Dynamic thermal simulation of a solar chimney with PV modules

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ABSTRACT

The issue of this paper is to present theoretical results for a solar chimney with thermal mass, where the glass surface is replaced by photovoltaic (PV) modules. A portion of the heat absorbed by the PV modules is dissipated to the air channel in convective form, and it exchanges radiation heat with the concrete wall. These cooling phenomena for the PV modules improve their efficiency with a lower working temperature. Both phenomena are heating process to the air and the concrete wall, that produce natural ventilation. The solar chimney is supposed to be isolated from any building. The results obtained are an average air mass flow rate around 0.02 kg/s along the day and night, and a maximum PV temperature of 321 K.

1. INTRODUCTION

The energy consumption for cooling and heating buldings increases every year. The construction of buildings with low thermal efficiency, without taking in consideration any solar design, is supplied with the thermal conditioning of buildings by electrical heating and cooling machines.

Natural cooling and heating techniques must been employed to improve the energy efficiency of buildings. These techniques have been employed in the traditional buildings for long time. Some of them can be recovered and adapted, other ones are being developed.

Natural ventilation in buildings is a cooling passive technique appropriate for warm climates. Solar chimneys are natural ventilation systems that take advantage of solar radiation to generate convective air flows. This convection pulls air out from inside the building, replacing it with air from outside.

The first studies on solar chimneys have been reported in 1993 by Bansal et al. They present a stationary state model to describe a solar chimney, consistent by a conventional chimney linked to an air solar heater. Hirunlabh et al. report on 1999 the results of an experimental solar chimney, composed by a glass surface, air channel and a metallic black wall as collector surface. Afonso and Oliveira published on 2000 the experimental results of a conventional chimney and a solar chimney to evaluate the contribution of the natural ventilation in buildings. Khedari et al. on 1999 make a comparative study among different configurations of solar chimneys, classified like; roof solar collector, modified Trombe wall, Trombe wall and metallic solar wall. On 2003 Ong and Chow report the experimental and theorical results of a solar chimney similar to the Hirunlabh one. On 2004 Martí-Herrero and Heras Celemin propose a dynamical model for a solar chimney with thermal inertia, composed by a glass surface, air channel, and a 20cm wide concrete wall.

Different configurations have been studied for solar chimneys. The metallic solar wall type produces an air flow due to the solar radiation, indicated for tropical climates. The thermal inertia type storage heats during the day, producing ventilation, even without solar radiation during the night, indicated for Mediterranean climates.

The design of the proposed PV solar chimney is shown in Figure 1.

2. PHYSICAL MODEL

The physical model proposed to describe the

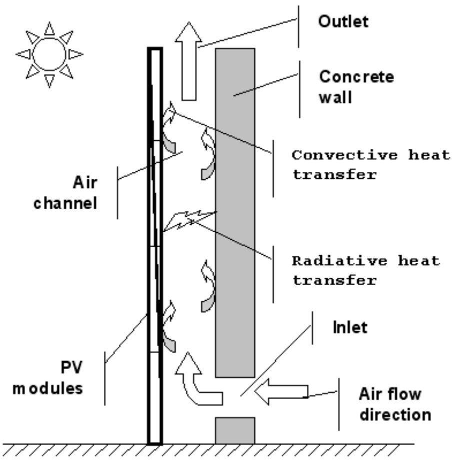

Figure 1: Design of a solar chimney with thermal mass and PV modules.

thermal behaviour for a thermal mass solar chimney with PV modules, is based on the one reported by Martí-Herrero and Heras Celemin on 2004, for a thermal inertia solar chimney. This dynamical model characterizes the system by representative temperatures for the different components (Ong and Chow, 2003): T_{pv} for PV modules temperature, T_f for the air channel temperature and 16 $T_{wi(i=1,16)}$ for the concrete wall temperature.

The model meteorological inputs are: solar radiation, ambient temperature and wind velocity. The physical properties of the different components are provided to the model. It calculates all the heat transfer phenomena considered and the representative temperatures of the system.

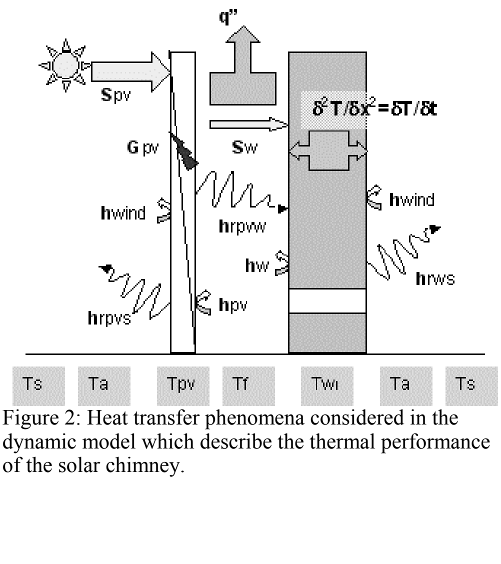

Figure 2: Heat transfer phenomena considered in the dynamic model which describe the thermal performance of the solar chimney.

The heat transfer phenomena considered in the dynamical model are shown in Figure 2 and they are:

- S_{pv}: Solar radiation gain for the PV modules;
- G_{pv}: Power generated by de PV modules;
- h_{rpvs}: Radiative heat transfer PV-sky;
- h_{wind}: Convective heat transfer by wind;
- h_{rpvw}: Radiative heat transfer PV-wall;
- h_{pv}: Convective heat transfer PV-air channel;
- q: Heat loss by the air that leave the chimney;
- S_w: Solar radiation solar gain by the wall;
- h_w: Convective heat transfer wall-air channel;
- δT/δx: Heat conduction equation;
- h_{rws}: Radiative heat transfer wall-sky.

The dynamic model proposed makes the energy balance for the PV modules, air channel and the concrete wall as shown in equations 1-4.

$$S_{pv} = h_{wind}(T_{pv} - T_a) + h_{rpvs}(T_{pv} - T_s) + \\ + h_{pv}(T_{pv} - T_f) + h_{rpvw}(T_{pv} - T_{w0}) \quad (1)$$

$$q = h_{pv}(T_{pv} - T_f) + h_w(T_{w0} - T_f) \quad (2)$$

$$S_w + h_{rpvw}(T_{pv} - T_{w0}) = \\ = h_w(T_{w0} - T_f) + k\frac{T_{w-1} - T_{w1}}{2\Delta x} \quad (3)$$

$$k\frac{T_{wi-1} - T_{wI+1}}{2\Delta x} = \\ h_{wind}(T_{wI} - _{Ta}) + h_{rws}(T_{wI} - T_s) \quad (4)$$

The conduction heat transfer for the interior of the concrete wall is described by:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (5)$$

Resolved by numerically using the next approximations:

$$\frac{\partial y}{\partial z} = \frac{y_{i+1} - y_i}{\Delta z} \quad (6)$$

$$\frac{\partial 2y}{\partial z2} = \frac{y_{i+1} - 2y_i + y_{i-1}}{\Delta z2} \quad (7)$$

The convective heat transfer due to the wind for the external surface of the PV modules and concrete wall is described by the experimental equation (McAdams, 1994):

$$h_{wind} = 5.7 + 3.8V \quad (8)$$

where V is the wind velocity.

The sky temperature, T_s, for the radiative heat transfer between the external surfaces and the sky is given by the experimental equation (Swinbank, 1963):

$$Ts = 0.0552T_a^{1.5} \quad (9)$$

The heat loss from the solar chimney due to the heated air that leaves the channel is given by the expression (Bansal et al., 1993):

$$q = \frac{\dot{m} c_f (Tf - Ta)}{\gamma WL} \quad (10)$$

where γ is 0.75 (Bansal et al., 1993), W y L are the dimensions of the chimney and $\dot{m}$ is:

$$\dot{m} = C_d \frac{\rho_f A_o}{\sqrt{1 + A_o / A_i}} \sqrt{\frac{2gL(T_f - T_a)}{T_a}} \quad (11)$$

where C_d is the discharge coefficient, A_o and A_i are the outlet and inlet areas and g us the gravity.

The convective heat transfer coefficients, h_{pv} and h_w, are calculated using the Nusselt number Nu_{if} where i is the solid surface:

$$h_i = \frac{N_{uif} \cdot K}{L} \quad (12)$$

The Nusselt number is calculated by a mathematical expression (Incropera and De Witt, 1996) dependent to the Rayleigh number, Ra_{if}, and Prandtl number, Pr.

If $Ra_{if} < 10^9$, a laminar flow is considered:

$$Nui_f = 0.68 + \frac{0.67Ra_{if}^{1/4}}{\left(1 + (0.492/\Pr)^{9/16}\right)^{4/9}} \quad (13)$$

If $Ra_{if} > 10^9$, a turbulent flow is considered:

$$Nui_f = (0.825 + \frac{0.387Ra_{if}^{1/6}}{\left(1 + (0.492/\Pr)^{9/16}\right)^{8/27}})^2 \quad (14)$$

3. CASE STUDY

The solar chimney with thermal inertia and PV modules proposed in this research, is based on the dimensions of the solar chimney with thermal inertia constructed in the Energetic Research Laboratory for Construction Components (LECE, Almería, Spain) (Fig. 3).

Figure 3: Experimental colar chimney with thermal inertia existing at LECE (Almería, Spain).

The dimensions are:

- 4m high;
- 20cm air channel width;
- 20cm concrete wall width;
- $0.04m^2$ inlet area;
- $0.25m^2$ outlet area.

The reinforced concrete wall is black painted on its interior surface for better absorption of the solar radiation. It is supposed that the solar radiation absorption, α_w, is 0.82; emissivity, ε_w, is 0.95; thermal conductivity, k_w, is 1.63 W/mK; heat capacity, c_w, is 1090 J/kgK and the density, ρ_w, is 2400 kg/m^3.

The physical properties of the air are given by empiric correlations dependent on the temperature, and fitted to the interval 300-350 K (Ong, 2003).

The PV modules have been supposed as generics ones, which properties are a solar radiation absorption, α_{pv}, of 0.70; electrical generation efficiency of 0.15; and reflection index, τ_{pv}, of 0.5. The PV modules are supposed to have no thermal inertia or thermal capacity.

The meteorological data is taken from a weather station at LECE for two sunny days at summer. It is shown in Figure 4. 313 K ambient temperature, 450 W/m^2 solar radiation over vertical surface and 8 m/s wind velocity are reached.

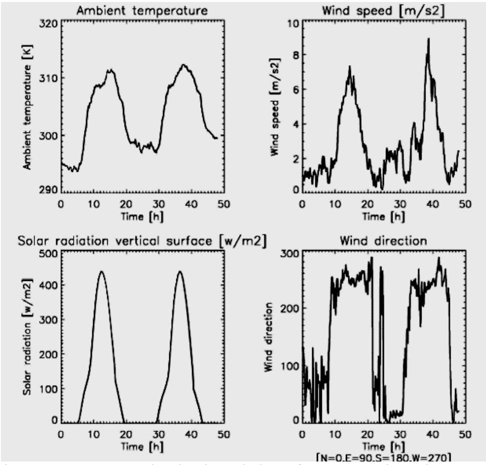

Figure 4: Meteorological real data from two days in summer at LECE, employed in the model proposed.

4. RESULTS

The results obtained by the application of the model proposed, with the real meteorological data available are shown in Figure 5. In all graphics is represented the ambient temperature.

The top graphic is the air mass flow rate in two cases; a) solar chimney with thermal inertia and glass cover and b) solar chimney with thermal inertia and PV modules. The air mass flow rate is higher during the two days in the first case. The results obtained in the case of PV modules show that, even with only 10% of solar radiation incidence over the concrete wall, a natural ventilation is obtained during the night. More than 0.02 kg/s of air mass flow is reached during most of the night.

The second graphic shows the temperatures evolution of the system, in the case of PV modules. The estimated work temperature for the PV modules reaches, as maximum, 321 K, and a maximum difference with ambient temperature of 10 K. The wall surfaces temperature show its thermal inertia with a soft wave variation.

The third graphic is the thermal fluxes evolution to the channel interior air. In this model the air absorption coefficient is null, so only by convective heat transfer can be heated. This graphic shows how the PV heat the air during the day, and the wall during the night.

In the forth graphic appear all the heat transfer phenomena considered in the model for the PV modules. The solar gain is the heating source, and the rest of phenomena are cooling process for the PV module, except during the night, when the radiative heat transfer from the wall heats the PV module.

5. DISCUSSION

The air mass flow rate obtained is high enough to consider this solar chimney configuration as a valid natural ventilation system (Khedari et al., 1999). The PV modules transfer heat to the air during the day, and the concrete wall during the night, and both give to this solar chimney configuration almost natural ventilation during all day. Only in the afternoon (17 h), when the PV modules temperature, inner surface wall temperature and ambient temperature tends to be equal, minor natural ventilation is produced. During two hours in the early morning, no natural ventilation is produced as well, but at these time it is not necessary.

The PV module estimated temperature reach 321 K, 10 k over ambient temperature. For equal solar irradiance, experimental measurements on ventilated PV façade (Wilshaw et al., 1996) are around 18 K difference temperature. Experimental thermal data on photovoltaic modules (Alonso and Balenzategui, 2004) obtains for the same solar irradiance, 15 K difference, but with 302 K ambient temperature, instead 313 K on this paper.

The more important cooling process for the module is the wind convective heat transfer according to the results obtained, due the real meteorological data, that show peaks of 8 m/s wind velocity. Equation (8) rules the convective heat transfer by the wind, and this equation has been questioned before (Martí-Herrero and Heras Celemin, 2004b) and is necessary to be revised.

6. CONCLUSIONS

The solar chimney with thermal inertia and PV modules replacing the glass surface proposed, acts as natural ventilation system appropriate to Mediterranean climates due to the nocturnal ventilation produced.

From the PV module point of view, the system does not overheat, and reaches work temperatures lowers to those reported on the bibliography, or similar in the ventilated cases.

To validate the model is required experimental

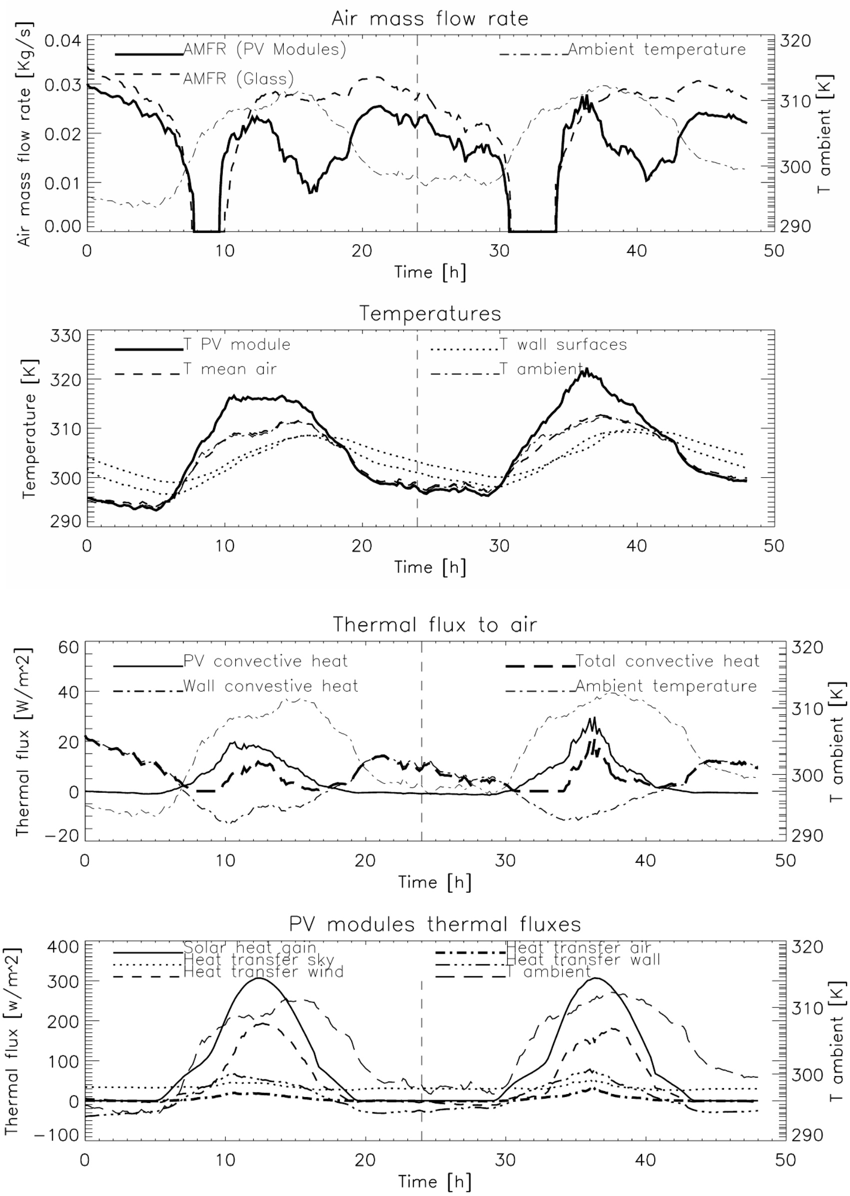

Figure 5: Theorical results obtained for a solar chimney with thermal mass and PV modules. First graphic: Evolution of air mass flow rate (AMFR) for the case of solar chimney with glass surface, and PV modules case. Second graphic: Temperatures evolution for all the system (PV modules case). Third graphic: Evolution of heat transfer process to inner air (PV modules case). Forth graphic: Evolution of heat transfer process in the PV modules.

work, considering heat capacity of the module (Knaupp, 1992), and revising the wind convective heat transfer equation (eq.4) (Marti-Herrero, et al., 2004b)

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