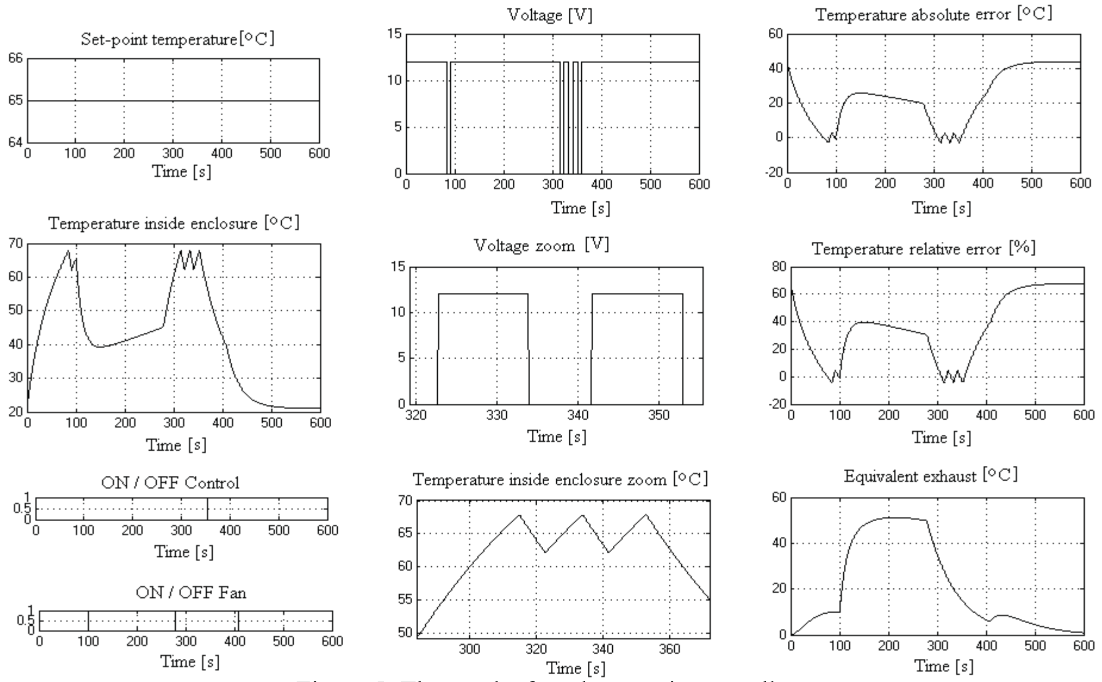


Figure 5: The results for a hysteresis controller.

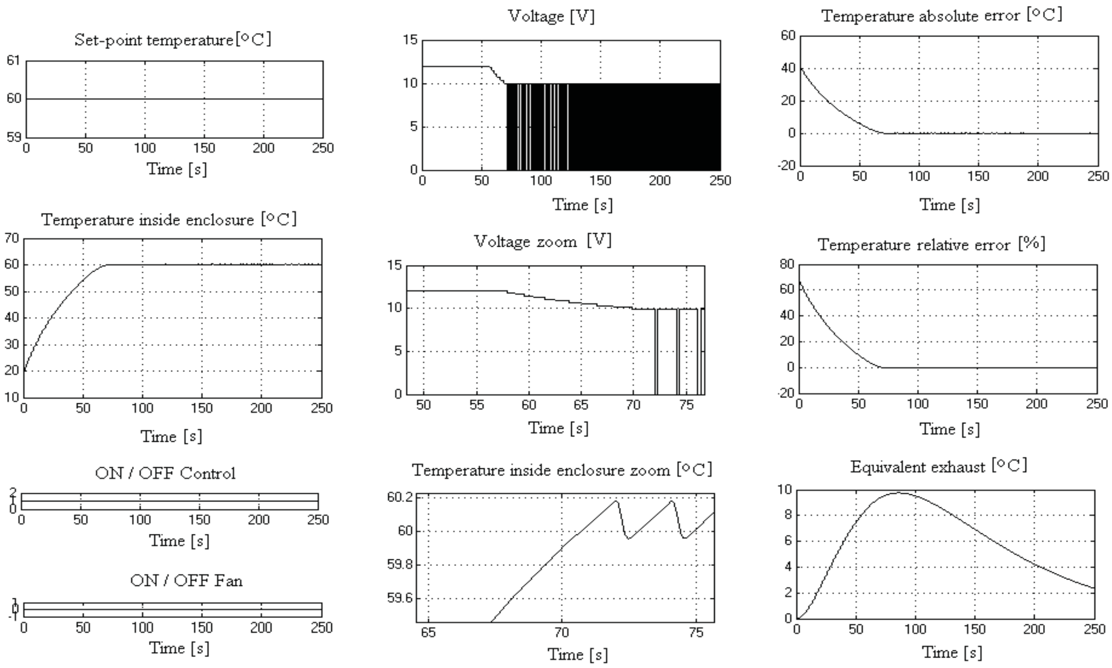


Figure 6: Simulation results for a digital PI algorithm without external perturbation.

4. CONCLUSIONS

Although the control for the temperature seems not to be a complex application, a careful design flow must be considered, including several important stages. An identification of the process with all its components is followed by several models and simulations, transformed gradually so that all the processing must be as closed as possible to the real-time operating conditions. The designer must always be prepared to build some relations for the on-line computations adapted to the target control processor and its software. A direct implementation of some well-known control algorithms could lead to very good results but the guarantee for acceptable results of a real-time platform is given by more sophisticated models, having samplers, quantizers, saturation blocks and a careful arrangement of all computations, in accordance with the arithmetic capabilities of a target microcontroller. The models presented consider complex thermal conditions for the environment and can include any control algorithm. Based on this results, a next paper will present the hardware system and the experimental results.

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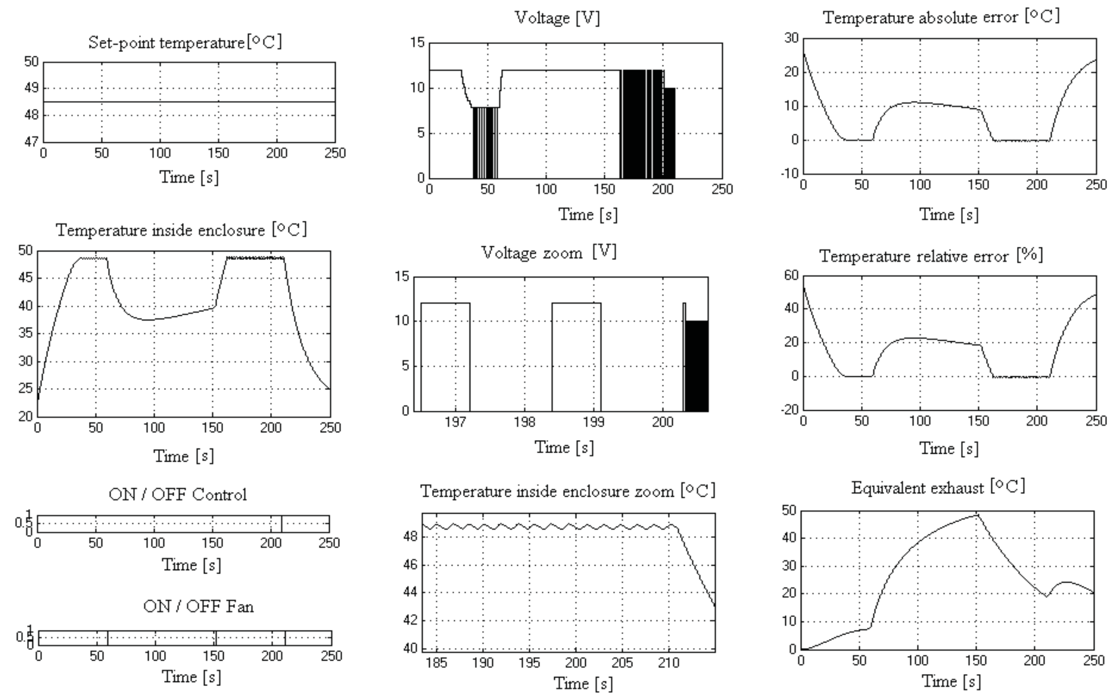

Figure 7: The results for a digital PI controller, with external perturbations.