Estimation of the main thermal parameters of a real size solar chimney from outdoor dynamic tests

M. J. Jiménez and M. R. Heras
Energy Efficiency in Buildings Unit, CIEMAT, Spain

J. Arce
Centro Nacional de Investigación y Desarrollo Tecnológico (CENIDET), México

ABSTRACT

The growing energy consumption for cooling of buildings is one important concern in Mediterranean countries. Natural ventilation plays an important role as passive energy saving strategy, regarding cooling of buildings in this climate. Solar chimneys are some of the most useful systems that make use of this strategy. But optimised implementation and quantification of the improvements achieved by these systems are required and must be assisted by a comprehensive thermal characterisation of them. However the performance of solar chimneys depends on combined and very complex physical phenomena. Frequently several approximations are assumed in theoretical analysis that can lead to certain degree of inaccuracy on the results.

This paper reports the experimental thermal characterisation of a solar chimney constructed and monitored at the LECE (Laboratorio de ensayos Energéticos para Components de la Edificación), from CIEMAT in Tabernas (Almería, Spain). The tests have been carried out in real size and dynamic outdoors weather conditions. The thermal characteristics of the solar chimney have been obtained by dynamic analysis of the data sets using system identification tools. The analysis has been done and validated using data from different testing conditions. The experimental results are compared to the bibliographic coefficients considered in previous theoretical studies.

1. INTRODUCTION

There are several experimental studies about natural ventilation, and particularly about solar chimneys. Afonso and Oliveira (2000) demonstrated that the highest temperature in the absorbent surface of a solar chimney is at medium high. Ong and Chow (2003) constructed a solar chimney, previously to a parametric study based in global energy balance, using electrical analogy. Another recent experimental study about solar chimneys was reported by Mathur et al., (2006). Martí and Heras (2006) reported a theoretical-experimental study of a real size solar chimney applied to Mediterranean climates.

Although the usefulness of solar chimneys as saving energy strategy, and though there are several reported studies, further research on these systems is still necessary. Most of these studies are theoretical, some of them carried out some laboratory tests and very few of these studies are related to real size tests, so more studies about these systems are necessary. It is particularly necessary optimise their implementation and quantify the benefits achieved by this implementation, which must be based in a comprehensive characterisation of solar chimneys. However the performance of solar chimneys depends on combined and very complex physical phenomena. Frequently several approximations are assumed in theoretical analysis that can lead to certain degree of inaccuracy on the results. Particularly the most frequent approximations applied to this analysis are related to:

- Convective heat transfer coefficients: Frequently approximated as constant or linear dependent on the wind velocity.
- Radiant heat exchange: Mean radiant temperature usually approximated by the ambient temperature.
- Sometimes it is assumed that the concrete wall surface only exchanges long wave radiation with the interior glass surface and vice versa, considering this exchange approximately following the same form as the exchange between two infinite parallel surfaces.
- 2D análisis
- Etc.

System identification can help to obtain more accurate and realistic representation of these effects, which can contribute to optimise the final implementation of solar chimneys as saving strategy in buildings.

This paper reports the experimental thermal characterisation of a solar chimney constructed and monitored at the LECE in Tabernas (Almería, Spain). The tests have been carried out in real size and dynamic outdoors weather conditions. The thermal characteristics of the solar chimney have been obtained by dynamic analysis of the data sets using system identification tools. In a first approach several subsystems have been considered for the analysis. This paper focuses on the modelling of one of these subsystems: the temperature of the collector surface, which plays a relevant role regarding the performance of the solar chimney. The analysis has been done and validated using data from different testing conditions. The results obtained can be used to improve the performance of model suggested in previous research (Martí et al., 2006) for the thermal characterisation of the solar chimney.

2. EXPERIMENT SET UP

2.1 Description of the studied solar chimney

It consists in a facing south solar chimney. 4.5m height, 1m width, and air channel 20cm thickness. The inlet area is 0.5x0.5 m^2, (Figs 1-2).

It is constructed using typical building materials. The absorber surface is made of reinforced concrete 15cm thickness black painted, to maximize the absorption coefficient. To reduce looses to the ambient, it has been protected by a glass cover 4mm thickness. The east and west walls are made with sandwiches of plywood and expanded polystyrene.

To minimize the effect of the external wind, a box has been installed at the inlet. Also a wind tracking protection device has been installed at the outlet to avoid inverse air flows due to the external wind.

Figure 1: View of the Solar Chimney

The considered chimney was designed to operate in summer time and it is provided with thermal inertia that delays its maximum efficiency to the night allowing the outdoors air inter into the building when the ambient air has its lowest temperature.

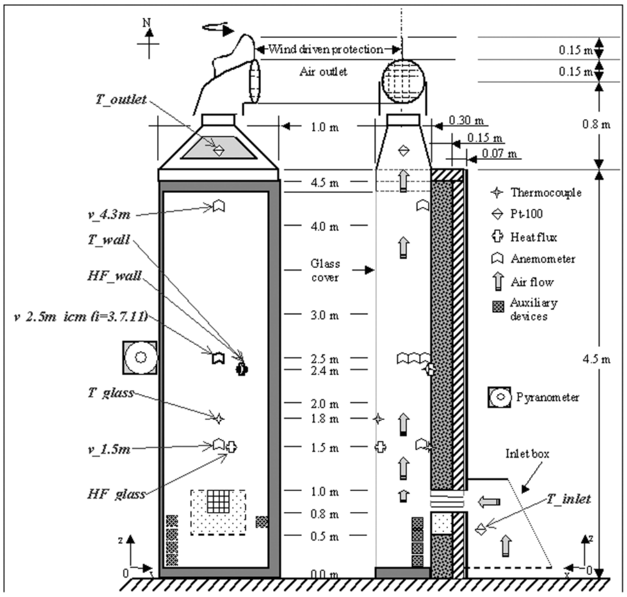

Figure 2: Solar Chimney Scheme. Sensor location.

The solar chimney is optimised when its efficiency, η_i, is maximised by maximising the ratio:

$$\eta_i \propto \frac{\dot{m}\left(T_{f,o} - T_{f,i}\right)}{G_v} \qquad (1)$$

where:

$\dot{m}$: air flow

$T_{f,o}$: outlet temperature

$T_{f,I}$: inlet temperature

G_v: solar radiation on the external surface

2.2 Measurement devices

Measurements and sensor location are indicated in Figure 2. The following devices have been used for the measurements:

- Air temperatures at inlet, outlet and ambient: Platinum thermorresitance PT100. 1/3 class B according to EIC 751.
- Wind velocity into the chimney channel: Hot wire anemometer.
- Solar radiation: Thermoelectric pyranometers. Secondary standard according to WMO.
- Heat flux density: Thermopile based device.
- Surface temperatures into the channel: Type T Thermocouples class 1 according to IEC-584-1982.
- Exterior and channel inlet relative humidity: Capacitive devices.

− Wind velocity: Cup anemometer based in an opto-electronic device.
− Wind direction: Vane potentiometer device.
All measurements are recorded using 3 dataloggers with a 16 bits a A/D converter.

3. DATA

The following data have been considered:

- Series 1: 16th to 18th of December 2005.
- Series 2: 20th to 22nd of December 2005
- Series 3: Series 1 and series 2.

The recorded data are shown in Figures 3-6.

These data were read every second and averaged and recorded minutely.

Heat fluxes to the air channel are considered positive.

It must be taken into account that in these files heat fluxes and surface temperatures were recorded without protection from solar radiation.

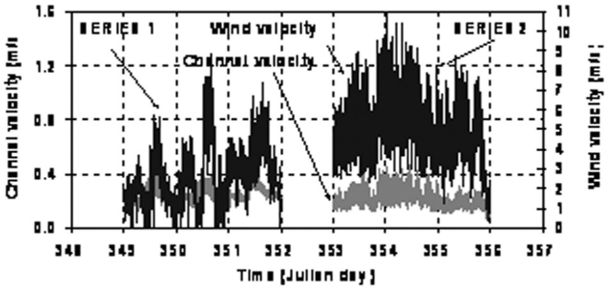

Figure 3: Outdoor and channel air velocities

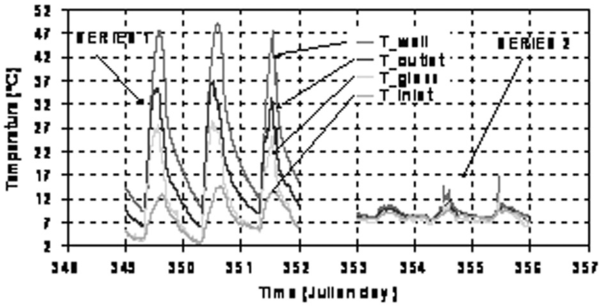

Figure 4: Wall, glass, inlet and outlet temperatures

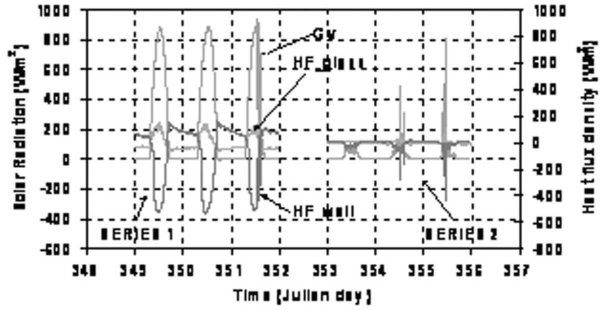

Figure 5: Heat fluxes and solar radiation

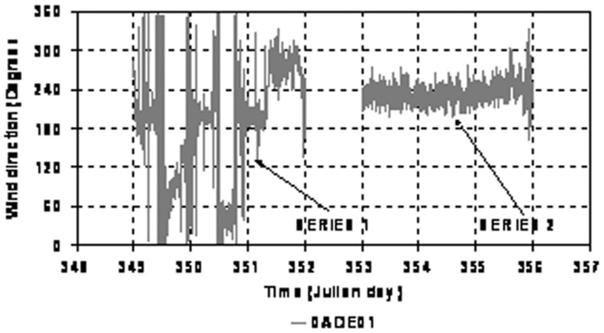

Figure 6: Wind direction

4. ANALYSIS

In order to simplify analysis and to avoid using measurements that could have been perturbed by the incident solar radiation only night periods have been considered for analysis.

This model has been built with the following assumptions:
− The concrete wall surface exchanges long wave radiation with all its surroundings surfaces.
− An effective area of 3.5m has been considered, corresponding to the glass surface measured from the top of the inlet.
− The airflow through the solar chimney is proportional to the air velocity measured into the air channel. Being the mean velocity in a section S of the channel, a constant parameter β multiplied by the air velocity v measured into the air channel.
− The temperature of the glass surface is constant along the surface.
− The heat flux density through the wall concrete surface is constant in the surface.
− The temperature of the concrete wall is constant in the surface.
− All heat transfer coefficients have the same form along the corresponding surface.

This system presents some similarities to a previously analysed system reported by Jimenez et al. (2007). However in the solar chimney there are some differences such as the non-constant airflow in the channel that increase the difficulty on the analysis.

A non-linear model in continuous time state space form has been considered.

This model has been implemented modelling the following states:

- T_2, Temperature of the concrete wall surface.
- T_{mrw}, defined as auxiliary state, modelling mean radiant temperature approximation seen from the concrete wall surface

The dynamics of the considered system, with these assumptions and for night periods are described by the following set of stochastic differential equations:

$$C_w \frac{dT_2}{dt} = -q\rho\beta S C_p v\left(T_o - T_i\right) + AHF_w + \\ + \sigma A\varepsilon_w\left(T_{mrw}^4 - T_2^4\right) + \sigma_1(\theta)\frac{d\omega_t}{dt} \qquad (2)$$

$$\frac{dT_{mrw}}{dt} = a\left(T_2^4 - T_{mrw}^4\right) + +\sigma_2(\theta)\frac{d\omega_t}{dt} \qquad (3)$$

And the data observed are described by the following measurement equation:

$$T_w = T_2 + e_1 \qquad (4)$$

As only night periods are considered for analysis, solar radiation is not into the model.

CTSM (Kistensen et al. 2003) has been used as software tool to obtain the required parameters.

5. RESULTS

The main parameters estimates are summarised in Table 1. These parameters are into the expected range but some of them present a high uncertainty which improvement will be considered in further analysis

If the residuals, (Figs 7-8) are observed it is concluded that the model shows a good performance modelling the considered output, in this case the temperature of the concrete wall.

The residuals as well as their average and standard deviation are in the range or under the uncertainty of the measurement device used for the considered temperature considered as output (Table 2 and Figs. 7-8). It is noticeable the low value of the average of the residuals that gives an estimation of the good performance of the model in steady-state (Table 2).

Considering the average and standard deviation of the residuals (Table 2), it is observed that this model presents good steady-state and dynamic performance, being better in the steady-state.

Table 1: Parameters obtained for the considered subsystem. All the units are in the international system.

	Series 1	**Series 3**
C_w	$(5.18\pm0.69)\cdot10^5$	$(5.68\pm0.65)\cdot10^5$
$q\rho Sc_p\beta$	$(9.8\pm1.2)\cdot10^3$	$(9.9\pm1.0)\cdot10^3$
ε_w	$(8.8\pm7.9)\cdot10^{-1}$	$(9.4\pm1.8)\cdot10^{-1}$

Table 2: Average and standard deviation of the residuals.

	Series 1	**Series 3**
Average	0.03	0.02
Standard deviation	0.9	0.7

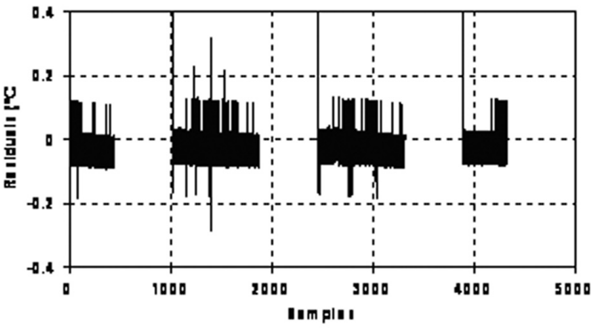

Figure 7: Residuals obtained for series 1. Notice that only night periods are considered for the analysis.

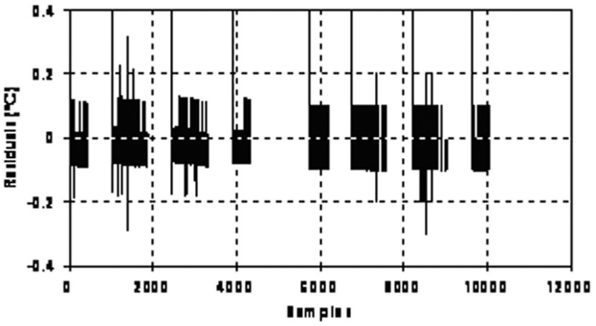

Figure 8: Residuals obtained for series 3. Notice that only night periods are considered for the analysis.

6. CONCLUSIONS

A model for the temperature of the collector surface has been found. This temperature plays an important role in the performance of the solar chimney. Taking into account the residuals obtained, the model shows a good performance modelling the considered output, in this case the mentioned temperature. Considering the average and standard deviation of the residuals it is concluded that this model presents good steady-state and dynamic performance, being better in the steady-state. High uncertainties have been observed in some of the parameter estimates which improvement will be considered in further analysis.

7. NOMENCLATURE

C_w	Heat capacity of the concrete wall
A	Total glass surface
ε_w	Emitance of the wall concrete surface.
σ	Stefan-Boltzman constant
T_g	Temperature of the glass surface
T_w	Temperature of the concrete wall surface
T_i	Air inlet temperature
T_o	Air outlet temperature

T_{mrw}	Mean radiant temperature approximation seen from the concrete wall surface.
HF_w	Heat flux density through the wall concrete surface (HF_wall in Figure 2).
v	Air velocity in the air channel (v-2.5m_7cm in Figure 2).
S	Section of the air channel
ρ	Air density
c_p	Air specific heat
q	Fraction of energy supply to the air gap and coming from the concrete wall.
β	Constant parameter that multiplied by air velocity measured into the air channel gives an estimation of the mean velocity in a section S of the channel.
a	Auxiliary constant coefficient
σ_{ii}	System error for i=1,2
e_{ii}	Measurement error for i=1,2

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