16th Triennial World Congress, Prague, Czech Republic

ROBUST H_∞ CONTROL APPLIED TO A SOLAR PLANT

M. A. Corchero, [1] **M. G. Ortega and F. R. Rubio**

Departamento de Ingeniería de Sistemas y Automática,
Escuela Superior de Ingenieros, Universidad de Sevilla,
41092 Sevilla, Spain

Abstract: This paper shows the application of robust control techniques to a solar plant integrated in an air conditioning system. Different structures in an specific loop are applied, because of the complexity of the whole system. Besides the classical feedback loop, the plant controller includes also a feed forward one to reject measurable disturbances as radiation. The design methodology and some simulations examples will be exposed. Finally, several experiments to test the validity of the controllers are performed in the real plant. *Copyright© 2005 IFAC*

Keywords: H_∞ control; Mixed sensitivity problem; Process control; Solar systems.

1. INTRODUCTION

Using solar energy for an air conditioning system has a lot of features which make it very interesting. On the one hand, the use of renewable energies, like solar one, instead of oil or coal, much more pollutant, is always desirable and innovative. Besides, solar radiation for cooling is particulary attractive, since, the more sun shines, the better conditions will be to make the plant work properly in cold-production purposes.

Among the multiple existing methods for refrigeration using solar radiation (Sayigh A.M., 1992), one of the most successful is based in an absorption machine which produce cold water in the output from hot water previously heated by the sun in the input.

This type of systems presents certain features (lack of manipulation capacity over the solar radiation source, existence of great disturbances in the process due to changes in environmental conditions, presence of dead-times due to fluid transportation, variable cooling demand, etc) that control strategies must address (Camacho, E,F, Berenguel, M., Rubio, F.R., 1997).

The H_∞ control theory has received a lot of attention in the last decade within research community due to robustness characteristics supplied by its controllers. This features make it a priori interesting to be used in controlling such a solar refrigeration system. The basic idea is to minimize the ratio between the energy of the error vector and the energy of the exogenous signals (Skogestad, S., Postlethwaite, I., 1996).

This paper deals with the sub-optimum solution of the problem based in the S/T or S/KS/T mixed sensitivity problem for building up the generalized plant , which allows to obtain the controller just by designing a nominal model and some suitable weighting matrices.

In this paper, the H_∞ control is used to regulate the absorption machine inlet temperature which establishes evaporator and absorber pressures. It is also worth mentioning that the controller con-

[1] Corresponding author. Tel.: +34-954-487487; fax: +34-954-487540

tains a feed forward action to treat with system disturbances. The results of the application are tested both in simulation and real plant experiments.

The paper is organized as follows: A brief description of the plant is given in section 2. Section 3 presents the models identification process. Following sections describe and presents the results obtained by the application of different control structures on the plant; S/T mixed sensitivity problem in section 4 and S/KS/T one in section 5. Finally, the conclusions of the work are exposed in section 6.

Fig. 1. Solar plant.

2. SYSTEM DESCRIPTION

In figure 1, a picture from the plant located at the System Engineering and Automatic Control Department of the University of Seville can be seen.

This solar air conditioning system consists on a collectors field that produces hot water which feeds an absorption machine as described before. The main components of the system, which are depicted in figure 2, can be described as follows:

- The main source of energy is solar radiation (Rad) which is used by the solar collectors to heat the circulating water. The field is composed of $151m^2$ of flat collectors and supply a nominal power of 50kW.
- The accumulation system is composed of two $2500l$ tanks working in parallel and it stores warm water. This water, which is supposed to be in a lower temperature (Tac), mixes with the one coming back from collectors field. The mixture is controlled by the three-way valve VM1 according to the following rule:
    - · VM1 on 0%: The water from the collectors field is recirculated entirely towards collectors field again.
    - · VM1 on 100%: The water is entirely conveyed towards the storage water tanks.
- The cooling system is an absorption machine that works with water as a cooling fluid and it requires its inlet temperature (Tsc) to be within the range of $75°C - 100°C$ for suitable work. In this device, different processes (absorption, evaporation, etc) occur which make energy exchanges to achieve cold water production.
- An auxiliary energy system consisting of a gas-fired heater can be used to complement the energy supplied by the collectors field when the solar radiation is not powerful enough.
- A load simulator (a heat pump) that allows tests for different load profiles to be performed.

The overall objective is to supply cold water to the air conditioned system at the required temperature. This means that the controller must keep the cooling system working at the desired operating point, and this is achieved by keeping the absorption machine inlet water temperature at the given set-point in the proper range; this will be the control objective for the strategies implemented in this paper.

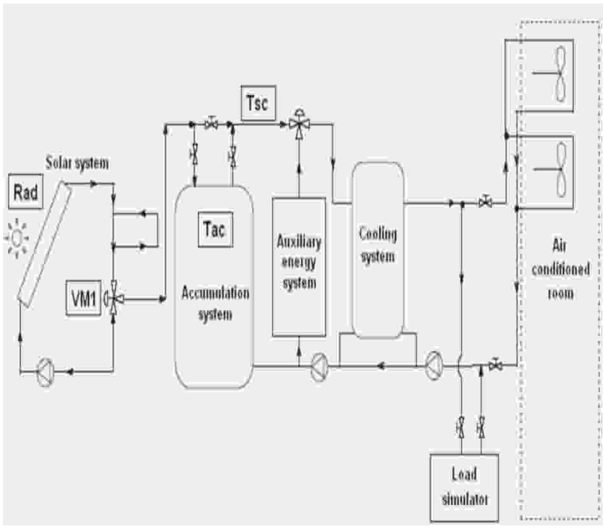

Fig. 2. Scheme of control loop.

3. DYNAMICS MODELS IDENTIFICATION

In this section, the procedure to obtain a suitable model of the system dynamics will be shown.

Both the VM1-Tsc and the Rad-Tsc dynamics are similar to a classic first order system with a certain delay, so an $ARX120$ structure (with a sampling time of $40s$) is selected to model them.

Thanks to several experiments, enough data were obtained to identify VM1-Tsc and Rad-Tsc characteristics. These data are subjected to an parametric model identification process implemented in a well-known software packet (Ljung, L., 1986). The obtained VM1-Tsc transfer function is shown in equation 2, which corresponds to a nominal 50% valve opening.

$$G_N(z) = \frac{0.001119z - 0.08281}{z - 0.9264} z^{-3} \qquad (1)$$

In the Rad-Tsc model identification experiment, a climatologic phenomenon like clouds must be expected to produce enough variability in radiation to give valid information. The estimated transfer function is:

$$G_d(z) = \frac{0.002049z - 0.000785}{z - 0.0.9836} z^{-2} \qquad (2)$$

These dynamic models, despite of theirs simplicity, are considered good enough for control purposes. For more information about the plant model identification, see (Delgado J., Bordons C., 2000).

4. H_∞ S/T MIXED SENSITIVITY PROBLEM BASED CONTROLLER DESIGN

The feedback controller design problem for this system can be formulated as an H_∞ optimization problem, with suitable features in disturbances rejection and robustness.

The optimal H_∞ problem is not solved yet, but a solution exists for the suboptimal problem. Thereby, the value of the energy ratio is decreased as much as possible by means of an iteration process. This is the synthesis process used in this paper and implemented in various well-known software packages (Balas, G., Doyle, J., Glover, K., Packard, A., Smith, R., 1995).

A configuration for building up the generalized plant is the S/T mixed sensitivity problem (Skogestad, S., Postlethwaite, I., 1996), which is exposed in figure 3, where $P(s)$ is the generalized plant and $K(s)$ is the controller.

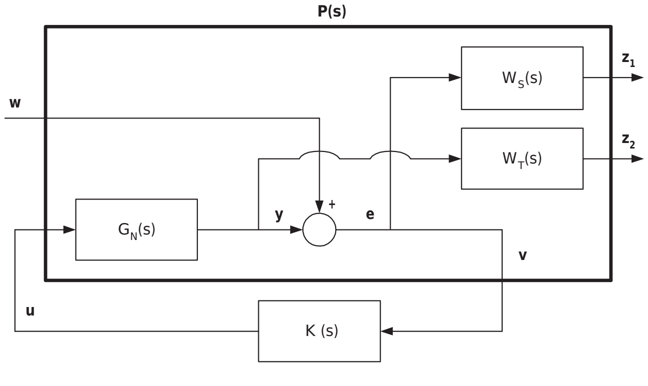

Fig. 3. S/T mixed sensitivity problem.

The terms $W_S(s)$ and $W_T(s)$ constitute weighting functions which allow the range of frequencies of main importance for the corresponding closed-loop transfer function to be specified.

Once the nominal model $G_N(z)$ has been chosen, the magnitude of the multiplicative output uncertainty can be estimated as follows:

$$|E_{o,i}(e^{j\omega T})| = |G_i^*(e^{j\omega T}) - G_N(e^{j\omega T})| \cdot |G_N(e^{j\omega T})^{-1}| \qquad (3)$$

where $G_i(z)$ stands for the different non-nominal systems at each operation point where suitable work of the controller is required.

As it is exposed in (Ortega, M.G., Rubio, F.R., 2004), the weighting function $W_T(s)$ must be designed under the following conditions: stable, minimum phase and with module greater than the maximum singular value of the uncertainty previously calculated for each non-nominal model and frequency, that is,

$$|W_T(jw)| \geq \bar{\sigma}(E_{o,i}(e^{jwT})) \quad \forall w, \forall i \qquad (4)$$

In the case of $W_S(s)$, it is proposed to have the following form:

$$W_S(s) = \frac{\alpha s + \omega_S}{s + \beta \omega_S} \qquad (5)$$

where each of the parameters is designed in the following way:

- α is the function gain at high frequency. An suitable value should be approximately about 0.5.
- β is the function gain at low frequency. A proper small value for these parameter may be 10^{-4}.
- $\omega_\mathbf{S}$ is the crossover frequency of the function. As initial value, a decade below the crossover frequency of the function $W_T(s)$ previously designed. It is proposed to vary ω_S according to the expression $\omega_S = 10^{(\kappa_i - 1)}\omega_T$ in order to shape the desired speed of the output response.

4.1 Application on specified closed loop in the solar plant

In order to design the controller which has been presented before, the nominal working point has been taken as an opening of the valve VM1 on 50%. The corresponding uncertainty diagram and the associated $W_T(s)$ function (eq. 6) are shown in figure 4.

$$W_T(s) = \frac{10^{-0.1}(2000s + 1)}{0.8s + 1} \qquad (6)$$

Taking into account that the crossover frequency of function $W_T(s)$ is about $6.3 \cdot 10^{-3} rad/s$, the function $W_S(s)$ is taken as shown in equation 7.

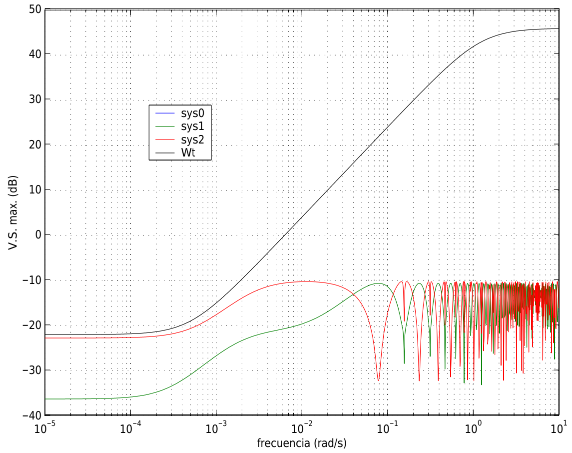

Fig. 4. Multiplicative output uncertainties and weighting function $W_T(s)$.

$$W_S(s) = \frac{0.5s + 10^{-0.25} \cdot 6.3 \cdot 10^{-3}}{s + 10^{-4} \cdot 10^{-0.25} \cdot 6.3 \cdot 10^{-3}} \tag{7}$$

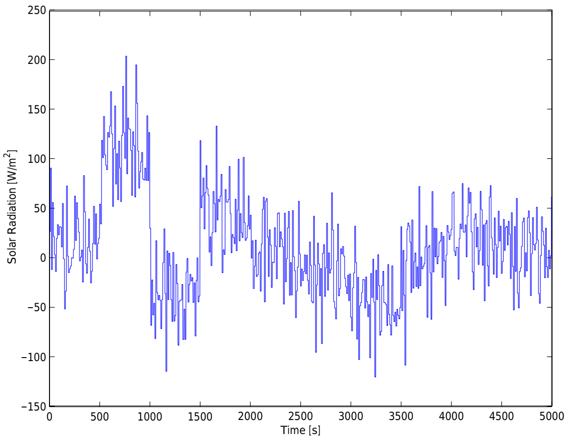

Fig. 5. Radiation pattern used in simulations.

Finally, a bilinear transformation of the nominal model has been applied to build up the generalized plant as a previous step to synthesize the controller. Thereby, with these weighting functions, the controller is designed by means of suitable functions for the solution of the H_∞ suboptimal problem.

Several simulation experiments were carried out in a suitable model of the system. Simulations were performed in Simulink environment including some features of the real process like solar radiation effect and saturation in the VM1 valve action. Figure 5 shows the radiation profile used and figure 6 shows the obtained response, in terms of output temperature (Tsc) and corresponding reference.

4.2 Experiments in the real plant

Some experiments to show the performance of the controller have been performed in the real system.

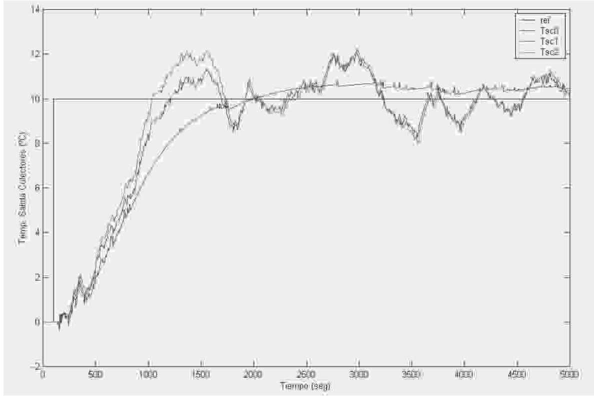

Fig. 6. Simulated tracking response in radiation conditions in Fig. 5.

A client-server data base access system (OPC) is used between the environment where the plant management system (CUBE) is implemented and the program which implements the control system (Matlab/Simulink). In this way, some numerical problems, such as controller fragility, are avoided.

Figures 7 and 8 show the behaviour of the output temperature (Tsc) together with its reference, the control action (VM1) and the disturbance variables, both solar radiation (Rad) and water from accumulators temperature (Tac). The parameter κ has been modified in the different experiments and the approximated values of *rising time* (t_s) and *overshoot* (δ) are also shown.

In the figures, it is clear the effect of the κ value in the response speed and overshoot. As κ increases, a faster response is obtained, although the overshoot of the response increases too.

Given the simple structure of the controller, and despite the effect of the disturbances, the overall performance, specially regarding to disturbance rejection (fig. 7) is fairly good, although this issue were not considered in the original control design.

5. H_∞ S/KS/T MIXED SENSITIVITY PROBLEM BASED CONTROLLER DESIGN

An improvement in the later control scheme will be made by a compensation loop of the disturbance introduced in the system by solar radiation (Rad). The compensation mechanism will consist in a feed forward loop of the disturbances, which will be included in the H_∞ calculus by means of a suitable algorithm.

On introducing the feed forward loop in the structure that was exposed before for the VM1-Tsc control, the resulting scheme is as the exposed one in figure 9.

The weighting functions $W_S(s)$ and $W_T(s)$ design methodology is exactly the same as the one presented in previous sections. The main difference

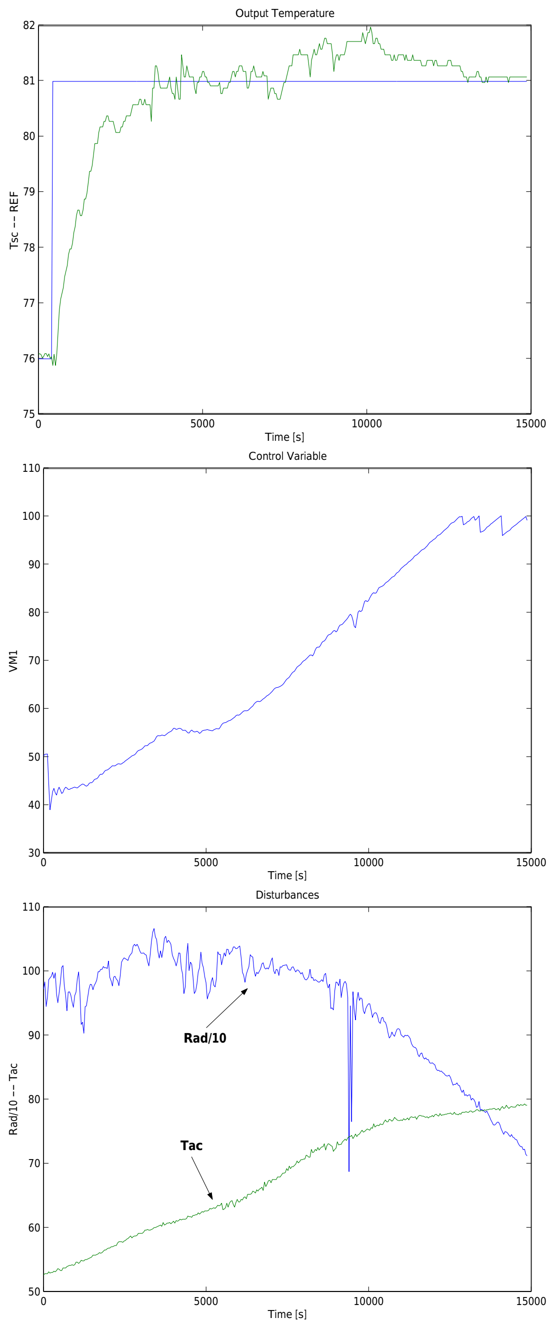

Fig. 7. Experimental results in VM1-Tsc control with $\kappa = 0.2$ ($t_s \simeq 3000s$ and $\delta \simeq 0\%$).

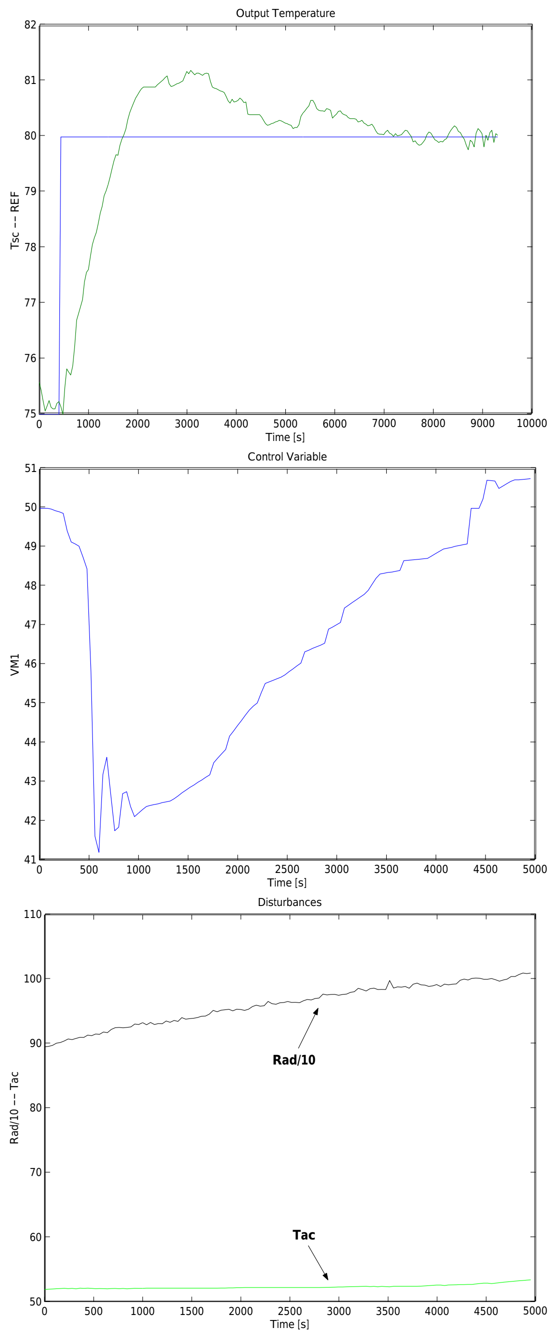

Fig. 8. Experimental results in VM1-Tsc control with $\kappa = 0.8$ (($t_s \simeq 1200s$ and $\delta \simeq 20\%$)).

observed in this structure is that now, besides error signal and output, the control signals (u_1 and u_2) are also weighted (because of numerical problems in the synthesis algorithm) by means of $W_{KS_1}(s)$ and $W_{KS_2}(s)$, respectively, which have been taken equal to unity.

In figure 10, the response of the simulated system in each operating point can be observed. The simulations have been made for controllers calculated for different values of parameter κ in $W_S(s)$ weighting function.

5.1 Experiments in the real plant

In figure 11, the results obtained in an experiment over the real plant is shown.

In these figures an important improvement in overall control performance is observed thanks to including the feed forward loop. This fact is especially evident in figure 11, between time instants 7000 and 10500 approximately, where an proper response of the controller is observed when an important disturbance (caused by clouds) in the radiation pattern occurs. Other characteristics like rising time or overshoot are conserved (even improved) from previous controller.

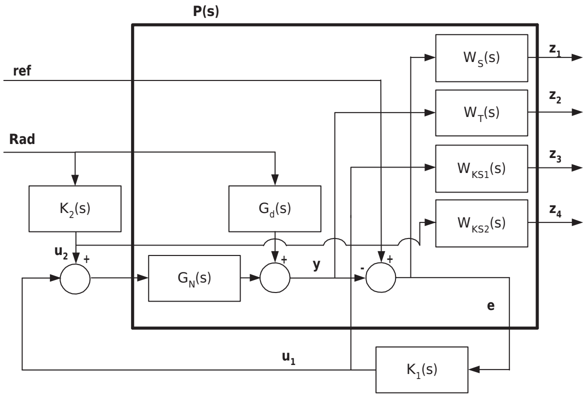

Fig. 9. Implemented feed forward control loop scheme.

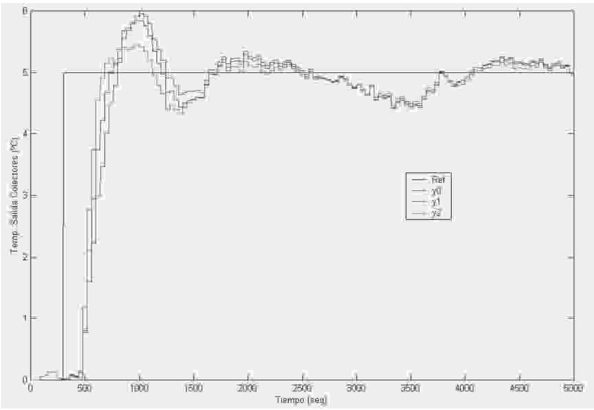

Fig. 10. Simulated tracking response in radiation conditions in Fig. 5.

6. CONCLUSIONS

A robust controller based in the H_∞ mixed sensitivity problem for the control of a solar plant has been designed. The resulting method is easy and is reduced to shaping an only parameter for each of the considered outputs. A basic feedback structure and a more complex one including a disturbance feed forward compensation loop have been designed. These controllers has been probed over the real plant, concluding that the achieved performance justifies the use of such kind of regulators over the system.

7. ACKNOWLEGMENTS

The authors wish to acknowledge Spanish Ministry of Education for funding this work under grants DPI 2004-06419 and DPI 2003-00429.

REFERENCES

Balas, G., Doyle, J., Glover, K., Packard, A., Smith, R. (1995). *μ-Analisys and Synthesis Toolbox User's Guide*. second ed.. The MathWorks Inc.. Natick, Mass.

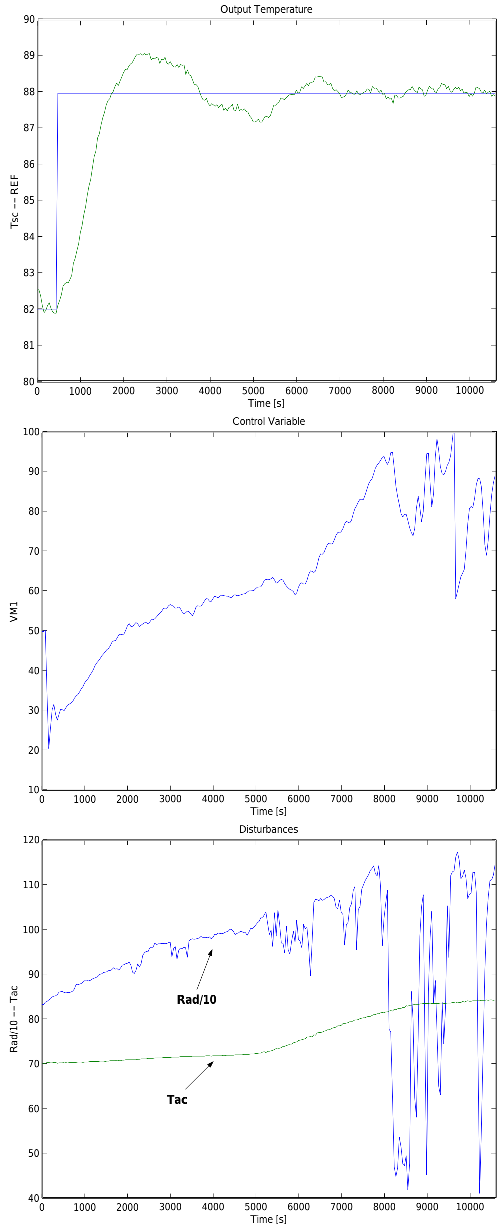

Fig. 11. Experimental results in VM1-Rad-Tsc control with $\kappa = 0.5$ (($t_s \simeq 1100s$ and $\delta \simeq 17\%$)).

Camacho, E,F, Berenguel, M., Rubio, F.R. (1997). *Advanced Control of Solar Plants*. first ed.. Springer.

Delgado J., Bordons C. (2000). *Modelado y simulacion de una planta solar de climatizacin (in spanish)*. PFC, ESI, Seville University.

Ljung, L. (1986). *System Identification Toolbox*. The Math Works, Inc.

Ortega, M.G., Rubio, F.R. (2004). "Systematic Design of Weighting Matrices for H_∞ mixed Sensitivity Problem". *Journal of Process Control* **14**(1), 89–98.

Sayigh A.M. (1992). *Solar Air Conditioning and Refrigeration*. Pergamon Press.

Skogestad, S., Postlethwaite, I. (1996). *Multivariable Feedback Control. Analysis and Design*. Jonh Wiley & Sons. New York.