On The Control of Parabolic Solar Collector: The Zipper Approach

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Abstract- Creative inspirations that marked the great moments of human genius are linked to seemingly insignificant details: an Apple for Newton, a Bath for Archimedes, and many other impressive examples. In this paper, we introduce a new controller design inspired from the functioning principle of "The zipper" in order to force the outlet temperature of the parabolic solar collector to track a desired reference. The proposed control scheme is based on the Lapunov stability analysis as well as the zipper functioning principle. A potential advantage of this latter consists in the possibility of extending the designing method to other systems governed by hyperbolic PDE and/or uncertain ODE models. Numerical simulations are done with real process parameters to show the effectiveness of the proposed controller.

Keywords Parabolic Solar Collector (PSC), the Zipper Controller (ZC), Thermal Energy.

1. Introduction

Renewable energies are no longer considered as an alternative for electrical energy production, but as a fatality imposed by the growing demand and resources limitations. Nowadays, solar energy is promoted to be an environment-friendly resource, due to its cleanliness and sustainability [1]. But, since photovoltaic systems are always criticized for their expensiveness and low rentability, solar thermal energy has become more convincing [2]. In fact, several solar thermal power plants have been constructed or are under construction worldwide.

In solar thermal power plants, the energy conversion takes place in two stages: *"solar-energy into thermal-energy"* and then *"thermal-energy into electrical-energy"*. In this context, solar collector’s technology is adopted to focus the radiant solar energy onto a receiver that absorbs and transforms it into heat. Afterwards, the thermal energy is used for powering a conventional thermal cycle to generate electricity [3].

In recent years, parabolic solar collectors have taken the lead upon a large range of other existing solar collectors and became the subject of many studies because they offer the possibility to control the produced thermal energy. Nevertheless, the complexity of the partial differential equation model of these systems remains an arduous constraint for the achievement of the control design. In fact, many approaches have been proposed in the literature to deal with this problem. These approaches can be classified, according to their principles, into two categories: "*Reduce Then Design (RTD)*" and "*Design Then Reduce (DTR)*" [4] [5]. The former consists in making some simplifications to reduce the complexity of the PDE model before the controller design. The most used theory for this is space discretization in which many methods are applied such as: the finite difference method, the finite element method and the finite volume method [6], [7]. While the latter uses the PDE model directly in the controller design, which is based on infinite dimensional description by using *Hilbert* and *Banache* spaces [8], [10]. After that, the resulting design scheme is reduced with a view towards its implementation.

The main drawback of RTD techniques is that the discrete linear model used to describe the original PDE is unable to represent accurately the behavior of the real process due to the loss of information in the discretization stage. Hence, the resulting controller may fail to achieve the desired performances. Indeed, the DTR techniques seem to be more accurate by using the original PDE model in the controller synthesis, but the fastidious analytic development remains the major constraint in their application.

The main novelty and contribution of the present work consists of a new method: taking advantage of the simplicity of the RTD method and benefitting from the accuracy of the DTR method by ensuring an optimization of the *"Complexity/Accuracy"* balance. The key idea of our design consists in providing an equivalent system that represents accurately the PDE system by using the finite difference method (RTD) taking into account the truncation errors resulting from the spatial discretization. Then, we introduce the principle of *"The Zipper Controller"* based on the resulting model.

The remainder of this paper is organized as follows: section (2) describes the parabolic solar collector model. In section (3), an equivalent uncertain state-space model is presented. Section (4) is devoted to the zipper controller design. Simulation tests are presented in section (5) to evaluate the controller performances. Finally, some concluding remarks are given in section (6).

2. Process Description and Modelling

The parabolic solar collector is an engineering process which aims to convert *"solar-energy"* into *"thermal-energy"*, an overall view of this system is given in Fig. 1. The receiver mirrors are selected to be *parabolically-curved* in order to focus the incident beams of solar radiation onto the focal line of the parabola thereby heating the thermal oil flowing through the absorber pipe. This latter is used, thereafter, in a heat exchanger to produce steam. The steam so produced can be used in a turbine [11] to drive an electric generator and/or supply the thermal energy for powering a conventional thermal cycle.

In most applications of parabolic solar collector a sun tracking system is used to maximize the solar absorption. However, the control of the outlet oil temperature remains a major constraint, due to the fact that the primary energy source (solar radiation) cannot be manipulated. To overcome this problem, a commonly used technic consists in acting on the oil flow rate by controlling the pump in the inlet of the pipe [12]. The physical model describing the relationship between the oil flow rate and the temperature evolution along the pipe is derived from the energy balance principle [13], in which the heat transport phenomena is described by the following hyperbolic PDE model: [3]

$$\frac{\partial T(t,x)}{\partial t}+\frac{q(t)}{s}\frac{\partial T(t,x)}{\partial x}=\frac{\nu_{\circ}\eta}{\rho\, c\, s}I(t) \qquad (1)$$

Where :

- $T(t,x)$: describes the temperature distribution along the receiver pipe.

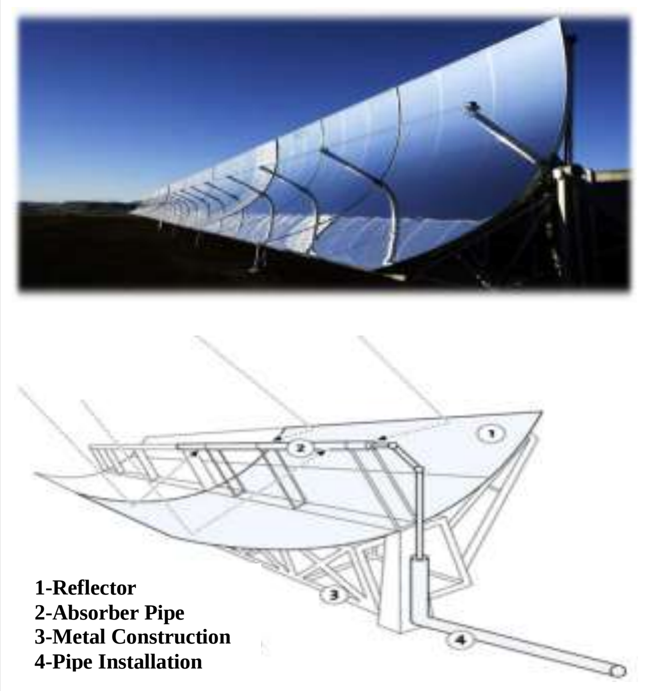

Fig. 1. Parabolic Solar Collector

- $I(t)$: is the source term which corresponds to the solar radiation.
- $q(t)$: is the control input which corresponds to the oil flow rate in the inlet.
- $\nu_{\circ}\,\eta$: describes the optical characteristics of the reflector mirrors.
- $\rho\, c$: describes the thermal properties of the oil flowing through the receiver pipe.
- $x \in [0,l]$ s : describes the dimensions of the receiver pipe (the longitudinal position and the cross sectional area respectively).

Due to the saturation constraint of the pump, and, in order to avoid a leakage of the thermal oil caused by the overpressure. Two restrictions are imposed on the process:

- The control input is subject to the pump saturation limits, i.e.
$$0 \le u_{\min} \le u(t) \le u_{\max}$$
- The difference between the inlet and the outlet temperature should not exceed an admissible limit.

Notation. *For clarity and simplicity, the temperature* $T(t,x)$ *is denoted by* $T_t(x)$ *throughout the rest of this paper.*

3. Uncertain State Space Synthesis

The finite difference method is one of the most useful approaches to deal with the PDE model complexity [**14**], [**15**]. In this approach, the PDE model is semi-discretized to a set of ordinary differential equations (ODEs) using the following identity:

$$\frac{\partial T_t(x)}{\partial x} = \frac{T_t(x) - T_t(x-\Delta x)}{\Delta x} \quad (2)$$

Where:

- Δx : denotes the spatial step size.

The above identity is derived from the Taylor Series Expansion (TSE) of $T_t(x)$ in a given space vicinity Δx , as follows:

$$T_t(x-\Delta x) = T_t(x) - \Delta x \frac{\partial T_t(x)}{\partial x} + \sum_{i=2}^{n} \frac{(-1)^i \Delta x^i}{i!} \frac{\partial^i T_t(x)}{\partial x^i} \quad (3)$$

Or equivalently :

$$\frac{\partial T_t(x)}{\partial x} = \frac{T_t(x) - T_t(x-\Delta x)}{\Delta x} + \sum_{i=2}^{n} \frac{(-1)^i \Delta x^{i-1}}{i!} \frac{\partial^i T_t(x)}{\partial x^i} \quad (4)$$

Let us denote by $R(\Delta x)$ the bias derived from the rest of the TSE, which is defined as follows:

$$R(\Delta x) \triangleq \sum_{i=2}^{n} \frac{(-1)^n \Delta x^{i-1}}{i!} \frac{\partial^i T_t(x)}{\partial x^i} \quad (5)$$

As it can be seen:

$$\lim_{\Delta x \to 0} R(\Delta x) = 0 \quad (6)$$

For simplicity, usually $R(\Delta x)$ is neglected. However, this leads to a loss of information on the system's behavior (due to the truncation error). To overcome this problem, all the previous works based on this method propose to choose Δx small enough in order to justify the negligence of $R(\Delta x)$ by satisfying the condition given by (**6**) or being close enough to the satisfaction of this latter and as a result the obtained model will be a high-order model, which leads to an increased computational cost. Furthermore, we can never achieve the accuracy of the real process despite the smallness of the spatial step size Δx .

Proposition 3.1. *To avoid the PDE model's complexity and get more accuracy, we propose to consider* $R(\Delta x)$ *as an unknown parameter in our design, i.e.* $R(\Delta x) = ?!$.

Consequently, the partial derivative of $T_t(x)$ with respect to "x" given by (**2**) will become as follows:

$$\frac{\partial T_t(x)}{\partial x} = \frac{T_t(x) - T_t(x-\Delta x)}{\Delta x} + \underbrace{R(\Delta x)}_{UNCERTAIN} \quad (7)$$

Hereby, the PDE model (**1**) is equivalent to the uncertain ODE defined as follows: $\forall\ x \in [x_1 - \Delta x,\ x_1]$

$$\frac{dT_t(x)}{dt} = (T_t(x-\Delta x)|_{x=x_1} - T_t(x)|_{x=x_1})\frac{q(t)}{s} + \frac{\nu_\circ \eta}{\rho\ c\ s} I(t) - \underbrace{\frac{q(t)}{s} R(\Delta x)|_{x=x_1}}_{UNCERTAIN} \quad (8)$$

The equivalent state space describing the uncertain ODE model (8) along the space horizon is obtained by choosing the following state variables:

$$x = (x_1 \ \cdots \ x_n) \quad with \quad x_i = T_t(l-(i-1)\Delta x)$$

Obviously, the equivalent uncertain state space model can be rewritten as follows:

$$(\Sigma)\begin{cases} \dot{x} = f(x) + g(x)\ u(t) + \xi(t) \\ y = c\ x \end{cases} \quad (9)$$

With:

$$f(x) = \frac{\nu_\circ \eta}{\rho\ c\ s}\begin{pmatrix}1\\ \vdots \\ 1\end{pmatrix} I(t) \ ; \ g(x) = \begin{pmatrix} g_1(x) \\ \vdots \\ g_n(x)\end{pmatrix} \ ; \ \xi(t) = \begin{pmatrix}\xi_1(t) \\ \vdots \\ \xi_n(t)\end{pmatrix}$$

$$c = (1 \quad 0 \quad \cdots \quad 0)$$

where:

$$g_i(x) = \frac{x_i - x_{i+1}}{s} \quad ; \quad \xi_i(t) = -\frac{q(t)}{s} R(\Delta x)$$

Two main features of the proposed method are worth mentioning. The first consists in its ability to ensure an optimization of the complexity/accuracy balance, by providing an equivalent uncertain state-space (USS) model which can describe accurately the real process with less complexity. The second one is the possibility of it being applied to describe all processes governed by a PDE model.

In the next section, we introduce the zipper controller for the resulting uncertain state space model.

4. Controller Design

Uncertain systems are challenging in terms of robust control design. In this case of study, we seek to provide a suitable framework to design a robust controller which can handle effectively the system's uncertainty derived from the truncation error.

4.1. Baseline Control Scheme:

The basic idea of the proposed method consists in confining the uncertain system (Σ) between two well defined systems, i.e.

$$\forall\ t \in [0, t_L] : \quad (\Sigma)_{\min} \le (\Sigma) \le (\Sigma)_{\max} \quad (10)$$

Hereafter, we coincide (Σ) at the desired reference, thanks to the inequality (**10**), by forcing $(\Sigma)_{\min}$ and $(\Sigma)_{\max}$ to track the same desired reference. Hereby, achieving the desired objective.

The principle of the proposed idea is inspired from the functioning principle of the zipper as illustrated in Fig. (**2**)

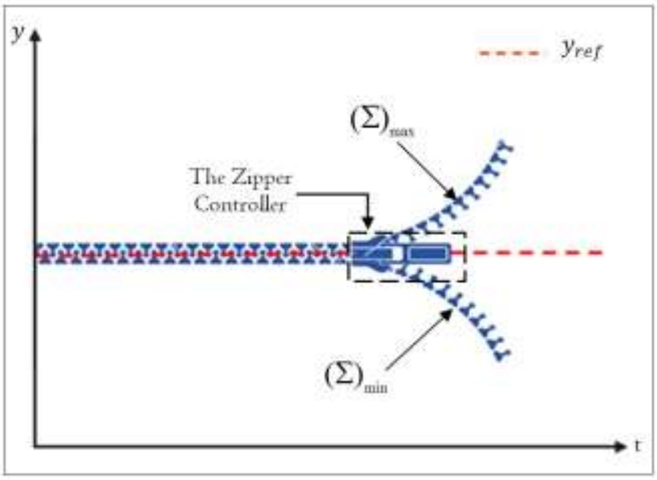

Fig. 2. Principle of the Zipper Controller

Before proceeding, we propose to emphasize the main steps leading to the controller design:

- *Firstly, we must define the system bounds* $(\Sigma)_{min}$ *and* $(\Sigma)_{max}$.
- *Thereafter, we establish a matching relationship between the control laws making* $(\Sigma)_{min}$ *and* $(\Sigma)_{max}$ *converge to the desired reference in order to have* (Σ) *coincide with it.*
- *Finally, the stability analysis of the final control scheme is carried out by resorting to the classic Lyapunov theory.*

In this contribution, we will focus on the control design for our system as a study case. Thus, we provide some remarks for extending "the zipper principle" to other class of uncertain systems.

- **1st Stage: (Definition of the Systems Bound)**

The systems bound are formally defined in the following proposition.

Proposition 4.1. *Let* $(\Sigma)_1$ *and* $(\Sigma)_2$ *be two nonlinear systems defined as follows:*

$$(\Sigma)_1 \begin{cases} \dot{x} = f(x) + g(x)\ u(t) - \xi_m \\ y = c\ x \end{cases}$$

$$(\Sigma)_2 \begin{cases} \dot{x} = f(x) + g(x)\ u(t) + \xi_m \\ y = c\ x \end{cases}$$

Where:

- ξ_m *: is the upper bound of* $|\xi(t)|$ *i.e.*

$$|\xi(t)| \le \xi_m$$

Then, the uncertain system (9) fulfills the following inequality:

$$(\Sigma)_{min} \begin{cases} \dot{x} = f(x) + g(x)\ u(t) - \xi_m \\ y = c\ x \end{cases} \le (\Sigma) \begin{cases} \dot{x} = f(x) + g(x)\ u(t) + \xi(t) \\ y = c\ x \end{cases} \le (\Sigma)_{max} \begin{cases} \dot{x} = f(x) + g(x)\ u(t) + \xi_m \\ y = c\ x \end{cases} \quad (11)$$

Proof:
Using the fact that the system uncertainty is a bounded function, we have:

$$|\xi(t)| \le \xi_m \quad (12)$$

Or equivalently:

$$-\xi_m \le \xi(t) \le \xi_m \quad (13)$$

By adding the term **[** $f(x) + g(x)\ u(t)$ **]** to the inequality (**13**), we obtain:

$$f(x) + g(x)u(t) - \xi_m \le f(x) + g(x)u(t) - \xi(t) \le f(x) + g(x)u(t) + \xi_m \quad (14)$$

Or equivalently:

$$\dot{x}\ \{(\Sigma)_{min}\} \le \dot{x}\ \{(\Sigma)\} \le \dot{x}\ \{(\Sigma)_{max}\} \quad (15)$$

By integrating the inequality (15) and multiplying by "c", we obtain:

$$y\ \{(\Sigma)_{min}\} \le y\ \{(\Sigma)\} \le y\ \{(\Sigma)_{max}\} \quad (16)$$

Which concludes the proof. ■

- **2nd Stage: (*Definition of the Matching Relationship*)**

Firstly, we must find the control laws ensuring the convergence of both $(\Sigma)_{min}$ and $(\Sigma)_{max}$ to the same desired reference.

By resorting to Lyapunov theory, we can easily reach this aim. In the following theorem we state the main result.

Theorem 4.1. *For nonlinear systems* $(\Sigma)_{min}$ *and* $(\Sigma)_{max}$ *, If the following control laws are applied (respectively):*

$$u_{min} = \frac{1}{g(x)}(\dot{x}_r - f(x) + \xi_m - \lambda e) \quad (17)$$

$$u_{max} = \frac{1}{g(x)}(\dot{x}_r - f(x) - \xi_m - \lambda e) \quad (18)$$

Where:

$\lambda \in \mathbb{R}^+$ *: is a scalar gain used to impose a selective degree of robustness and/or stability.*

Then, these systems exhibit asymptotic reference tracking.

Proof:

The proof is omitted for brevity**.** We can easily obtain this result by resorting to the classic Lyapunov method. ■

Thereafter, to establish the matching relationship we propose to discuss the definition of the tracking error as follows:

- *If the tracking error is negative (i.e. $y \le y_r$): in this case, we must apply $u_{\min}$ in order to force $(\Sigma)_{\min}$ to converge to the desired reference. Hereby, we also force the convergence of (Σ) via the inequality (**11**).*

- *If the tracking error is positive (i.e. $y \ge y_r$): in this case, we must apply $u_{\max}$ in order to force $(\Sigma)_{\max}$ to converge to the desired reference. Hereby, we also force the convergence of (Σ) via the inequality (**11**).*

Indeed, we can summarize the above discussions in the following proposition.

Proposition 4.2. *From the above discussions, we can define the matching relationship as follows:*

$$u(t)\begin{cases} u_{\min} & if \quad e \le 0 \\ u_{\max} & if \quad e \ge 0 \end{cases} \tag{19}$$

Or equivalently

$$u(t) = \frac{1}{2}[\gamma_1 u_{\min} + \gamma_2 u_{\max}] \tag{20}$$

Where:

$$\begin{cases} \gamma_1 \triangleq 1 - sgn(e) \\ \gamma_2 \triangleq 1 + sgn(e) \end{cases} \tag{21}$$

- **3rd Stage:(*Stability Analysis of the Final Control Scheme*)**

As a consequence of the previous stages, we can now state the main contribution of this paper.

Theorem 4.2. *Consider the PDE system (1) under the equivalent USS representation (9), if the following control law is applied:*

$$u(t) = \frac{1}{g(x)}(\dot{x}_r - f(x) - \xi_m sgn(e) - \lambda e) \tag{22}$$

Then, this system exhibits asymptotic reference tracking.

Proof:

From Theorem 1 and *Proposition 3*, the control law derived from "*the zipper principle*" can be obtained by substituting (17) and (18) in (20):

$$u(t) = \frac{1}{g(x)}(\dot{x}_r - f(x) - \xi_m sgn(e) - \lambda e) \tag{23}$$

Then, let $V(t)$ be a positive definite function defined as follows:

$$V : \mathbb{R} \longrightarrow \mathbb{R}^+$$
$$V(t) = \frac{1}{2}e^2(t)$$

Where $e(t)$ is the tracking error defined as follows:

$$e(t) = x(t) - x_r(t) \tag{24}$$

The time derivative of $V(t)$ is expressed as follows:

$$\begin{aligned} \dot{V}(t) &= e(t)\ \dot{e}(t) \\ &= e(t)\ (f(x) + g(x)\ u + \xi - \dot{x}_r) \end{aligned} \tag{25}$$

By substituting (**23**) in (**25**), we obtain:

$$\dot{V}(t) = -\lambda e^2 + (\xi(t) - sgn(e)\xi_m)\ e \tag{26}$$

As it can be seen:

$$(\xi(t) - sgn(e)\xi_m)e = (sgn(e)\xi(t) - \xi_m)\,|e| \tag{27}$$

And we have:

$$(sgn(e)\xi(t) - \xi_m)\,|e| \le 0 \tag{28}$$

Hereby, $\dot{V}(t)$ is semi-negative definite. Hence, we conclude the asymptotic stability for the predefined reference. ■

5. Simulation Results

In this section, we carried out simulations to evaluate the performances of the proposed control scheme under different conditions. Simulations are done with real values of process parameters (see Appendix A), which are those of the solar platform belonging to the Spanish research energy center *(CIEMAT*, *Almería_Spain)*. The other simulation parameters are summarized in Tab.1.
Figure (3) illustrates the functioning principle of the zipper controller for a step reference. To assess the reference tracking performances, we consider two reference signals characterized by a high dynamics; *"staircase-reference"* and *"sinusoidal-reference"*. The obtained results are illustrated in Fig (4).

Parameter	***Value***
Inlet Temperature $T_0(t)$	*200°C*
Solar Radiation	*900 W/m²*
Sampling Time For Simulation	*36 s*
Number of discretization	*20*

Table. 1. Simulation Parameters

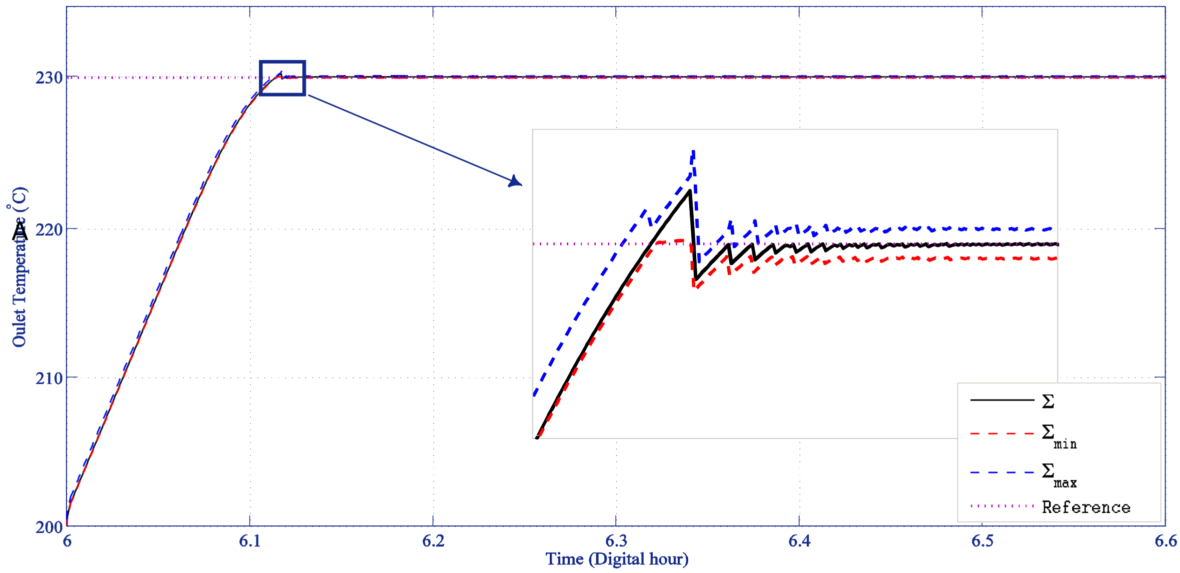

Fig. 3. Step Response

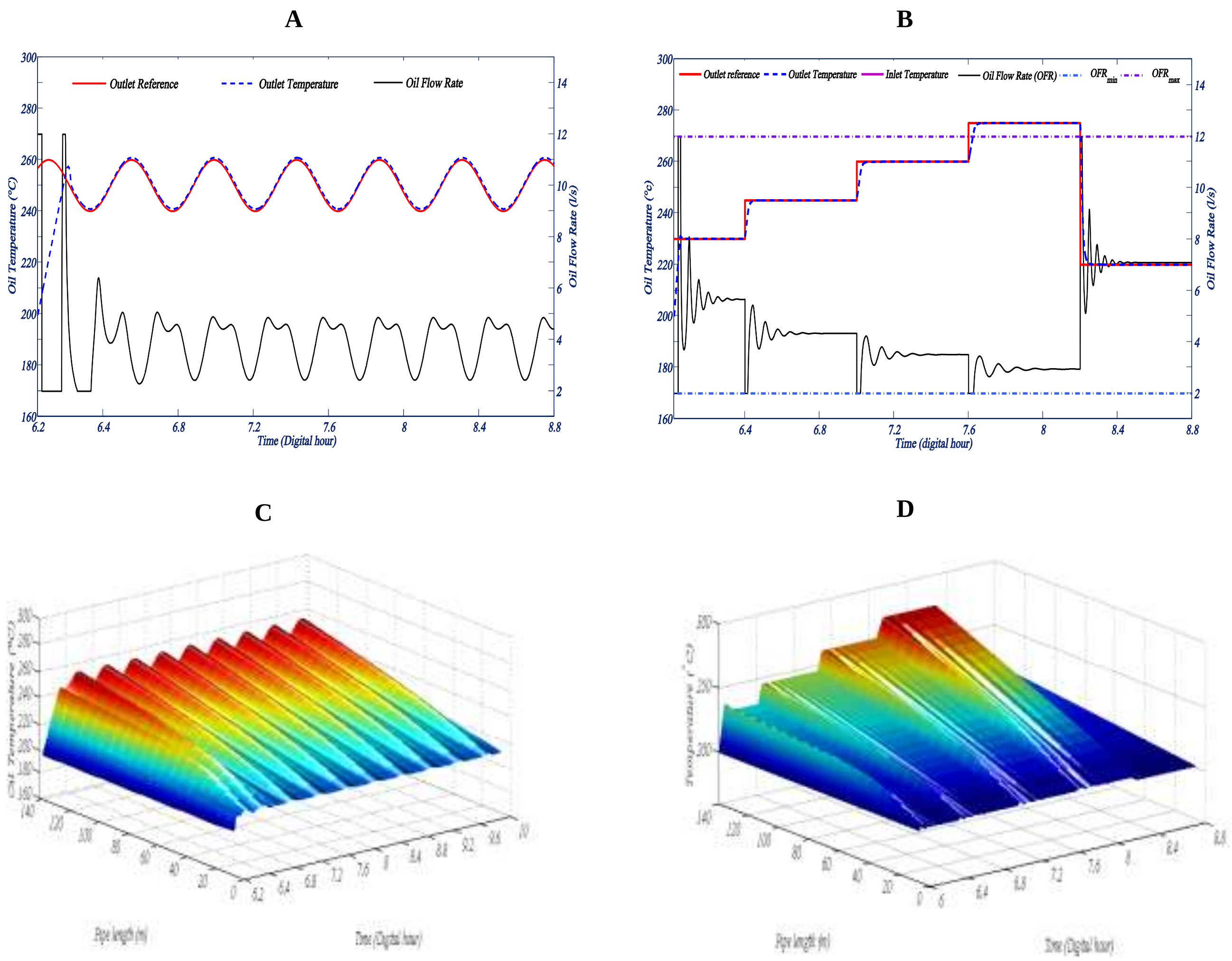

Fig.4. Evolution of the PSC system for a "staircase" and "sinusoidal" references. (A, B) represents the reference tracking, and the applied oil flow rate (the control input). (C, D) describes the temperature evolution inside the pipe for both references.

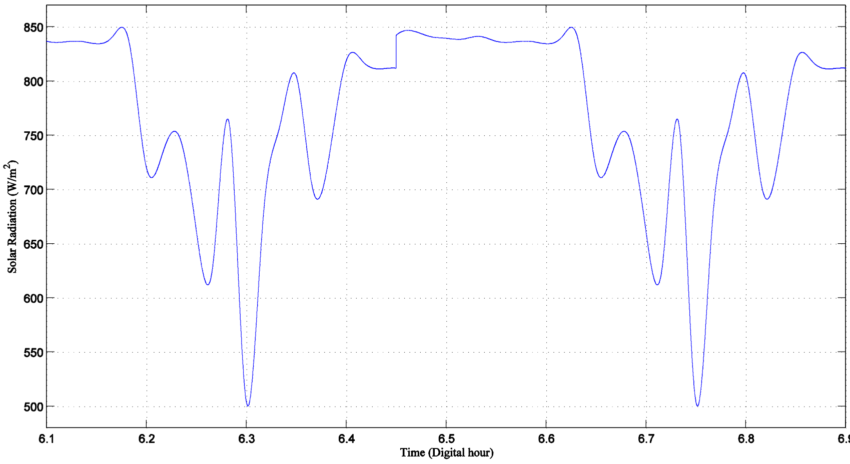

Fig. 5. Solar Radiation Profile

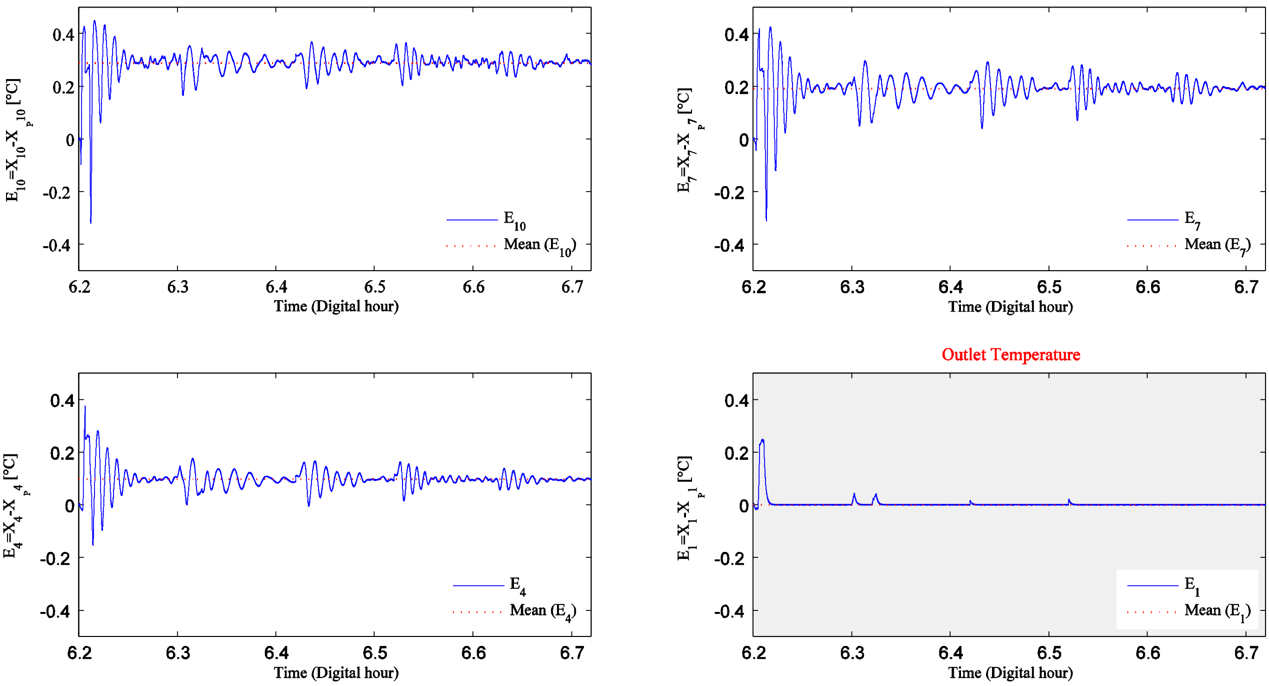

Fig. 6. Robustness Test

In order to assess the robustness of the zipper controller against modeling error and/or parameters variation, we consider a brutal change in the solar radiation caused by passing clouds, and we check the tracking performances of this latter. Indeed, we apply the solar radiation profile (**5**) to the parabolic solar collector (in the steady-state). Figure. **6** shows the tracking error obtained by comparing the perturbed and non-perturbed system. As it can be seen an attenuation of the perturbation effects while approaching to the pipe extremity (the system output). Hereby, we conclude the robustness of our controller against perturbations.

To allow fair evaluation of the proposed control scheme, we carried out a comparative study with sliding mode controller (SMC) under the same conditions of solar radiation and inlet temperature. This comparison is based on the following performance criteria:

- Integral of the absolute tracking error (IAE)

$$IAE=\int_0^t |e(t)|\, dt$$

- Integral of the Time-weighted Absolute Error (ITAE)

$$ITAE=\int_0^t t\,|e(t)|\, dt$$

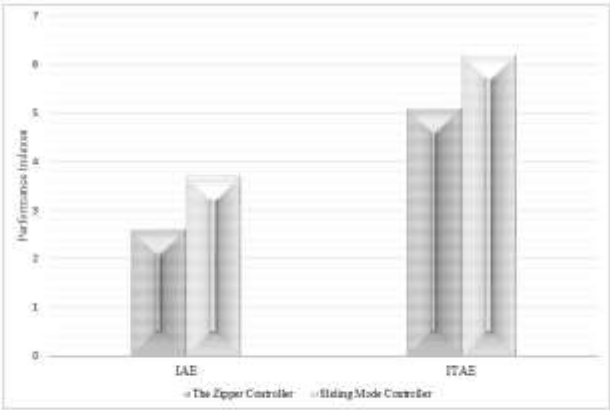

Fig. 7. Controller Performance Indexes

As it can be seen the zipper controller presents better performance indexes compared to the Sliding Mode Controller.

6. Conclusion

The ultimate aim of this work was to control the outlet temperature of a parabolic solar collector. This aim is reached thanks to the proposed modeling approach which helped us reduce the PDE model's complexity by providing an equivalent model obtained using the finite difference method and taking into account the truncation error as an unknown parameter. Thereafter, a new controller design inspired form the functioning principle of the zipper as well as the Lyapunov stability analysis is introduced to reach the control objective. Simulations with real process parameters are carried out to illustrate the effectiveness of the proposed controller. The obtained results show good tracking performances and robustness against parameter variation and modelling errors.

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Appendix A

Symbol	*Description*	*Value*
c	*Specific Heat Capacity*	*1820 J.C^{-1}.Kg^{-1}*
ν_0	*Optical Mirror Efficiency*	*73%*
ρ	*Density*	*903 Kg.m^{-3}*
η	*Mirror Optical Aperture*	*1.83 m*
l	*Pipe Length*	*142 m*
s	*Cross Sectional Area*	*0.0006 m^2*

Table.2. PSC Model Parameters

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