Thermal performance analysis of a solar chimney, based on the experimental study of the main driving variables in a physical prototype

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ABSTRACT

This work presents the thermal behavior of a stand-alone experimental solar chimney during one year. The dimensions of the solar chimney are 5.60 m high, 1.0 m width, and 0.52 m depth. The absorber plate is made of a common reinforced concrete wall of 4.5 m high, 1.0 m width and 0.15 m depth. This system was designed and constructed in 2003, and it is located in the "**L**aboratorio de **E**nsayos Energéticos para **C**omponentes de la **E**dificación ***(LECE)"*** at the "**P**lataforma **S**olar de **A**lmería ***(PSA)"*** in Spain. The inlet of this solar chimney was redesigned, and also the instrumentation of the system was increased and improved recently, as well as its air outlet fitting. During one year (2014), the solar chimney was monitored and several experimental variables were measured. The results present the temperature profiles of the different measured elements of the solar chimney as well as the air flow rate through the solar chimney channel. It was observed that the effect of the outdoor wind added to the thermal effects plays an important role affecting the performance of the solar chimney studied.

KEYWORDS

Natural Ventilation; Solar Chimney

1 INTRODUCTION

The use of conventional systems of heating and air conditioning to achieve thermal comfort represents nowadays a high percentage of the energy consumption in buildings. Therefore it contributes to the problem of the global warming.

With the purpose of contributing to the decrease of emission of pollutants, the use of non-renewable energy resources must be limited and the use of renewable resources of energy must be promoted. The following renewable resources can be mentioned: *wind, solar, thermal, photovoltaic, and biomass energies*.

The new bioclimatic designs of housings and buildings should consider the utilization of these renewable sources of energy and the use of passive systems of air conditioning, like wind towers, Bansal et al., (Bansal et al., 1994), trombe walls Ben et al., (Ben et al., 1991), and solar chimneys, Bouchair (Bouchair, 1994). The treatment of these sources of energy and its application represent a new challenge.

Part of the thermal comfort and the improvement of the air quality to the interior of housings and buildings are obtained through the use of natural ventilation. Among some experimental studies on these passive systems we can mention those undertaken by Khedari et al., (Khedari et al., 2000). They carried out an experimental research with four types of solar chimneys (The Solar Collector of Roof, the modified Trombe wall, the Trombe wall and the Metallic Solar Wall) connected to a room of 25 m³. Common materials were used in the construction, and the surface area was 2 m² each one. The results show that the four devices allow inducing natural ventilation which improves thermal comfort and reduce overheating of the room up to 50 %.

An experimental study in laboratory conditions of Solar Chimneys was published by Chen et al., (Chen et al., 2003). The internal dimensions of the Solar Chimney were; 1.5 m high, 0.62 m width and a changeable space of the width of the channel (0.1 to 0.6 m). Uniform heat flows were applied of 200, 300, 400, 500 and 600 W/m² across one of the walls. The angle of inclination of the Chimney was changed from 15º to 60º every 15º with regard to the vertical position. The results show that there was a maximum air flow rate reached when the angle of inclination of the chimney was 45º with a width of 0.2 m and a height of 1.5 m of the chimney applying 400 W/m², which is equivalent to 45 % more than for a vertical chimney under similar conditions. It was observed that the distributions of temperatures and speeds of the air were uniform through the width of the studied chimney.

Khedari et al., (Khedari et al., 2003), conducted an experimental study of the operation of a solar chimney integrated into a room of a building equipped with air conditioning (AC) and a volume of 25 m³. The results showed that the use of a solar chimney together with AC's system can diminish up to 30 % the electric power consumption, compared with the consumption of energy that would demand a building that uses only AC's systems.

Among the experimental studies to small scale, it can be mentioned the one held by Chakraborty and Fonseca (Chakraborty and Fonseca, 2005). Emad (Emad, 2006), conducted an experimental study using diverse technologies on the passive cooling in scaled models of rooms with metallic structures. The following technologies of cooling were used; a white Roof to diminish the heat gains to the interior of the room, thermal insulation over and/or below the roof, roof with water tank with and without insulation, evaporative cooling and by using a solar chimney.

The conclusion obtained was that the best modifications of the roof, to diminish the temperature inside enclosures constructed with metallic structures in hot regions, are the evaporative cooling and the solar chimney. The use of the solar chimney is an effective technology to reduce the temperature inside enclosures with metallic structures, beside producing ventilation and getting thermal comfort.

Another experimental study of passive cooling using a solar chimney and a wetted roof in a humid and warm climate in Thailand has been done by Chungloo and Limmeechokchai (Chungloo and Limmeechokchai, 2006). The results showed that the system works better when the use of the chimney and the water scattering in the roof there are combined. Burek and Habeb (Burek and Habeb, 2007), carried out experimental studies in a vertical channel, simulating the thermal performance of a solar chimney. Heat was supplied to the absorber plate through an electrical heater. The tests consisted in obtaining the profiles of temperature and air velocity of the in the channel, changing the amount of heat given to the system (200-1000 W) in steps of 200 W each one, for different depths of the channel (2.0 cm, 4.0 cm, 6.0 cm, 8.0 cm, 10.0 cm, and 11.0 cm), allowing that the system should reach the permanent conditions in each of the cases. The results showed the profiles of temperature of the different elements. It was concluded that the mass flow rate depends on the heat flow supplied to the system, as well as on the depth of the channel. Also it was observed that the efficiency of this system only depends on the amount of heat supplied.

Arce et al., (Arce et al., 2009) presented an experimental study of a full scale solar chimney outdoors. The solar chimney was not connected to any room to ease its independent study. The results showed that for a maximum irradiance of 604 W/m^2, about 13:00 hours, on September 15th, 2007, a maximum increase of the air temperature of 7 ºC was obtained. The system showed this day an average air flow rate of 177 m^3/h. It was observed that the air flow rate across the chimney is influenced by a difference of pressures between the entry and the exit caused by thermal gradients, and mainly by the outdoor wind speed.

Jiménez et al., (Jiménez et al., 2010) presented an experimental study of a full scale solar chimney outdoors. Data were recorded and analysed for one year (2007-2008). However, data of three days selected from this period were discussed, (one day for winter, one for autumn and one day near the beginning of summer). The authors concluded that, the air flow rate in a solar chimney is associated not only with the thermal effect and wind speed, but also with the combination of both effects on the system.

The purpose of the present study consists in continuing the previous work, with some modification on the same experimental passive system *(solar chimney)*. This study is supported by the experimental information acquired during one year.

2 PHYSICAL MODEL

Figure 1, shows a front view of the solar chimney in study. The above mentioned system has the following dimensions: 5.60 m, 1.20 m width and 0.52 m deep. The system is in vertical position and facing south. The main components are: an absorbing plate, thermal insulation, a glass cover, and wood around the lateral and back side.

The absorber plate has 0.15 m of thickness, 1.0 m of width and 5.0 m high, it was made of concrete, in which solar incident radiation is absorbed and stored. Thermal insulation was used to reduce heat losses from the absorber plate. The glass cover was 5 mm of thickness and was used to reduce convective and radiative losses to the environment, and at the same time it takes part of the air channel. Other accessories like wood around the lateral and back side, an air inlet in the low back side and an air exit at the top, are also included. In order to measure the main variables, such as air temperature and air velocity inside the channel, sensors and instruments were set up.

In order to measure the environmental conditions, a meteorological station and a system to record and process the information, are located close to the solar chimney. The experimental data of different variables are measured every second, but they are averaged and recorded every minute.

Figure 1. Photograph of the solar chimney.

A lateral view of the solar chimney is shown in Figure 2, as well as the instrumentation set up. Thirty thermocouples type “T”, previously calibrated were used to measure temperature, and nine hot wire anemometers (Mod. TSI-8475) were used to measure the air velocity.

With the purpose of avoiding a counter flow through the air channel, a driving air protection was set up at the top. The hood moves itself with the wind direction, which generates a fall of pressure near the exit and, at the same time, it helps to the air extraction. Thus, wind forces add to the thermal ones. In order to avoid air whirlpools at the entry of the solar chimney, a wooden box with some perforations was installed.

3 OPERATION GENERAL PRINCIPLE

The functioning of a solar chimney is originated when a difference of air pressure takes place between the entry and the exit, inducing an air flow through the system in positive or negative direction. Certainly, it is always intended to obtain positive differences of pressure, with the purpose of ventilating a house or a building.

4 RESULTS

Data recorded for one year (2014) were analysed. The information corresponds to the solar chimney of LECE at the Plataforma Solar of Almería in Spain. Data of three days from this period were selected, and will be discussed in the following. These days were selected with clear sky, and representative enough of the period attending to the levels of South Vertical Global Solar Radiation: High, moderate and low, near the beginning of winter, spring and summer respectively.

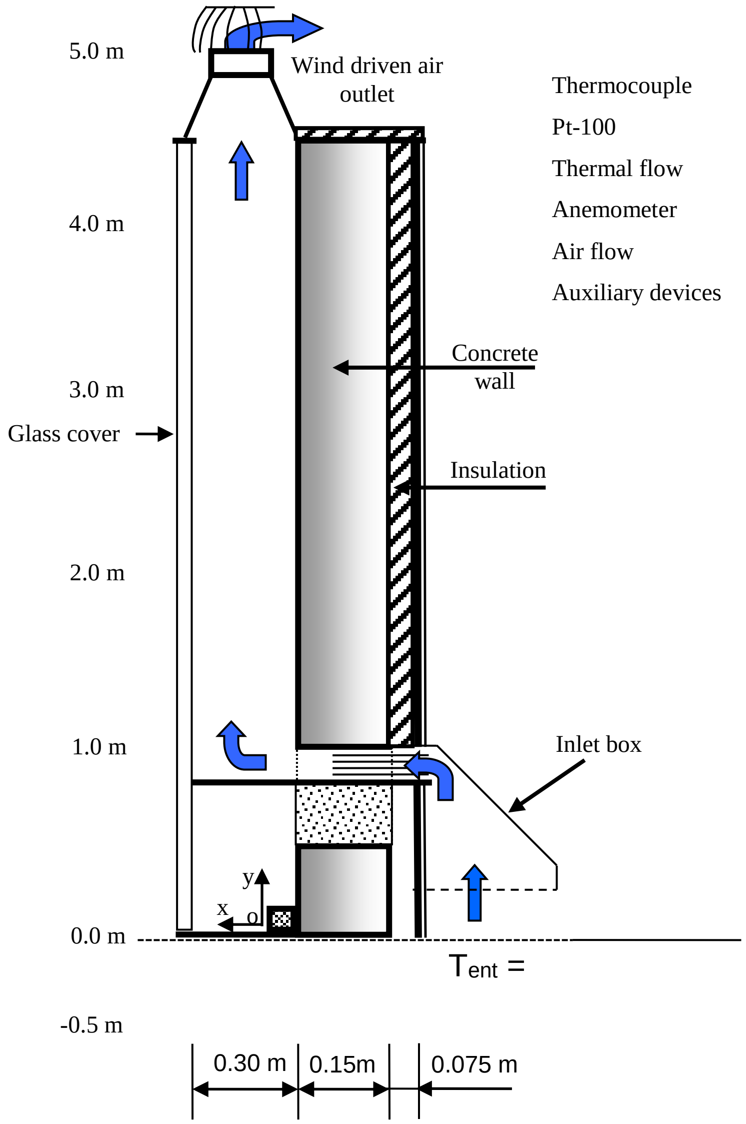

Figure 2. Lateral view of the solar chimney and the instrumentation set up.

4.1 Irradiance

Figure 3-a shows, from high to low intensity, the South Vertical Global Solar Radiation (SVGSR), the Horizontal Global Solar Radiation (HGSR), and the Diffuse Solar Radiation (DSR), on a clear day of winter (26/12/2014).

The SVGSR and the HGSR, on a clear day near the beginning of spring (05/03/2014), are shown in Figure 3-b. Both irradiances are quite near, due to the location and the day of the year. Furthermore, in Figure 3-b, the DSR is shown , which is smaller than that shown in Figure 3-a.

Near the beginning of summer (20/06/2014) HGSR, SVGSR and DSR, from high to low intensity, are shown in Figure 3-c. It is observed that the magnitudes of SVGSR and HGSR are inverted as the days and seasons of the year progresses.

The effects produced by the SVGSR, and by the (DSR), will be noticed on the surface temperatures of the absorber plate, in the air temperature in the channel flow and on the flow rate through the system. This will be discussed in the next paragraph.

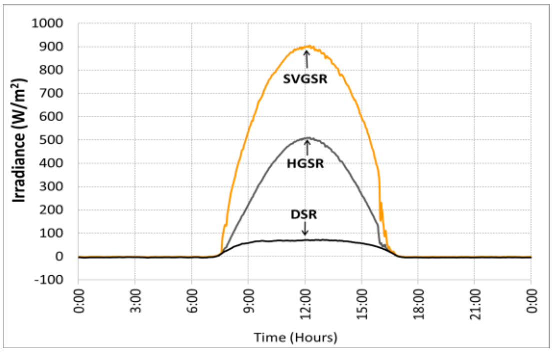

Figure 3-a. Solar radiation (VGSR, HGSR and DSR) on December 26th, 2014 (~winter).

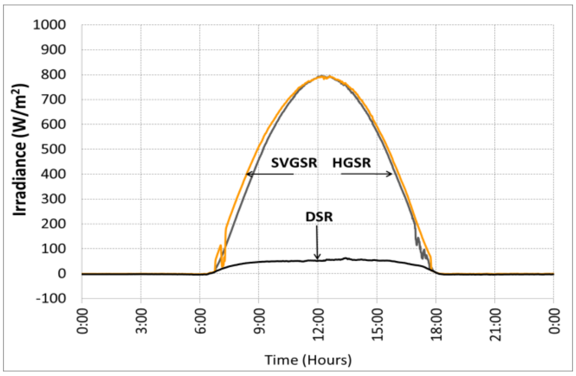

Figure 3-b. Solar radiation (SVGSR, HGSR, and DSR) on March 5th, 2014 (~spring).

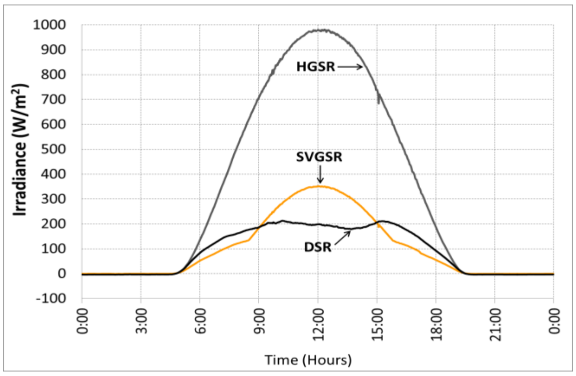

Figure 3-c. Solar radiation (HGSR, SVGSR and DSR) on June 20th, 2014 (~summer).

4.2 Wall temperatures

Similarly, for the same days, tendencies of the surface temperature for the absorber plate of the solar chimney are shown in Figure 4-a, Figure 4-b, and Figure 4-c. The surface temperature sensors are located at four different heights 1.5, 2.0, 3.0 and 4.0 m. Small differences in some cases and big ones are observed in others for each figure. For example, in Figure 4-a, the biggest differences of temperature among those tendencies are approximately 3 ºC. The highest value is the surface temperature located at 3.0 m, which is 52 ºC around 15:00 hours. The smallest values observed are approximately 15 ºC located between 6:00 and 8:00 hours. This fact produces a maximum surface temperature increment of approximately 37 ºC, because of the SVGSR received on the absorber surface.

Figure 4-b shows the surface temperatures on March 5th, 2014. The magnitudes of the trends are also very similar to each other, except that temperature at 4.0 m high, which is noticeably minor due to a shade on the zone of the surface caused by the top part of the chimney itself. Maximum values of 50 ºC between 14:00 and 15:00 hours and minimum values of approximately 17 ºC between 6:00 and 8:00 hours are observed. This fact produces a maximum surface temperature increment of approximately 33 ºC, 4 ºC lower than the case for winter due to the minor SVGSR received on the absorber surface.

Figure 4-c, shows the surface temperature on June 20th, 2014, trends are also very similar at each other, maximum values between 32 and 35 ºC around 13:00 hours are observed. The minimum values found are 24 ºC between 5:00 and 6:00 hours, this fact produces a surface temperature increment of 9.5 ºC approximately, due to minor solar radiation received (SVGSR) on the absorber surface.

The effect of the increases on surface temperatures in the absorber plate will be observed in the average increase of the air temperatures in the channel of the chimney, and at the same time in the air flow rate across the system. The above, will be described in the following paragraphs.

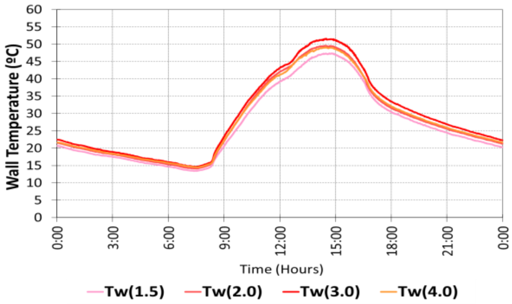

Figure 4-a. Wall temperatures at four different heights on December 26th, 2014 (~winter).

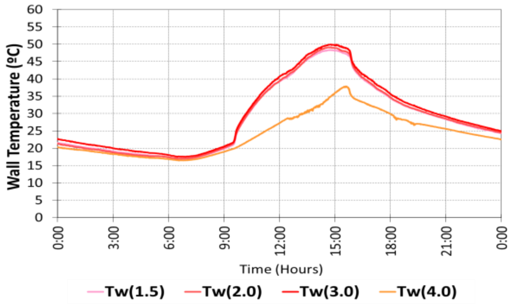

Figure 4-b. Wall temperatures at four different heights on March 5th, 2014 (~spring).

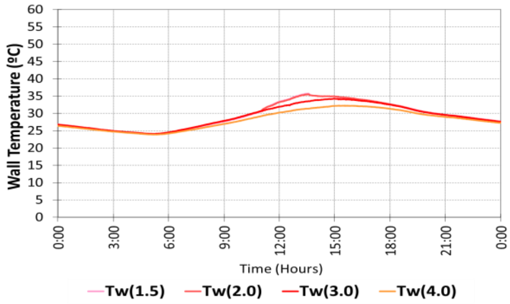

Figure 4-c. Wall temperatures at four different heights on June 20th, 2014 (~summer).

4.3 Air temperatures

The energy stored in the absorber surface in the solar chimney is transferred to the adjacent fluid, first by conduction and then by convection, so that, the greater difference between the average temperature of the surface and the temperature of the air at the entry, the greater will be the energy gained by the air inside the channel and the greater its increase of temperature. Therefore, on December 26th, 2014 (Figure 5–a), presents an average daily increase of 7.3 ºC, and a maximum increase of 14.0 ºC around 14:00 hours, approximately two hours after receiving the maximum solar radiation, due to thermal inertia of the system.

An average daily increase of 4.7 ºC is found on March 5th, 2014 (Figure 5-b) and 1.7 ºC on June 20th, 2014 (Figure 5-c). The above temperature increments will influence the air flow rate across the system, which will be discussed in the following paragraph.

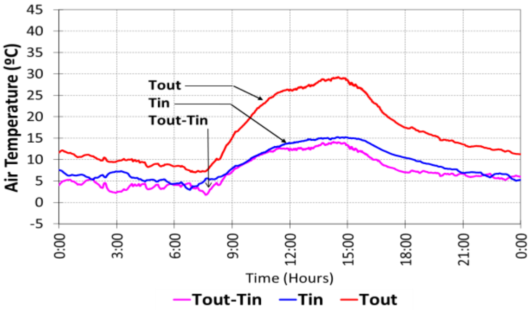

Figure 5-a. Air temperatures on December 26th, 2014 (~winter).

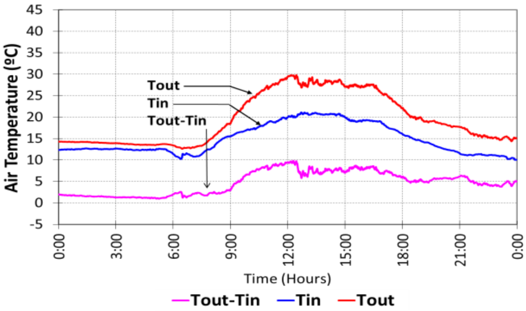

Figure 5-b. Air temperatures on March 5th, 2014 (~spring).

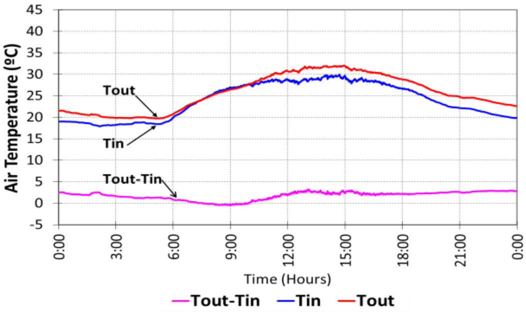

Figure 5-c. Air temperatures on June 20th, 2014 (~summer).

4.4 Air flow rate

In this section the air flow rate across the system is analysed, which is associated with the energy acquired while it is flowing along the channel of the chimney, and due to this fact it presents an associated increase of air temperature.

In the Figure 6-a, an average air flow rate of 91.5 m^3/h daily is obtained, with an outdoor wind speed of 1.4 m/s. In case of Figure 6-b, for the same schedule, there is an air flow rate of 96.5 m^3/h, and a corresponding averaged outdoor wind speed of 4.3 m/s. Analogously, in the Figure 6-c, in the same schedule, there is an air flow rate of 100.1 m^3/h, and a corresponding outdoor wind speed of 2.9 m/s.

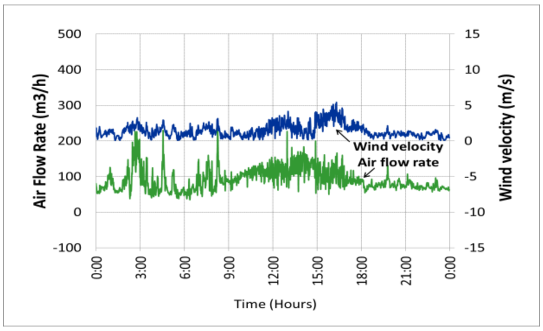

Figure 6-a. Air flow rate and outdoor wind velocity on December 26th, 2014 (~winter).

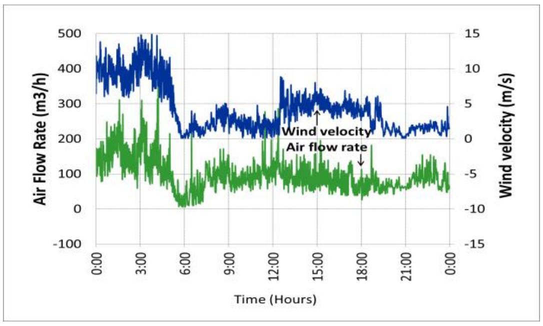

Figure 6-b. Air flow rate and outdoor wind velocity on March 5th, 2014 (~spring).

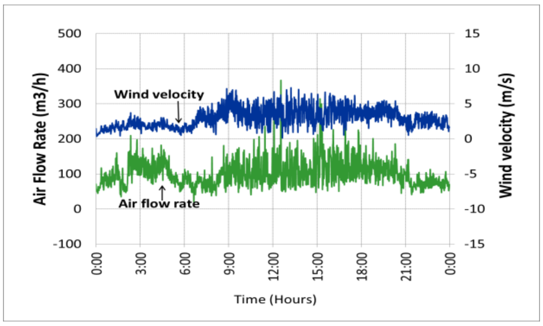

Figure 6-c. Air flow rate and outdoor wind velocity on June 20th, 2014 (~summer).

The results are summarized in Table 1, by the daily averaged values. The increase of the air temperature (ΔT_{air}), the mean air temperature (Tm_{air}), the outdoor wind speed 10 meters height (V_{wind}), and the Air Flow Rate (AFR). In the case of solar radiation, the maximum values are just at noon, in solar time.

Table 1: Average values from 00:00 hrs to 24:00 hrs

Parameter	**Winter (26/12/2014)**	**~ Spring (05/03/2014)**	**~ Summer (20/06/2014)**
Max.-SVGSR (W/m^2)	900	800	350
Max.-HGSR (W/m^2)	500	800	980
ΔT_{air} (ºC)	7.3	4.7	1.7
Tm_{air} (ºC)	12.5	17.2	24.8
V_{wind} (m/s)	1.4	4.3	2.9
AFR (m^3/h)	91.5	96.5	100.1

It was expected that the air flow rate was associated only with the increase of air temperature. Nevertheless we can realize that it is also influenced by the outdoor wind speed mainly, and also, it may be influenced by wind direction, which must be proved.

5 CONCLUSIONS

In spite of having a higher solar radiation (SVGSR) of 900 W/m^2 on the glass surface of the solar chimney in the considered winter day, and consequently of having a maximum increase in the temperature of the air in the channel of the chimney (7.3 ºC), we have a lower air flow rate in the system (91.5 m^3/h) with regard to the ~spring case (96.5 m^3/h) when there is a lower average increase daily of temperature (4.7 ºC) and there is lower average solar radiation (800 W/m^2) on the glass surface. The previous fact is attributed to the low daily average wind speed of 1.4 m/s in the first case, while in the second case such speed is 4.3 m/s. Whereas in ~summer with a wind speed of 2.9 m/s, a value between that one of ~spring and winter, an air flow rate of 100.1 m^3/h is obtained, remarkably higher than that one in winter and even noticeably higher that one in ~spring. This may be due to the higher mean air temperature (Tm_{air}=24.8 ºC) against 17.2 ºC and 12.5 ºC of ~spring and winter respectively.

According to the results, the air flow rate in a solar chimney is associated not only with the thermal effect and wind speed, but also with the combination of both effects on the system, and very probably with the wind direction.

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