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Dynamic physical model for a solar chimney

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Abstract

The aim of this research is to investigate the theoretical usefulness of a solar chimney with thermal inertia applied to the Mediterranean climates, offering nocturnal ventilation benefits. A mathematical dynamical model is proposed to evaluate the energy performance of a solar chimney with 24 cm concrete wall as storage surface for solar radiation. The results obtained with the proposed model are coherent with several models response and experiments reported on solar chimneys. As well, the difference of the proposed model to others is the incorporation of an unsteady state and the inclusion of thermal inertia. The results show that for a 2 m height and width of air channel of 14.5 cm, 0.011 kg/s air mass flow rate is obtained for 450 W/m^2. The 24 cm thickness concrete wall, reaches its greater temperature 2 h later with respect to the maximum ambient temperature, maintaining its temperature over the beginning of the night, so nocturnal ventilation is achieved. The model shows the interest in continuing investigating on this cooling techniques and to built a solar chimney with thermal inertia for future experimental research.
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1. Introduction

Energy consumption in the building sector is clearly an important factor in the total energy bill, and it continues to increase. Cooling and heating in buildings are techniques used to condition their environments. Research and development of natural methods for this conditioning are assuming to increase the importance in modern building in order to bring about savings in energy.

Natural cooling is one of the techniques used for conditioning buildings, and solar chimneys are systems which when applied to buildings, can generate this natural cooling. Solar chimneys are natural ventilation systems which can contribute to improve the energy efficiency of buildings, and it is therefore necessary to investigate their behavior from the energy point of view.

Those components for buildings conditioning which use natural ventilation take advantage of solar radiation to generate convective air flows, which pull air out of the interior of the building, replacing it with air from outside. In this case the parameters of interest for bioclimatic construction are, the air flow rate through these systems, and the amount of energy which they supply to the building.

These cooling systems present some analogies with Trombe walls. The first studies which model the energetic performance of this system were reported by Hocevar and Casperson (1979) who worked with a Trombe wall 2.2 m high, and with an air channel varying in dimension from 0.025 to 0.2 m. In this work, the velocity profiles and temperatures through the air channel vary considerably during the day, additionally testing reveal that these profiles are functions of the channel width, room temperature, absorbed solar radiation, massive wall temperature and height of the inlet and outlet openings. Akbarzadeh et al. (1982) published the results of a 2.66 m height Trombe wall and variable width air channel between 0.10 and 0.35 m, and they conclude that the heat transfer in

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Nomenclature

A_o	area of the outlet of the chimney (m^2)	Ra_{if}	Rayleigh number for the surface i
A_i	area of the inlet of the chimney (m^2)	Rad	solar radiation on vertical surface ($W\,m^{-2}$)
C_d	coefficient of discharge of air channel	S_g	solar radiation gain by the glass ($W\,m^{-2}$)
c_f	specific heat of air ($J\,kg^{-1}\,K^{-1}1$)	S_w	solar radiation gain by the wall ($W\,m^{-2}$)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)	T_a	ambient temperature (K)
c_w	specific heat of wall ($J\,kg^{-1}\,K^{-1}$)	T_f	fluid temperature (K)
g	gravitational constant ($m\,s^{-1}$)	$T_{f,i}$	inlet fluid temperature (K)
h_g	convective heat transfer coefficient between glass and air channel ($W\,m^{-2}\,K^{-1}$)	$T_{f,o}$	outlet fluid temperature (K)
h_{rga}	radiative heat transfer coefficient between glass ambient ($W\,m^{-2}\,K^{-1}$)	T_g	glass temperature (K)
h_{rwa}	radiative heat transfer coefficient between wall and channel ($W\,m^{-2}\,K^{-1}$)	T_s	sky temperature (K)
h_{rwg}	radiative heat transfer coefficient between wall and glass ($W\,m^{-2}\,K^{-1}$)	T_w	wall temperature (K)
h_w	convective heat transfer coefficient between wall and air channel ($W\,m^{-2}\,K^{-1}$)	V	wind velocity ($m\,s^{-1}$)
h_{wind}	convective wind heat loss coefficient ($W\,m^{-2}\,K^{-1}$)	W	width of air channel (m)
k	thermal conductivity of the concrete wall ($W\,m^{-1}\,k^{-1}$)	α	thermal diffusivity ($m^{-2}\,s^{-1}$)
K_f	thermal conductivity of the air ($W\,m^{-1}\,k^{-1}$)	α_g	absorptivity of glass
L	height of solar chimney (m)	α_w	absorptivity of interior surface wall
M	coefficient of heat transferred to the air that leave the chimney ($W\,m^{-2}\,K^{-1}$)	β	coefficient of expansion of air (K^{-1})
$\dot{m}$	air mass flow rate ($kg\,m^{-1}$)	Δt	interval of time (s)
Nu_{Lif}	Nusselt number for the surface i	Δx	distance between nodes of the concrete wall (m)
P_r	Prandtl number	ϵ_g	emissivity of the glass
$\dot{q}''$	heat transfer to air stream ($W\,m^{-2}$)	ϵ_w	emissivity of the wall
		γ	constant in mean temperature approximation
		μf	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
		ρf	mean interior air density ($kg\,m^{-3}$)
		$\rho_{f,o}$	outlet air density ($kg\,m^{-3}$)
		ρ_w	wall density ($kg\,m^{-3}$)
		σ	Stefan–Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
		τ	transmissivity of glass

the interior can be described by free convection in turbulent regime between two surfaces to different temperature, and suggest a optimal air channel of 0.25 m. Bouchair (1988) using an electrically warmed up Trombe wall point out that the greater air volume flow rate is obtained, when the width of the air channel is the tenth of the height of the Tromble wall.

The solar chimneys are similar in physical concept to the Trombe walls. The difference relies on the purpose of each system; the solar chimneys serve to produce natural ventilation, and therefore cooling, whereas the Trombe walls are used for heating by radiation and warmed up air. The constructive difference is the heat insulation between the solar chimney and the indoors, as opposed to the radiator function of the Trombe wall towards the interior of the building. This function of a radiator is the one that exists, in warm climates. The Trombe walls are not viable and it is necessary to propose modifications, which have been insufficiently studied in this regard. Therefore solar chimneys are prioritized for warm climates because of the cooling that they can produce.

The first studies about solar chimneys began with Bansal et al. (1993) which developed a mathematical model for a steady state of a solar chimney consisting of a conventional chimney connected to a solar air collector. Khedari et al. (1999) shows the experimental results of natural ventilation effect by a solar chimney in the temperature and air renovation in a school. The results obtained in the school of 25 m^2 and with only one room, show the viability of the system. Afonso and Oliveira (2000), published the results of a solar chimney compared with a conventional chimney. They proposed a non-steady model of heat transfer in a single horizontal dimension, applying a model based on finite differences. In this model, the coefficients of heat transfer vary throughout the day according to temperatures. The measurements of air flow were made with tracer gas techniques, that agreed with the the results of the simulation. Ong (2003) propose a mathematical model of heat transfer in a steady state for a solar chimney, and contrast the model with a real solar chimney (Ong and Chow, 2003). The solar chimney is characterized by three temperatures: average temperatures of the glass, air and wall. The experimental setup is a solar chimney of 2 m height and the air channel width between 0.10 and 0.30 m, in real meteorological conditions. The most satisfactory results with the simulation in contrast to the experimental data were for solar radiation intensity of 200 to 650 W/m^2 and 0.3 m width air channel.

In Mediterranean climates, nocturnal natural ventilation is of prior interest. This can be implemented through a solar chimney incorporating an element with an appropriate thermal inertia.

2. Objectives

The objective of this work is to propose a developed physical model that describes the thermal and dynamic performance of a solar chimney with an accumulating element. The scheme of the proposed chimney is sketched in Fig. 1. There is a glass surface oriented to the south where the solar radiation cross trough, and a concrete wall that works as a capturing surface, which warms up the air in the interior of the channel. The concrete wall, due to its thermal inertia, produces natural convection even when solar radiation is not impinging it. This chimney is supposed to be isolated from any construction in order to eliminate other thermal effects not directly related to the solar chimney. This dynamic model is applied to evaluate the viability to undertake experimental studies to deep in the knowledge of these systems for nocturnal natural ventilation.

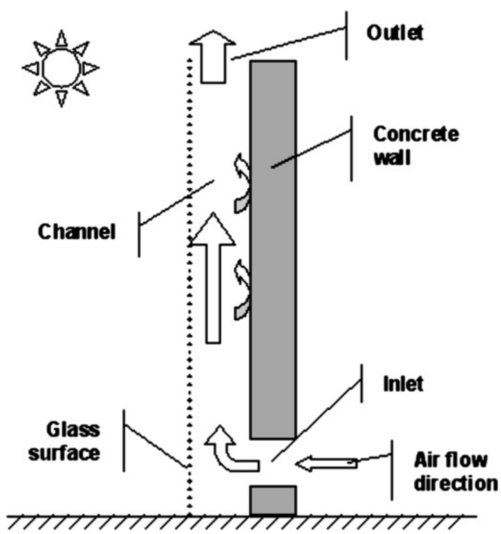

Fig. 1. Basic design of the solar chimney with a massive element for high thermal inertia.

3. Physical model

The heat transfer processes are considered in the horizontal dimension. The physical processes involved in this model are presented in Fig. 2. It is assumed that the glass as well as the inner air flow remain at only one temperature each, T_g and T_f respectively (Ong and Chow, 2003). The concrete wall is described by 16 temperatures T_{wi}, two corresponding to both vertical surfaces, and 14 for the interiors. It is assumed that the thermal inertia of the glass, and also the radiative heat absorption of the air are negligible. As the solar chimney is isolated from any building, the two outer surfaces, oriented to the north and the south, interchange heat with the ambient.

3.1. Concrete wall

The thermal inertia associated with the concrete wall characterize this model that describes the thermal performance of the solar chimney. For that reason, the thermal inertia is introduced in the model through the equation of heat conduction in a solid:

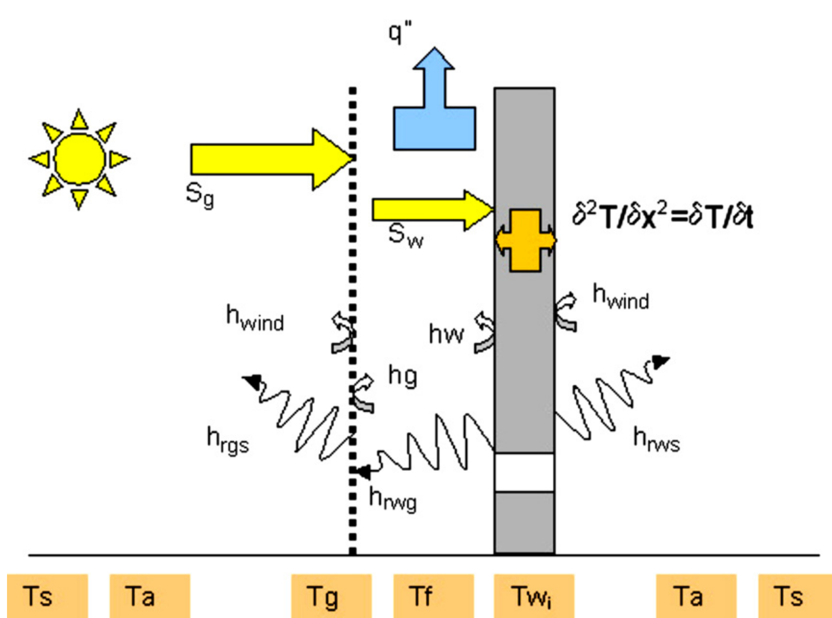

Fig. 2. Scheme of the processes of heat transfer that are considered in the dynamic model with thermal inertia for solar chimney.

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

where α is the thermal diffusivity:

$$\alpha = \frac{k}{\rho c_p} \quad (2)$$

being; k the thermal conductivity, ρ density of the solid and c_p the specific heat. In this way, the outer and inner layer temperatures of the concrete wall can be calculated.

In order to solve this equation the following approximation for the partial derivatives substituting them for the corresponding finite differences, is used:

$$\frac{\partial T}{\partial x} = \frac{T(x+\Delta x) - T(x)}{\Delta x} = \frac{T_{i+1} - T_i}{\Delta x} \quad (3)$$

$$\frac{\partial T}{\partial t} = \frac{T(t+\Delta t) - T(t)}{\Delta t} = \frac{T^{n+1} - T^n}{\Delta t} \quad (4)$$

and it can be demonstrated that:

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1} + T_{i-1} - 2T_i}{\Delta x^2} \quad (5)$$

Introducing Eqs. (4) and (5) into Eq. (1) and using notation T_i^n, where the subscript i is referenced to the dependence of the temperature at the distance x, and the superscript n with time t, it is obtained:

$$\frac{T_{i+1}^n + T_{i-1}^n - 2T_i^n}{\Delta x^2} = \frac{1}{\alpha}\frac{T_i^{n+1} - T_i^n}{\Delta t} \quad (6)$$

T_i^{n+1} is the temperature in the node i for the time $n+1$. This term can be isolated in Eq. (6) as a function of temperatures at time n. In this way, knowing the temperatures in the system at time n, the temperatures in the system can be known at a time Δt, so $n+1$. Isolating T_i^{n+1} in Eq. (6) it is:

$$T_i^{n+1} = \frac{\alpha \Delta t}{\Delta x^2}(T_{i+1}^n + T_{i-1}^n - 2T_i^n) + T_i^n \quad (7)$$

In order to solve Eq. (1) three boundary conditions are needed, two spatial and one time dependent, that are

- T_i^0, initial temperature for any node in the solid.
- T_0^n, temperature at every time n in contact with the node 0.
- T_{I}^0, temperature at every time n in contact with the node I.

As T_0^n, and T_{I}^n, are in the surfaces of the wall, an energy balance is made at those points, being S_{w} the solar radiation gain.

- T_0^n

$$S_{\mathrm{w}} = h_{\mathrm{w}}(T_0^n - T_{\mathrm{f}}^n) + h_{\mathrm{rwg}}(T_0^n - T_{\mathrm{g}}^n) + k\frac{\partial T}{\partial x} \quad (8)$$

- T_{I}^n

$$k\frac{\partial T}{\partial x} = h_{\mathrm{wind}}(T_{\mathrm{I}}^n - T_{\mathrm{a}}^n) + h_{\mathrm{rws}}(T_{\mathrm{I}}^n - T_{\mathrm{s}}^{\mathrm{a}}) \quad (9)$$

The partial derivatives are replaced by $\frac{(T_{i-1}^n - T_{i+1}^n)}{2\delta x}$, resulting:

- T_0^n

$$S_{\mathrm{w}} = h_{\mathrm{w}}(T_0^n - T_{\mathrm{f}}^n) + h_{\mathrm{rwg}}(T_0^n - T_{\mathrm{g}}^n) + k\frac{(T_{-1}^n - T_1^n)}{2\Delta x} \quad (10)$$

- T_{I}^n

$$k\frac{(T_{\mathrm{I}-1}^n - T_{\mathrm{I}+1}^n)}{2\Delta x} = h_{\mathrm{wind}}(T_{\mathrm{I}}^n - T_{\mathrm{a}}^n) + h_{\mathrm{rws}}(T_{\mathrm{I}}^n - T_{\mathrm{s}}^n) \quad (11)$$

In the case of T_0^n, the temperature of interest from this boundary condition is T_{-1}^n, that following from (10) is

$$T_{-1}^n = \frac{2\Delta x}{k}(S_{\mathrm{w}} - h_{\mathrm{w}}(T_0^n - T_{\mathrm{f}}^n) - h_{\mathrm{rwg}}(T_0^n - T_{\mathrm{g}}^n)) + T_1^n \quad (12)$$

For the case T_{I}^n, the temperature of interest is $T_{\mathrm{I}+1}^n$, that following from (11):

$$T_{\mathrm{I}+1}^n = T_{\mathrm{I}-1}^n - \frac{2\Delta x}{k}(h_{\mathrm{wind}}(T_{\mathrm{I}}^n - T_{\mathrm{a}}^n) + h_{\mathrm{rws}}(T_{\mathrm{I}}^n - T_{\mathrm{s}}^n)) \quad (13)$$

Therefore, Eq. (7) that calculates the new temperature of each node. However, in the particular case of the first and last nodes (T_0^{n+1} and T_{I}^{n+1}), it is necessary to use Eqs. (12) and (13), respectively.

3.2. Glass and fluid

In order to calculate the temperatures of the glass and fluid, their energy balance must be expressed first.

The glass is characterize by unique temperature, ignoring it is thermal mass, as a consequence of the thermal balance between the solar radiation absorption, radiative heat transfer from the concrete wall, convective heat transfer from the air's channel, and the heat transfer with the atmosphere (wind and sky):

- T_{g}^n

$$S_{\mathrm{g}} + h_{\mathrm{g}}(T_{\mathrm{f}}^n - T_{\mathrm{g}}^n) + h_{\mathrm{rwg}}(T_0^n - T_{\mathrm{g}}^n) = h_{\mathrm{wind}}(T_{\mathrm{g}}^n - T_{\mathrm{a}}^n) + h_{\mathrm{rgs}}(T_{\mathrm{g}}^n - T_{\mathrm{s}}^n) \quad (14)$$

Regarding the fluid, air in this case, the time dependent parameter is the heat transfer to fluid that leaves the chimney in every Δt, M, explain forward.

- T_{f}^n

$$h_{\mathrm{w}}(T_0^n - T_{\mathrm{f}}^n) = h_{\mathrm{g}}(T_{\mathrm{f}}^n - T_{\mathrm{g}}^n) + M(T_{\mathrm{f}}^n - T_{\mathrm{a}}^n) \quad (15)$$

Isolating T_{f}^n from (15), it is obtained:

$$T_{\mathrm{f}}^n = \frac{h_{\mathrm{g}}T_{\mathrm{g}}^n + MT_{\mathrm{a}}^n + h_{\mathrm{w}}T_0^n}{h_{\mathrm{g}} + h_{\mathrm{w}} + M} \quad (16)$$

Introducing (16) in (14) and clearing T_g^n it is

$$T_g^n = \frac{S_g + \frac{h_g M T_a^n}{h_g + hw + M} + \frac{h_g h_w T_0^n}{h_g + hw + M} + h_{rwg} T_0^n + h_{wind} T_a^n + h_{rws} T_s^n}{h_g + h_w + h_{rwg} + h_{wind} - \frac{hg^2}{h_g + h_w + M}} \quad (17)$$

Finally, the equations that describe the system are Eqs. (17), (16), for the glass and the fluid, and Eq. (7) for the concrete wall, where in the case of $i = 0$ Eq. (12) is also used, and in the case of $i = \mathrm{I}$ Eq. (13).

3.3. Heat transfer coefficients

3.3.1. Heat transfer to the air that flows outside of the chimney

The energy transmitted to the air that leaves the chimney, $\dot{q}''$, has the mathematical form:

$$\dot{q}'' = \frac{\frac{dm}{dt} c_f (T_{f,o} - T_{f,i})}{WL} \quad (18)$$

where W and L are the width of the channel and the height of the chimney, and c_f the heat capacity of the air.

Experimentally it is found that the fluid average temperature related to the inlet temperature, $T_{f,i}$ and of outlet temperature, $T_{f,o}$ (Hirunlabh et al., 1999) can be expressed in the following way:

$$T_f = \gamma T_{f,o} + (1 - \gamma) T_{f,i} \quad (19)$$

where γ takes the value of 0.75 according to Hirunlabh et al. (1999) and 0.74 in the study of Ong and Chow (2003).

The heat transmitted to the air that leaves the chimney can be rewritten considering $\dot{q}''$ in the following way:

$$\dot{q}'' = \frac{\dot{m} c_f (T_f - T_{f,i})}{\gamma WL} = M(T_f - T_{f,i}) \quad (20)$$

M represents the heat transfer to fluid that leaves the chimney.

$$M = \frac{\dot{m} c_f}{\gamma WL} \quad (21)$$

$\dot{m}$, is the air volume that crosses the chimney and according to Bansal et al. (1993) and Andersen (1995) it has the following expression:

$$\dot{m} = C_d \frac{\rho_{f,o} A_o}{\sqrt{1 + A_o/A_i}} \sqrt{\frac{2gL(T_f - T_a)}{T_a}} \quad (22)$$

where $\rho_{f,o}$ is the density of the air when leaving the chimney, A_o and A_i are inlet and outlet area of the chimney openings.

3.3.2. Radiative heat transfer coefficients

h_{rwg} is the radiative heat transfer coefficient between the wall and the glass.

$$h_{rwg} = \sigma \frac{(T_g^2 + T_w^2)(T_g + T_w)}{1/\epsilon_g + 1/\epsilon_w - 1} \quad (23)$$

h_{rgs} is the radiative heat transfer coefficient between the glass and the sky.

$$h_{rga} = \sigma \epsilon_g (T_g + T_s)(T_g^2 + T_s^2) \quad (24)$$

h_{rws} is the radiative heat transfer coefficient between the wall and the sky.

$$h_{rwa} = \sigma \epsilon_w (T_{wI} + T_s)(T_{wI}^2 + T_s^2) \quad (25)$$

where the sky temperature, T_s, according to Swinbank (1963) has the experimental expression:

$$T_s = 0.0552\, T_a^{1.5} \quad (26)$$

3.3.3. Convective heat transfer coefficients

h_{wind} is the convective heat transfer coefficient due to the wind, that affects the glass and the later surface of the wall. It takes the following experimental expression according to McAdams (McAdams, 1994), that only depends on the velocity module of the wind:

$$h_{wind} = 5.7 + 3.8\ \mathrm{V} \quad (27)$$

h_g, h_w are the convective heat transfer coefficients between glass and the fluid and the wall and fluid. These coefficients are calculated through the Nusselt number $Nu_{L_{if}}$, where i is the solid surface

$$h_i = \frac{Nu_{L_{if}} \cdot K}{L} \quad (28)$$

The $Nu_{L_{if}}$ calculation is done through experimental correlations given by Incropera and DeWitt (1996), where $Nu_{L_{if}}$ depends on the Rayleigh number, Ra_{if} and the Prandtl number, Pr, being the latter dependent only on the type of fluid. The Rayleigh number depends on the temperature difference between the surface and the fluid.

If $Ra_{if} < 10^9$ there is laminar flow and the expression to calculate $Nu_{L_{if}}$ has the form:

$$Nu_{L_{if}} = 0.68 + (0.67 Ra_{if}^{1/4})/(1 + (0.492/Pr)^{9/16})^{4/9} \quad (29)$$

If $Ra_{if} > 10^9$ there is turbulent flow and $Nu_{L_{if}}$ is:

$$Nu_{L_{if}} = \left[0.825 + \frac{0.387 Ra_{if}^{1/6}}{(1 + (0.492/Pr)^{9/16})^{8/27}}\right]^2 \quad (30)$$

where:

$$Ra_{if} = \frac{g\beta(t_i - t_f)L^3}{\alpha v} \quad (31)$$

3.3.4. Solar radiation gains

S_g is the radiation solar gain in the glass and depends on its absorptance α_g and the incident solar radiation over vertical surface Rad.

$$S_g = \alpha_g \cdot \mathrm{Rad} \quad (32)$$

S_w is the radiation solar gain in the concrete wall and depends on the radiation transmitted by the glass τ and on the absorptance of the concrete wall, α_w.

$$S_w = \alpha_w \tau \cdot \mathrm{Rad} \quad (33)$$

4. Analysis

In order to evaluate the model proposed it is necessary to define the dimensions and physical characteristics of a solar chimney with thermal inertia. The proposed dimensions correspond to studied solar chimneys values and with experimental data published (Hirunlabh et al., 1999; Ong and Chow, 2003).

In addition, a series of real weather data, corresponding to two days of measurements 27 and 28 of July 2003 in the Energetic Research Laboratory for Construction components (LECE Almeria Spain). This two consecutive days have been selected from measurements during 30 days because the incident solar radiation was complete with clear sky conditions and the force of the wind was the lowest from the whole measuring period. These data is minutely recorded and represented in the Fig. 3.

The analysis for each component is

Glass: It is assumed that the glassed surface has a thickness of 0.5 mm, absorption coefficient, α_g, is 0.006; transmissivity, τ_g, is 0.84; and emissivity, ϵ_g, is 0.8.

Fluid: The considered channel width of the chimney is 14.5 cm. The inlet and outlet air opening areas are 0.025 m^2. The fluid is air which physical properties are given by empiric correlations proposed by Ong (2003). These correlations depend on the temperature and are fitted for the interval of 300–350 K. Dynamic viscosity (kg/ms)

$$\mu_f = (1.846 + 0.00472(T_f - 300)) \times 10^5 \quad (34)$$

Density (kg/m^3)

$$\rho_f = 1.1614 - 0.00353(T_f - 300) \quad (35)$$

Thermal conductivity (W/mK)

$$k_f = 0.0263 + 0.000074(T_f - 300) \quad (36)$$

Specific heat (J/kgK)

$$C_f = (1.007 + 0.00004(T_f - 300)) \times 10^3 \quad (37)$$

Wall: The wall is assumed to be made of reinforced concrete, 24 cm of thickness and 2 m height. The inner surface of the wall is painted black, it is therefore assumed that its 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 a density, ρ_w, is 2400 kg/m^3.

In order to determine the number of intervals or nodes in which the concrete wall is divided the following convergence criterium is used:

$$\frac{\alpha \Delta t}{\Delta x^2} < 0.25 \quad (38)$$

In this case, the weather data is recorded every minute, and therefore the distance between nodes, Δx, can be determined. In this case:

$$\Delta x = 0.015 \text{ m} \quad (39)$$

Thus, for a thermal diffusivity of the concrete which value is $\alpha = 6.23 \times 10^{-7}$ m^2/s and $\Delta t = 60$ s:

$$\frac{\alpha \Delta t}{\Delta x^2} = 0.17 < 0.25 \quad (40)$$

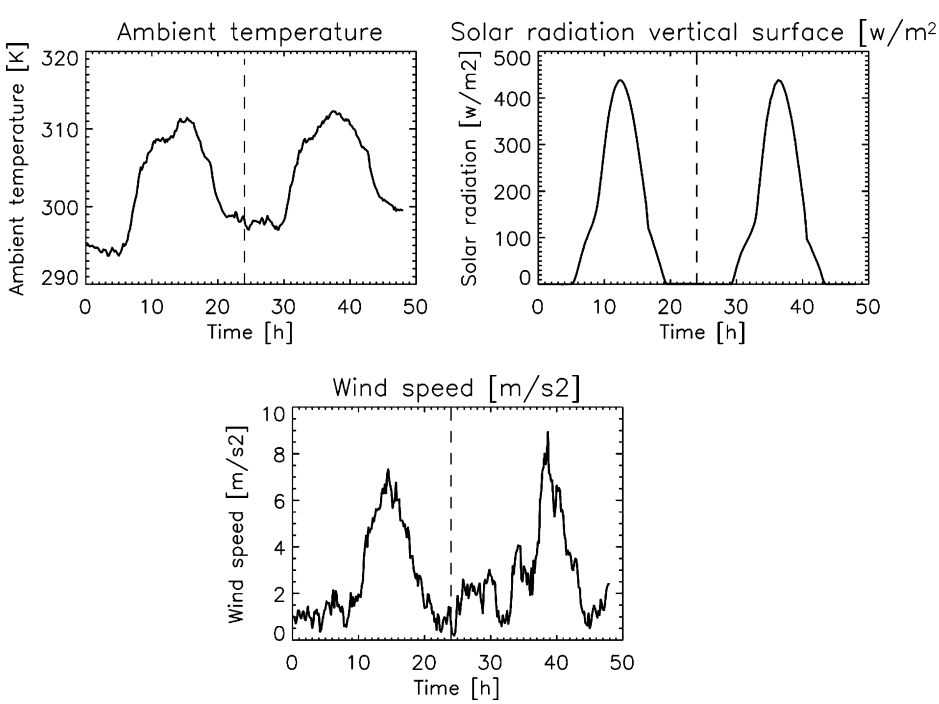

Fig. 3. Weather real data, corresponding to tow days, employed in the physical model evaluation as input data.

This is the reason why applying a distance between nodes of 0.015 m, 16 points are obtained, where the temperature of the wall is calculated. Finally it is determined $I = 15$, which is certain to apply in the Eqs. (7), (12) and (13) that describe the thermal performance of the concrete wall.

In order to solve this equation system, it is necessary to take into consideration certain aspects. The new temperatures of the wall depends on the temperatures and heat transfer parameters at a previous time, as it is seen in the Eqs. (7), (12) and (13). However, the glass and fluid temperatures need to know the heat transfer parameters in that same time, because their equations were deduced from an instantaneous energy balance. This equation system is solved iteratively until the system converges.

5. Results

The results obtained by the applied the proposed dynamic model to a series of real weather data, are shown in the Figs. 4–6.

In the case of Fig. 4 is appraised in thermal evolution, that both glass and inner air, reach inferior temperature at sunrise. This is due to two phenomena: The radiative losses of glass towards the sky along the night, and the temperature of the wall, that to those hours also is inferior to the ambient temperature, due to its thermal inertia, Fig. 5.

The inertial displacement of the proposed concrete wall is 2 h for the inner surface of the wall, and 3 h for the surface exposed to the atmosphere. The interior of the wall reaches its higher temperature 5 hours later, after to the temperature.

In Fig. 6 the air volume that crosses the chimney is shown and it reaches its maximum value at 22:00 h. The volume air flow is superior to 0.010 kg/s during most of the time of simulation, except at sunrise when it is nil, since the thermal inertia of the system causes the ambient temperature to be greater than the system temperature in those first hours of the day.

The temperature difference between the inner surface of the concrete wall than the outer temperature reaches 9 K at midnight, produces a volume air flow of 0.012 kg/s.

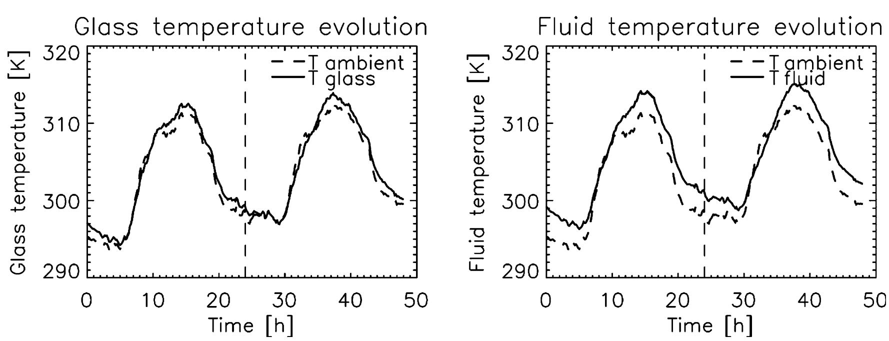

Fig. 4. Evolution of the glass (left) and the inner air temperatures (right) applying the proposed dynamic model.

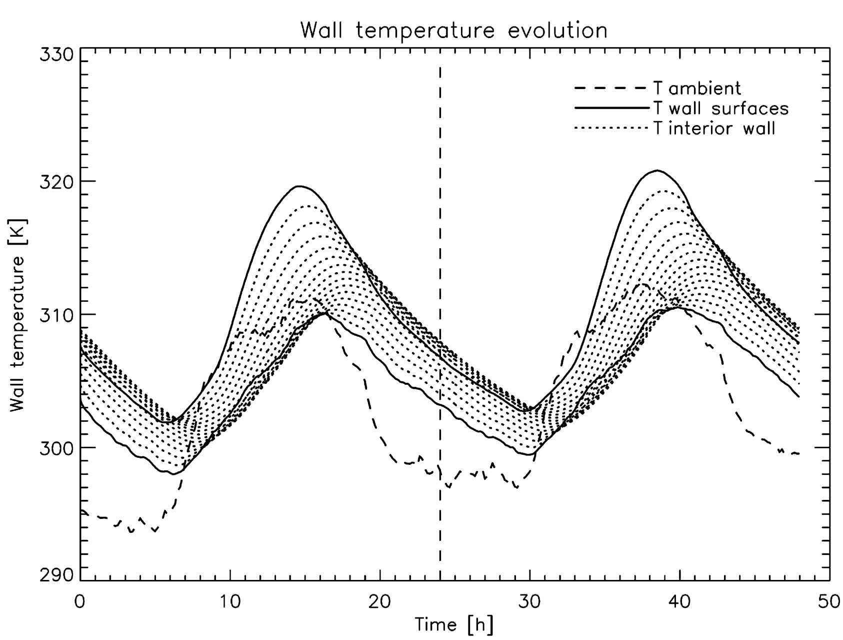

Fig. 5. Evolution of the wall temperature applying proposed dynamic model.

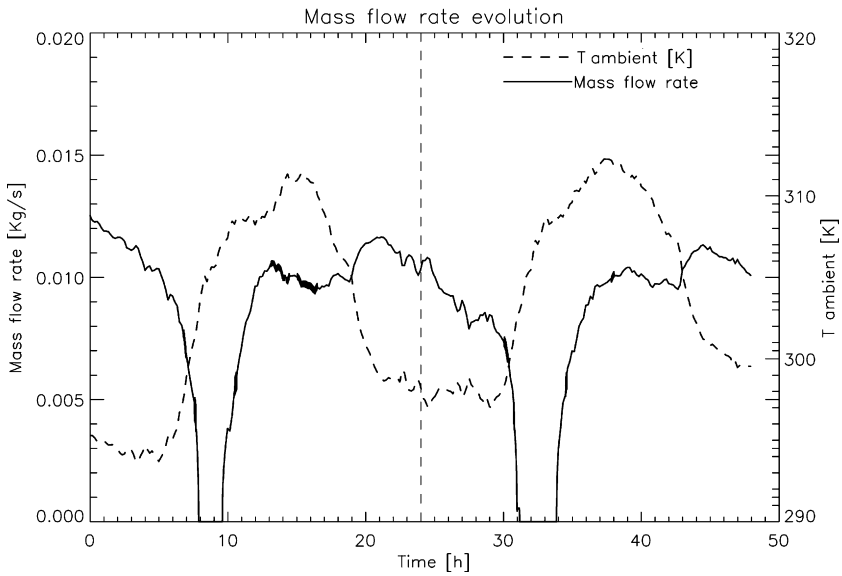

Fig. 6. Evolution of the mass flow that crosses the chimney applying the proposed dynamic model.

6. Discussion

The dynamic model proposed to describe the performance of a solar chimney with thermal inertia has been evaluated with real meteorological data showing coherent results in the evolution of the temperatures with the proposed physical problem. The dimensions selected for the simulation, have been chosen to be able to contrast these theoretical results with other experimental works from the bibliography. In the bibliography, the experimental data is for the evaluation of steady models of chimneys without thermal inertia, and in this work proposes a dynamic model. This implies that only qualitative considerations can be used to contrast the experimental data and results.

With a maximum solar radiation on a vertical surface of 450 W/m^2, the proposed dynamic model shows an air flow mass superior to 0.010 kg/s, and maximum of 0.012 kg/s. Hirunlabh (Hirunlabh et al.) published the experimental measures of a solar chimney, with identical dimensions to the simulation presented in this article, 2 m height and a air channel 14.5 cm width. The solar chimney has a glassed surface, and a black metallic plate acting as a capturing surface of the solar radiation. The thermal inertia of the system proposed by Hirunlabh is not relevant. For solar radiation values of 400 W/m^2 a volume air flow of 0.014 kg/s is given in this paper. It is necessary to emphasize that the temperature that reaches the metallic plate of the solar chimney of Hirunlabh, is about to 345 K, whereas in the case of the concrete wall of the solar chimney with thermal inertia, the proposed model calculates a maximum temperature of 320 K. The difference in the values of the volume air flow can be explained by this temperature difference.

Other experimental reference of the bibliography is from Ong and Chow (2003), that evaluates a steady mathematical model to describe the thermal performance of a solar chimney, contrast the simulation with a similar solar chimney in dimensions and forms to the Hirunlabh one. Ong measures experimentally an air flow mass around 0.010 kg/s for the width of air channel of 10 cm, while the air flow mass reaches 0.015 kg/s for a width of air channel of 20 cm and for an incident solar radiation of 400 W/m^2. The air mass flow rate simulated through the dynamic model proposed in this article is between both values measured by Ong, considering that the width of air channel from the simulation is of 14.5 cm.

7. Conclusions

The dynamic model proposed to describe the energetic performance of a solar chimney with thermal inertia shows satisfactory results that do not contradict the experimental data that exists in the bibliography. The simulation has been carried out with real weather data, giving a solid support to the theoretical results. The proposed concrete wall, 24 cm thick, reaches its higher temperature 2 h later than the ambient temperature, maintaining its temperature widely above the ambient temperature when solar radiation no longer exists. As a consequence, a nocturnal natural ventilation is produced, which is very interesting for Mediterranean climates with very warm nights. The dynamic model proposed for the description of a solar chimney with thermal inertia, shows the interest in continuing investigating on the topics of cooling techniques, and it shows the viability of future experimental investigations.

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