https://doi.org/10.3311/PPme.16198

Periodica Polytechnica Mechanical Engineering, 65(1), pp. 47–55, 2021

Experimental Analysis of Height to Base Length Effect in Trapezoidal Prism Inclined Solar Chimney

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Received: 11 April 2020, Accepted: 23 October 2020, Published online: 09 December 2020

Abstract
The use of a solar chimney for ventilation has a very significant environmental and economic impact. The aim of this work is to found the optimum ratio between height and base length in trapezoidal prism-shaped solar chimney. The idea is to give more flexibility to the architectural design in buildings and offer the possibility of combination with other passive or active systems. Trapezoidal shape of solar chimney can be interesting not by increasing the efficiency comparing with other shapes like the rectangular. It may be more aesthetically pleasing, easily to be installed and retrofitted on trapezoidal roofs even on existing buildings. For this reason, three differents ratios of height to base length (h/l = 1), (h/l = 1.5) and (h/l = 2) have been experimentally studied. Two correlations to predict solar chimney exit air velocity and efficiency were developed and tested; good agreement with experimental results is proved. Results show that the flow rate increase by increasing (h/l) in a logarithmic tendency. The optimum thermal efficiency is given where h/l = 1.65. An approach using RETScreen4 software was also carried out and showed that 1 m² solar chimney installed in favorable conditions can cover 37 m² of living space in term of ventilation. For a 120 m² house, solar chimney system saves the equivalent of 23.9 liters of gasoline per year.

Keywords
solar chimney, natural ventilation, buoyancy force, buildings, comfort

1 Introduction

Natural ventilation of buildings is the flow generated by buoyancy driving force and by the wind. The governing feature of this flow is to refresh air in an interior space from the external ambient to provide comfort. In order to improve natural ventilation, passive systems are being increasingly proposed, so that can replace mechanical ventilation systems; because of their potential benefits in terms of: operational cost, energy requirement and carbon dioxide emission which has a negative impact on the environment.

Natural ventilation is expected to provide cooling energy savings on the order of 10 % and fan power savings on the order of 15 % of annual energy consumption when climatic and operational conditions are suitable [1].

In view of the fact, the using of passive techniques becomes a good strategy for energy efficiency of buildings and generally, building sector consumes 35.3 % of final energy demand [2].

Solar chimney is a simple and efficient tool to improve natural ventilation. It transforms solar irradiation into kinetic energy to extract air from the interior space.

Further, solar chimneys can be combined with other techniques. Chungloo and Limmeechokchai [3] confirm that the application of cool ceiling and solar chimney, which reduces the ceiling temperature by 2–4 °C, does not only increase the circulation in the upper and lower regions of the room, but also reduce the air temperature in the room by 0.5–0.7 °C.

Ding et al. [4] combined the intermediate space of a double-skin façade with a solar chimney to improve natural ventilation performance in experimental and numerical study.

Shiv and Subhash [5] numerically studied a borehole heat exchanger assisted by a solar chimney; they establish that the room temperature can be maintained

Cite this article as: Belhadj, O., Benzenine, H., Saim, R. "Experimental Analysis of Height to Base Length Effect in Trapezoidal Prism Inclined Solar Chimney", Periodica Polytechnica Mechanical Engineering, 65(1), pp. 47–55, 2021. https://doi.org/10.3311/PPme.16198

at 25–30 °C, at 4.9 ACH (Air Changes per Hour) by this integrated approach in peak summer and winter conditions. Many other researchers combined passive techniques with solar chimney in their studies e.g. [6–10].

Solar chimney can be used not only for ventilation but also for heating if fan is used to direct the heated air into the building. When solar chimney is attached to wall, the working mechanism is similar to Trombe wall. It operates as passive heating by supplying warm air that heated up by the solar collector into the room. In moderate climate, when the outdoor temperature is lower than the indoor temperature, solar chimney participates significantly in cooling. Zhai et al. [11] offer a rich review for the applications of solar chimneys in buildings.

Vertical chimney is the simplest and most clear design. Many studies carried out to understand their impact and behavior. Afonso and Oliveira [12] compared conventional and solar chimney; they observed between 10 % and 22 % efficiency increase by solar assistance for the average climatic data of Portugal. Amori and Mohammed [13] examined the effect of positions of air entrance namely: bottom entrance, side entrance, and both side and bottom entrances on the natural ventilation. the study also showed that the use of paraffin as PCM (Phase Change Material) can extend the ventilation period.

Ong [14] proposed and compared a mathematical model of a solar chimney with experimental data of others, satisfactory correlation was obtained.

For many situations, vertical chimney may be not the good architectural arrangement, e.g. when the roof is designed to be a solar chimney, this is why different geometries are studied to obtain the maximum thermal efficiency and flow rate. Wei et al. [15] examined a series of solar chimneys comprising a slanted section on the roof and a vertical section near the south wall in a typical two-story house. They studied numerically the effect of some parameters namely: the length and the total width of the chimney,the inclination angle of the second floor entrance, the length ratio of the vertical section to the inclined section and the inclination angle of the chimney on the ventilation performance. The study showed that ventilation improves with increasing length of the chimney. The study also found that the mass air flow rate first increased and then decreased with the width of the chimney, indicating the existence of an optimal aspect ratio, near 12:1. The results of DeBlois et al. [16] show that with the proposed rooftop design, the chimney airflow is induced mainly by buoyancy forces whenever the temperature difference from interior to ambient differs by more than a few degrees, so there is the potential to provide effective free cooling. Bassiouny and Korah [17], by means of a numerical and analytical investigation, proposed a correlation to estimate Air Changes per Hour depending of inclination angle, solar intensity, and chimney width. Mathur et al. [18], show that the optimum absorber inclination varies from 40° to 60° depending upon the latitude of place; they announce that 45° inclination offers a rate of ventilation 10 % higher compared to 60° and 30° inclinations for the location studied. Kong et al. [19], also found that the optimum inclination angle varies from 45° to 60°, depending on the latitude and season of operation. Sakonidou et al. [20] developed a mathematical model to determine the inclination that maximizes natural air flow inside a solar chimney; the model has good agreement with the 1m solar chimney at different inclination. Chen et al. [21] show that a maximum air flow rate was achieved at an inclination angle around 45° for a 200 mm gap and 1.5 m high chimney, and the air flow rate is about 45 % higher than that for a vertical chimney. Saifi et al. [22] confirm that the optimal thermal pulling is reached at chimney inclination angle of 45°.

The inclination angle is a very important parameter to maximize the ventilation rate. In conclusion, air flow and thermal efficiency are like sine and cosine of inclination angle. Contrary to thermal efficiency; air flow increase by increasing the inclination angle, because small inclination angle showed a high flow resistance but greater angle affects irradiation capture and then thermal efficiency (Fig. 1). The optimum angle depends on: geographic situation; time; and day of year. For fixed angle many researchers agree for 45°.

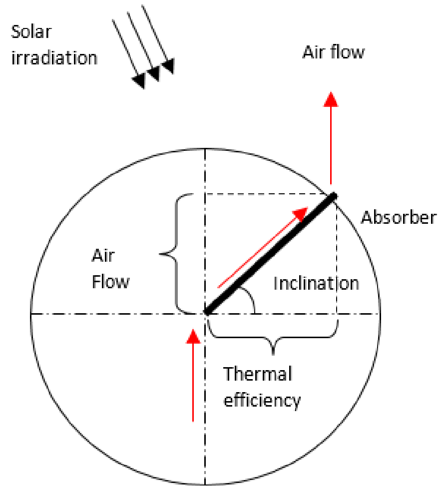


Fig. 1 Schematic optimum inclination angle of the solar chimney

Many techniques are used to improve natural ventilation performances in buildings. For it, several geometries of solar chimneys were studied by numerous researchers. This work is part of this framework; it aims to obtain the maximum thermal efficiency and flow rate by a trapezoidal prism solar chimney. Three different shapes based on the height to base length (h/l) changing were studied and compared experimentally.

2 Theory

Air Changes per Hour in natural ventilation, which is the ratio of the air volume flow rate Q to the total volume of the room V can be calculated from Eq. (1) as defined by ASHRAE [23]

$$\mathrm{ACH} = \frac{Q \times 3600}{V}, \tag{1}$$

where Q and V are in m^3/s and m^3 respectively.

Natural ventilation can be provided by wind or buoyancy forces, for the simple case of cross ventilation or wind drive ventilation with an isolated enclosure, the air flow rate can be calculated by Eq. (2) [24]

$$Q = K \times A \times V, \tag{2}$$

where Q is the air flow rate in m^3/h. K is the coefficient of effectiveness. A is the area of the smaller opening in m^2 and V is the velocity of outside air in m/h. Wind driven ventilation is solely dependent on wind direction and wind intensity.

In buoyancy driven natural ventilation, the air flow is induced by thermal effect. It can be calculated using Eq. (3) [24]:

$$Q = K \times A\left[H\left(T_{\mathrm{in}} - T_{\mathrm{out}}\right)\right]^{1/2}, \tag{3}$$

where Q is the volumetric flow rate in (m^3/h). A is the free area of inlet opening in (m^2). K is a constant depending on the resistance offered by the opening. T_{in} is the average indoor air temperature at height H (m) in °C and T_{out} is the average outdoor air temperature in °C.

Buoyancy driven natural ventilation is also referred as stack ventilation. It could be mixing or displacement depending upon the position of the openings and the nature of the stack effect [1]. The details of wind drive and stack ventilation modeling can be found in [25].

A solar chimney generates air movement by buoyancy forces, in which hot air rises and exits from the top of the chimney, drawing air through the building core in a continuous cycle. The driving force on the air column in the chimney is the difference in the density of the air inside and outside the chimney. If the height of the chimney is such that the normal variation of pressure and temperature in the atmosphere can be neglected, together with temperature changes within the chimney due to adiabatic expansion, the pressure difference can be given by Eq. (4) [26]

$$\Delta P = 11.67\left(1 - \frac{T_a}{T_c}\right)h, \tag{4}$$

where h is height of chimney, T_a is ambient air temperature and T_c is temperature inside the chimney.

Neglecting losses in the chimney a reasonable assumption for a chimney of diameter greater than 1/10 of its height), the air velocity at the top of the chimney can be given by

$$v = \sqrt{\frac{2\Delta P}{\rho_l}}, \tag{5}$$

where ρ_l is the density of the air at chimney temperature. However, this analysis is based upon a simplified model [26].

In case of measured average velocity, air flow rate through the chimney can be calculated as

$$Q_{vent} = V_{avg} \times A_{\mathrm{out}}, \tag{6}$$

where V_{avg} is the average velocity at the exit cross-section of the chimney (m/s), A_{out} is the outlet cross-section area of the chimney (in m^2), Q_{vent} is the flow rate of the hot air (m^3/s).

The thermal efficiency of the solar chimney is calculated by

$$\eta = \frac{\rho_l Q_{vent} C_p \left(T_{\mathrm{out}} - T_{\mathrm{in}}\right)}{I \times S}, \tag{7}$$

where η is the thermal efficiency, ρ_l is the density of the air at chimney temperature, C_p air specific heat (J/kg °K), T_{in} and T_{out} are temperatures at chimney inlet and outlet, I incident solar radiation (W/m^2), S is the absorber area. ρ_l and C_p can be taken from [17]:

$$\rho_l = 1.1614 - 0.00353(T - 300) \tag{8}$$

$$C_p = 1007 + 0.004(T - 300). \tag{9}$$

3 Experiment procedures

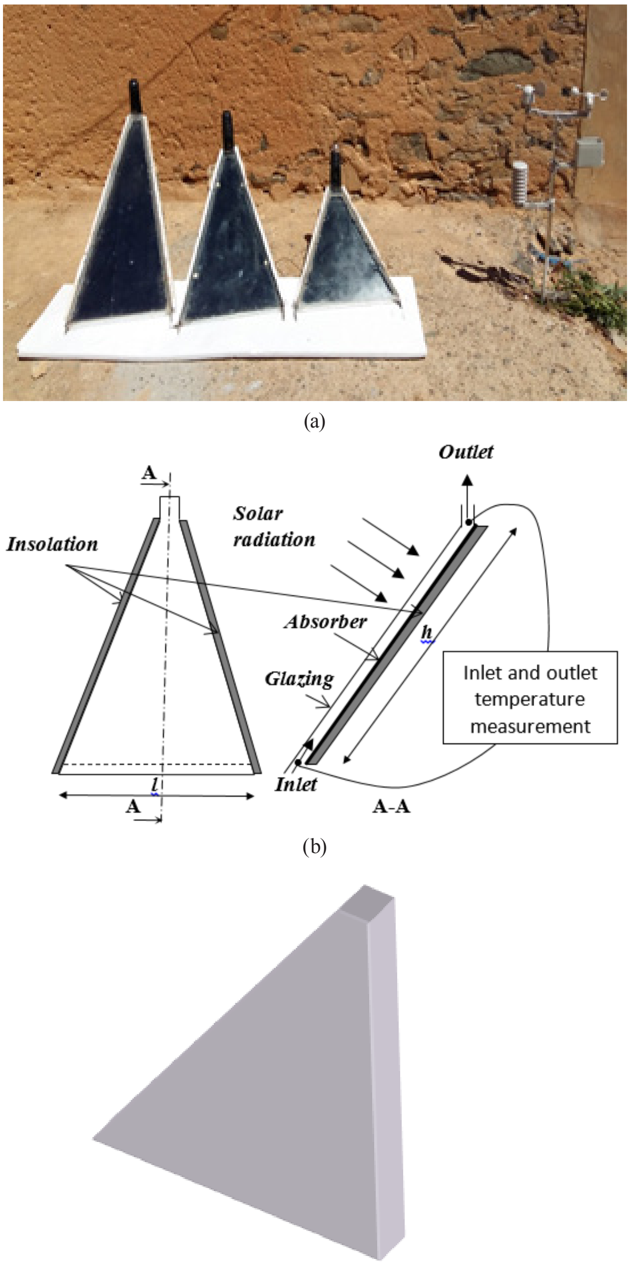
The experiments are performed in Fellaoucene, Algeria 35°3'28" N, 1°35'37" W, altitude: 280 m) on a selected clear day (April 14th, 2019).

Three chimneys with different height h = 0.5 m, h = 0.75 m and h = 1 m are used, bases lengths and gaps are the same: 0.5 m and 20 mm respectively.

Parts of the solar chimneys were the absorbers made of black painted steel 2 mm thickness; walls were insulated with 20 mm expanded polystyrene. A commercial glass of 3 mm thickness served as the glazing for the chimneys.

The chimneys were positioned to minimize the wind effect; they were installed in a surrounded courtyard of an old house, the height of the entourage is 3 m (Fig. 2 (a)).

Chimneys were south facing and inclined 45° to horizontal plan in order to optimize thermal efficiency and air flow.



(c)

Fig. 2 (a) Solar chimneys and weather station installation, (b) Schematic experimental setup, (c) 3D illustration of the solar chimney (trapezoidal prism shape)

The cylindrical outlet is used to allow the combination with other systems such as Stack height effect improvement and facilitates adding of other systems like heat recovery or heating by means of a fan to direct hot air to the internal space in future studies. In addition $S_1/S_2 = 12$, where S_1 and S_2 are inlet and outlet sections. This is to create the Venturi effect with the aim of increasing the air velocity and improve measurement accuracy. The velocity of the hot air was measured at the outlet of the chimneys by using multifunctional Hand-held digital anemometer with sensitive wheel; it allows the measurement of the average air velocity with a maximum error of 5 %. Wheel diameter is approximately the same of the outlet of the chimneys.

Solar radiation was measured by means of a pyranometer model TM-206 with an accuracy of ±10 W/m^2. For temperature measurement, six thermocouples with LCD display and an accuracy of ±0.5 °C are installed in the air flow region at the middle of the inlet and outlet area of solar chimneys. An infrared camera testo 875-1i was also used to view temperature distribution, Glazing temperature was carried out by means of the software treatment tool (IRsoft) given by the manufacturer of the camera.

Portable AERCUS weather station was onsite installed to indicate the wind velocity and direction, ambient temperature, humidity and atmospheric pressure.

4 Results and discussion

Solar radiation was measured during the test period on a selected clear day (April 14th, 2019). As shown in Fig. 3 (a), the measurements were taken each 30 minutes between 11:45 AM and 15:15 PM.

In local conditions of temperature and relative humidity (Fig. 3 (b)); chimneys receive the maximum irradiation between 13:00 and 14:00; the average ambient temperature was 29.5 °C and 30 % of relative humidity. Three chimneys with height to bases length $h/l = 1$, $h/l = 1.5$, and $h/l = 2$ are used, they are south facing and 45° inclined in order to maintain the optimum thermal efficiency and air flow.

Fig. 4 (a) and (b) is taken by the infrared camera. Glazing temperature profiles of the three solar chimneys in Fig. 4 (c) was carried out by means of the software treatment tool (IRsoft) given by the manufacturer of the camera. The emissivity of the commercial glass is 0.90 [13].

The temperature fields presented in Fig. 4 (b) by the thermal camera are the reflection of the convective and dynamic structures of the flow. In fact, it is clear that low gradients and temperatures are generated near the inlet of each chimney because fresh air is always sucked. However,

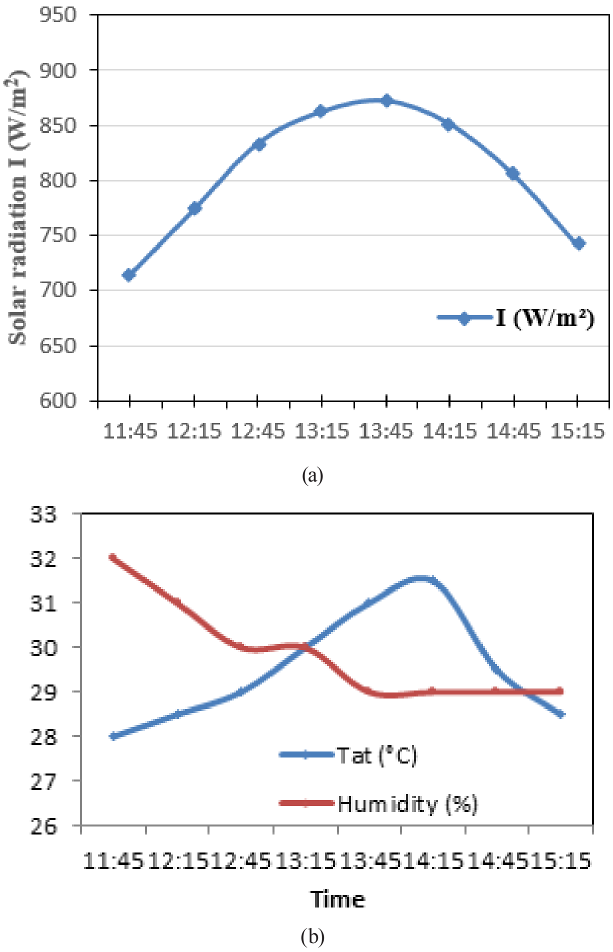


Fig. 3 (a) Solar radiation during the test period in the selected clear day (April 14th, 2019), (b) Ambient temperature and relative humidity during the test period

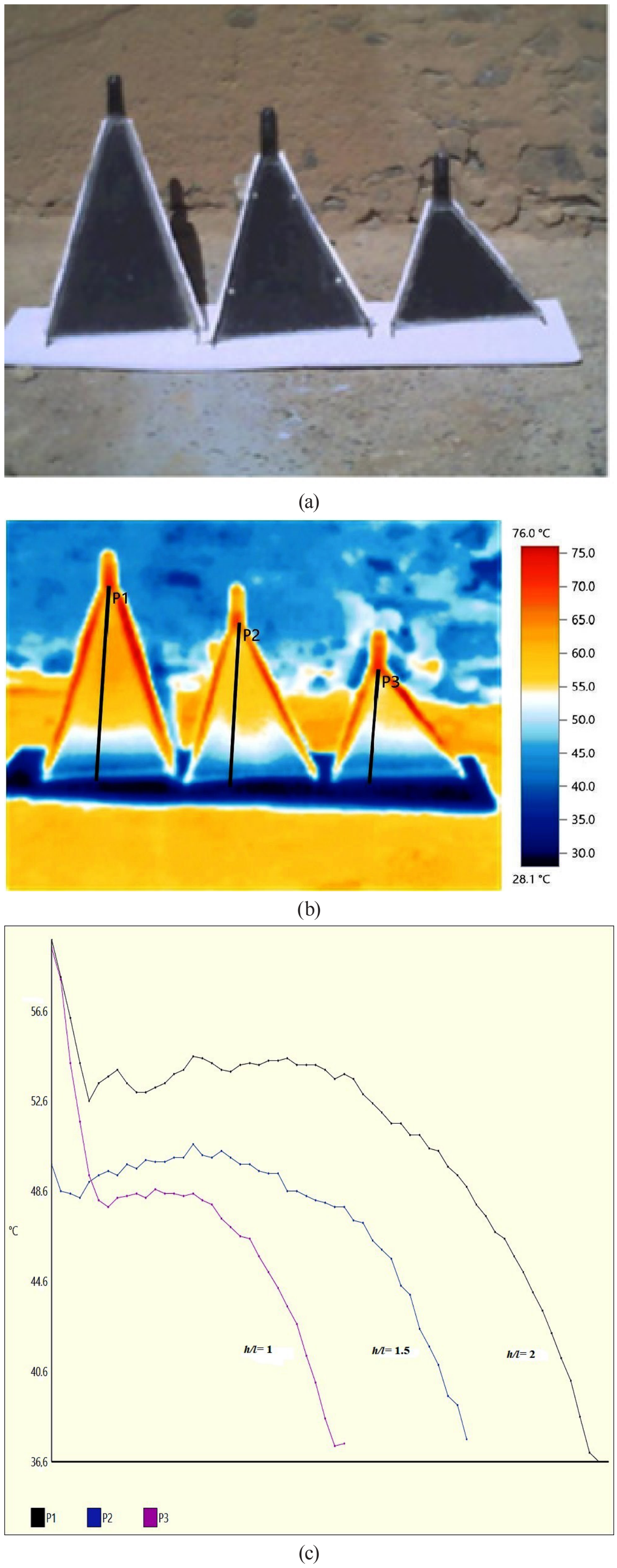


Fig. 4 (a) Real image (April 14th, 2019 at 14:40), (b) Thermal image (April 14th, 2019 at 14:40), (c) Glazing temperature profiles

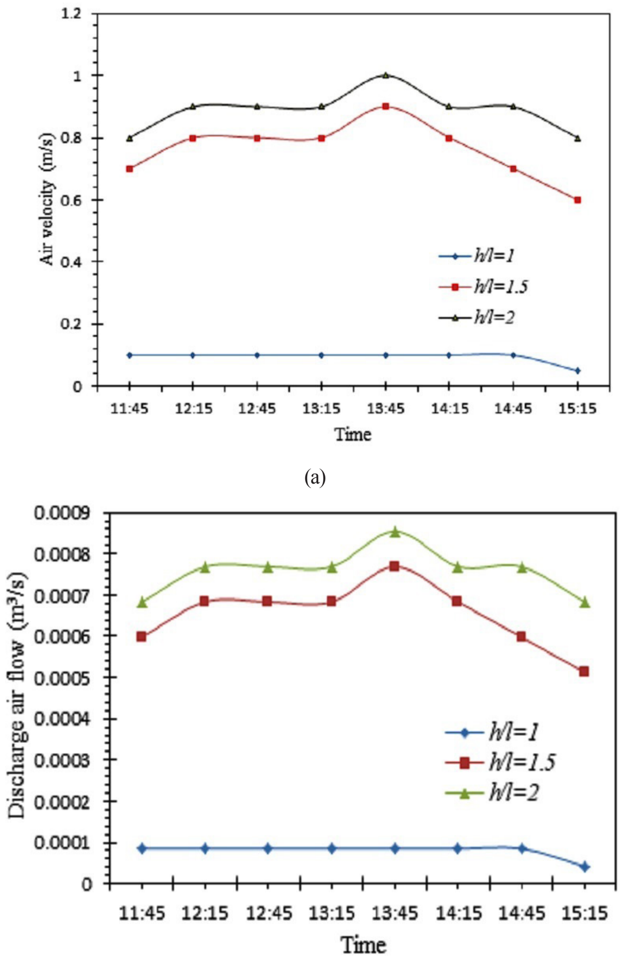
the temperature level began to increase ever more from the medium approaching the exit. This is due to the heat exchange between the absorber and air. Heat is generated by the greenhouse effect inside the chimneys and by thermal expansion, air density decreases to generate the buoyancy driving force therefore the ventilation process.

Fig. 4 (c) presents the glazing temperature profiles in cross sections $P1$, $P2$ and $P3$ (Fig. 4 (b)), temperature values was given by means of the software treatment tool (IRsoft) delivered by the manufacturer of the camera.

For the chimneys of ratio (h/l = 1), (h/l = 1.5) and (h/l = 2) respectively. The temperature near the entrances of the three chimneys is around 37.5 °C, and then increases subsequently in the middle until it reaches the maximum near the exit. The highest glazing temperature was 57.1 °C in the longest (h/l = 2) and the shortest (h/l = 1) solar chimneys, while the maximum glazing temperature presented for the (h/l = 1.5) solar chimney is 50 °C. Significant temperature difference is observed between the three chimneys, it depends on the absorber area and the air flow. Long chimney (h/l = 2) deliver important flow (Fig. 5 (b)), however, it has big absorber surface. The short one give the same glazing temperature as the long one even it has the smallest absorbing area; this is due to the low flow rate passage (Fig. 5 (b)).

The medium sized solar chimney (h/l = 1.5) is the optimum comparing with the studied cases in this work, it has a low glazing temperature but the best thermal efficiency (Fig. 6) so the desired heat exchange inside.

Fig. 7 shows the air temperatures at the exit of chimneys. They are changing with the intensity of solar radiation, the maximum air temperature recorded is 72 °C at 13:15 in the longest chimney (h/l = 2). During the test period; outlet air temperatures in h/l = 1 solar chimney



(a)

(b)

Fig. 5 (a) Outlet air velocity for different chimneys, (b) Discharge volumetric flow from solar chimneys cases

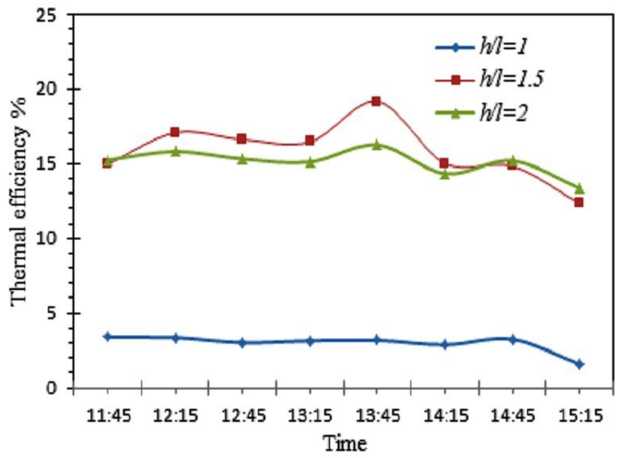


Fig. 6 Thermal efficiency from solar chimneys cases during the test period.

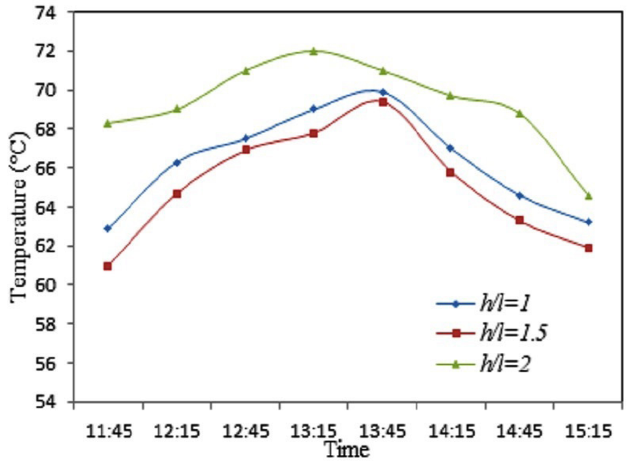


Fig. 7 Outlet temperature for different chimneys

are highest than these of (h/l = 1.5). Discharge flow was obtained from Eq. (6) and measured air velocity.

The results of Fig. 5 (a) and (b) indicate that the lowest airflow at the outlet corresponds to the shortest solar chimney (h/l = 1). For the same dimensions of the base, the use of this small height gives rise to a resistance to the air flow inside the solar chimney. This generates more exchange time and subsequently, a higher temperature of the air at the outlet as shown in Fig. 7. In Fig. 5 (b), discharge air flow is illustrated. It takes the same curving of exit air velocity because of the constant inlet and outlet sections in all chimneys cases.

Outlet air velocity reach the maximum value (1 m/s) in the longest chimney (h/l = 2). The chimney with (h/l = 1) deliver hot air slowly; in this case, the velocity didn't exceed (0.1 m/s) during the test period. The peak velocity value in case of (h/l = 1.5) chimney was (0.9 m/s).

Fig. 8 shows the variation of the average air velocity at the exit of chimneys by their height to base length ratio (h/l). The velocity increase by increasing the (h/l), the evolution has a logarithmic tendency.

A correlation is developed to estimate the air velocity at the outlet of trapezoidal prism chimneys, with inlet by outlet section ratio equivalent to ($S_1/S_2 = 12$)

$$V = 0.09 + \left[0.75\ln\left(\frac{h}{l}\right)\right]^{1/3} \quad \text{with} \quad h/l \geq 1. \tag{10}$$

Estimated results by the developed correlation Eq. (10) in Fig. 8 show a maxim error of 0.7 % at the present experiment conditions. Correlation Eq. (10) can be multiplied by a coefficient of correction (k) in order to add the effect of climatic conditions, geographic location and time of year; therefore it becomes:

$$V = k\left[0.09 + \left[0.75\ln\left(\frac{h}{l}\right)\right]^{1/3}\right], \tag{11}$$

where h and l are the chimney height and base length respectively, k is the coefficient of correction.

Thermal efficiency was calculated using Eqs. (7)–(9) and experiment results. Fig. 6 indicates the thermal efficiency of chimney cases for the test period; the solar energy transferred into the air movement to improve the ventilation reach its higher rate in the $h/l = 1.5$ chimney mainly for solar intensity higher than 800 W/m^2. Between 700 and 800 W/m^2 the efficiencies are similar in $h/l = 1.5$ and $h/l = 2$ scenarios.

Experimental results show that the optimum value of the average thermal efficiency, Fig. 9, is obtained by the chimney with $h/l = 1.5$, in $h/l = 1$ chimney case, the thermal efficiency didn't exceed 3.36 %.

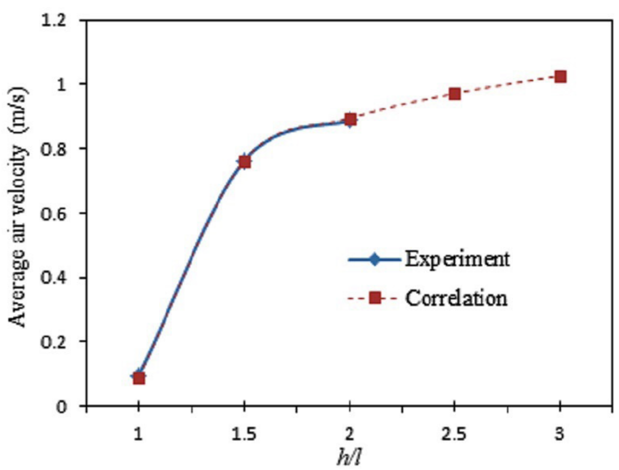


Fig. 8 Average outlet air velocity for different chimneys during the test period and developed correlation

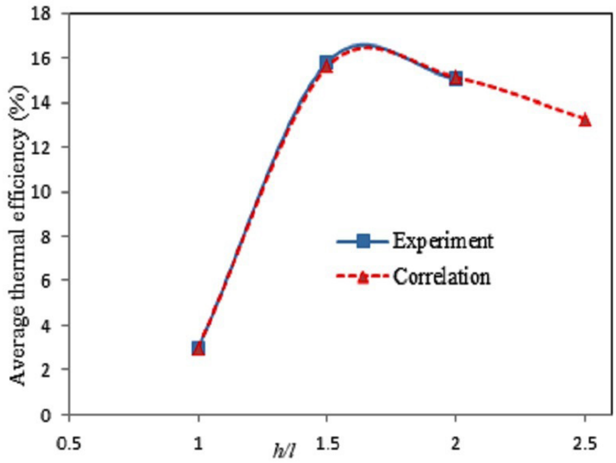


Fig. 9 Average thermal efficiency and developed correlation

Another correlation is developed to estimate the thermal efficiency of trapezoidal prism chimneys as

$$\eta = 3 + 70\frac{\ln(h/l)}{(h/l)^2} \quad \text{with} \quad h/l \geq 1. \tag{12}$$

As shown in Fig. 9, the developed correlation gave very close results compared with the experiment. The maximum recorded error is 0.2 in the efficiency value. Using correlation Eq. (12), the efficiency reach its maximum by $h/l = 1.65$.

5 Economic and environmental benefits

The solar chimney was simulated in RETScreen4 to estimate the thermal energy gain during a year; it shows the technical evaluation and an outlook of economic and environmental benefits.

The solar chimney system performance was simulated as a non-operating fan during the solar radiated period. The economic inputs were based on cost estimated and suggested values.

The selected location of climate data in RETScreen database Tlemcen/Zenata (is near the experiment location 10 Kilometers).

The power of the fan was calculated by using the experimental data, The air flow is given from (Eq. (6)) and measured air velocity and then converted into the power of electrical motor driving the fan using a rule-of-thumb of 475 L/s per kilowatt (750 cfm/hp) of fan motor capacity [27]. The required airflow is that given in Table 1 [23].

The RETScreen model is capable to perform a detailed economic analysis using some cost and interest parameters such as discount and inflation rates, GHG (Green House Gases) emission reduction credit, project life, energy cost, escalation rate, etc. The inflation rate of 4 %

Table 1 Total ventilation air requirements

Area Based	Occupancy Based
0.10 L/s per square meter of floor space	8 L/s per person, based on normal occupancy

and 30 years project life are used. An estimated initial cost is also used; the electricity price is given from the national electricity provider invoice.

In term of GHG emission, the results show that using an efficient solar chimney in ventilation system in a 120 m^2 floor space house save the equivalent of 23.9 liters of gasoline Fig. 10.

The economic analysis show that the payback period is 16.3 years; it means a desirable investment.

6 Conclusions

Experimental study is used to investigate trapezoidal-prism solar chimney behavior, three chimneys with different height to base length are used h/l = 1, h/l = 1.5 and h/l = 2). The following conclusions can be extracted:

- The h/l = 1 chimney case offered significant high outlet temperature with low flow rate which results in a stagnation of the air inside the chimney due to high resistance in the passage.
- The chimney with h/l= 1.5 gave the best thermal efficiency compared with the two other studied cases.
- In h/l = 2 scenario, the chimney delivered the higher flow rate.

Two correlations were developed to predict air velocity and thermal efficiency, it was found that:

- Air velocity increase by increasing h/l in a logarithmic tendency.
- The optimum thermal efficiency can be taken by h/l = 1.65.

The investment benefits economic and environment) was also carried out with RETScreen4 software, it showed that:

- Using an efficient solar chimney in ventilation system in a 120 m^2 floor space house save the equivalent of 23.9 liters of gasoline.
- The payback period is 16.3 years.

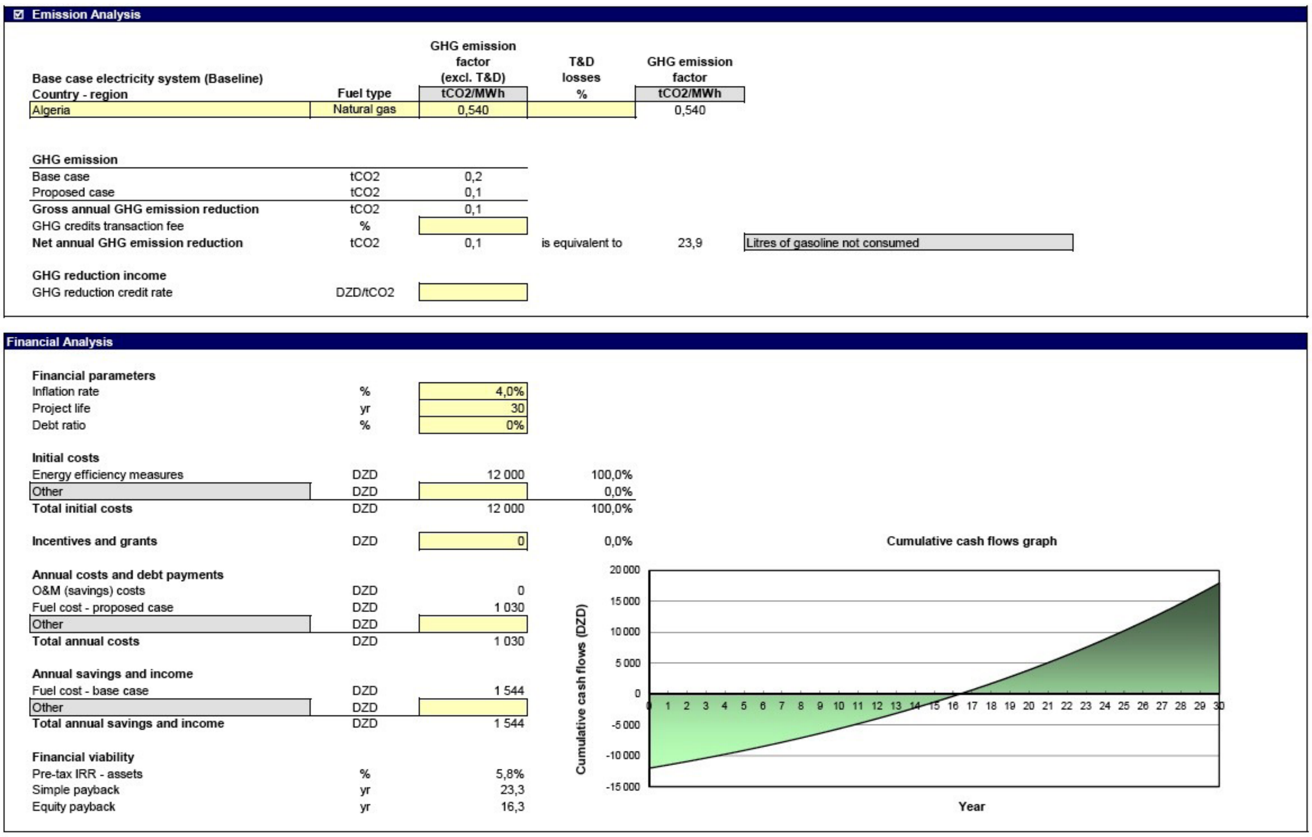


Fig. 10 Emission and financial analysis

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