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New Passive Cooling as a Technique for Hot Arid Climate

Amr Sayed Hassan Abdallah

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Abstract

Cooling of buildings is an essential target for engineers and builders in the hot arid climate of Egypt. New cooling system was integrated into a single room built in Assiut University (El-Gorib site) in Assiut, Egypt. A passive cooling technique was integrated inside a short wind tower made from expanded paper (wet pad) 0.1 m thick. A water tube was installed on the top of the expanded paper with small nozzles. The results show that outlet air temperature from the wind tower is 27.3°C. The calculated predicted mean vote (PMV) is within the recommended range (−0.5 < PMV < +0.5). This indicates that occupants remain satisfied with indoor thermal environment after using the passive cooling system and the difference is nearly 6–7 K between outdoor and indoor. The system achieves the acceptable airflow rate with an average of 450 ppm for CO_2 concentration during daytime. The relative humidity did not exceed 57% most of the time. The maximum airspeed inside the solar chimney was 3.5 m/s under the effect of a high solar radiation of 890 W/m². The findings show that solar chimney with passive cooling tower design (SCPC) system achieves comfortable thermal conditions with a significant improvement in building energy conservation.

Keywords: inclined solar chimney, passive cooling, thermal comfort, carbon dioxide concentration

1. Introduction

Solar chimney with passive cooling tower design (SCPC) is a system that uses solar energy that strikes the aluminum and glass in a chimney to generate a buoyancy force in the chimney. This force drives outside hot air to pass through the evaporative pad (expanded paper) and causes reduction of indoor temperature, high humidity and constant enthalpy [1]. The thermal

performance of solar chimneys using different configurations has been experimentally investigated by different researchers. The concept of metallic solar wall (MSW) on a full-scale model was studied for a single-room house under tropical climatic conditions in Thailand. It was shown that a MSW with 2 m height and 0.145 m air gap (cavity between glass and aluminum) can produce a mass flow rate up to 0.02 kg/s for a house with a base area of 11.55 m^2 and a height of 2.68 m and optimum natural ventilation. Such low-cost solar chimney construction can significantly reduce heat gain in the house by creating adequate flow rate to improve thermal comfort [2]. The thermal performance of a solar chimney was investigated on a full-scale model under Mediterranean daylight and night-time conditions for natural ventilation. A 4.5 m high, 1.0 m wide and 0.15 m thick reinforced concrete wall was used as a solar absorber, whose southern surface was painted matte black with insulation on the side and back surfaces. The absorber wall was covered by glass of 0.1 m thickness to reduce the convection heat. With this configuration, a maximum flow rate of 374 m^3/h was reported at a solar intensity of 604 W/m^2 occurring at around 13:00 h. Discharge coefficient was experimentally determined to carry out volumetric flow rate calculation. It was concluded that the airflow rate through a solar chimney system is greatly affected by the pressure difference between openings caused by thermal gradients and by wind velocity [3]. An experiment of solar-induced ventilation strategy was conducted. The experiment consisted of two parts, namely, a roof solar collector and a vertical stack. The purpose of the roof solar collector was to capture as much solar radiation as possible, thus maximizing the air temperature inside the channel of the roof solar collector. The heated air inside the channel rose and flowed into the vertical stack due to the pressure difference between the two zones. Meanwhile, the vertical stack was important in providing significant height for sufficient stack pressure. The walls of vertical stack were insulated to minimize the heat loss to the environment. The findings indicated that the proposed strategy was able to enhance the stack ventilation, both in semi-clear sky and overcast sky conditions. The highest air temperature difference between the air inside the stack and the ambient air was achieved in the semi-clear sky condition, which was about 9.9°C (45.8–35.9°C). Besides, in the overcast sky condition, the highest air temperature difference was 6.2°C (39.3–33.1°C) [4]. Also, an experimental study of a vertical channel simulating a solar chimney and a Trombe wall was conducted. The vertical channel had a transparent cover and an absorber plate, painted matte black. The vertical channel was open at both ends, and its dimensions were 1.025 m high, 0.925 m wide and 0.02 m–0.11 m variable depth. Heat input to the absorber plate was supplied by electrical means (200–1000 W) in steps of 200 W. Air temperature and velocity measurements inside the channel were obtained. The results showed that air temperature was increased continuously along the channel height, while the cover and the absorber plate temperatures were not. The cover temperature, as well as the absorber plate temperature, increased continuously to the middle height and then began to decrease. The authors concluded that the mass flow rate is a function of the heat input as well as on the channel depth, while the efficiency of the system is a function of the heat input only [5].

It was concluded that a serious problem of discomfort exists inside houses in projects of new Assiut city based on natural ventilation strategy only [6–9]. Traditional passive techniques were used in ancient architectures to achieve the desired summer comfort without the need

for mechanical cooling systems [10]. This traditional technique was based on natural environmental conditions such as wind, water and vegetation to achieve significant indoor thermal comfort [11]. It was concluded that if passive solar solutions are integrated in existing buildings, building energy demand can be reduced [12]. Many researches have been conducted to examine passive cooling strategies in the buildings. Maerefat and Haghighi studied solar chimney integrated with evaporative cooling cavity. This integrated system was capable of providing good indoor conditions during daytime in the living room [10]. Alemu et al. developed a model using passive cooling technique in earth air tunnel. This model investigated the integration of passive techniques [13]. Developing solar chimney with direct evaporative cooling tower using numerical simulation was done using COMIS-TRNSYS software to provide indoor thermal comfort under the climatic conditions of Assiut, Egypt. The results show that the system generates 130.5 m³/h with indoor thermal comfort of 80% acceptable range [7, 8]. Macias et al. developed a passive cooling system for a residential building. Natural ventilation was enhanced with the aid of a solar chimney, and fresh air was cooled down by circulation within the duct area of the building. It was found that the passive cooling system allowed for ensuring thermal comfort through low conventional energy consumption based on a 2-year monitoring period [14] .

No experimental studies were found for the integration of solar chimney with cooling strategies in residential buildings in Egypt except for the ventilated Trombe wall as a solar heating and cooling for building retrofitting in semiarid climate (Saint Katherine, Egypt) [15]. The purpose of using solar chimney is to generate natural air movement and improve stack-induced ventilation with low CO_2 concentration and indoor comfort for low-energy buildings in Egypt. The main aim of this study is to investigate the performance of an (SCPC) integrated within a room as a passive cooling technique to provide sufficient fresh cooled air, indoor comfort, and reduce room cooling loads. This stage is the second phase of a project for developing an integration of solar chimneys with passive cooling technique (SCPC) to reduce energy used in buildings in Assiut, Egypt.

2. Test room and SCPC system description

A single room was built in Assiut University (El-Gorib site) in Assiut, Egypt. Room dimensions are 3.8 x 3.8 x 2.8 m (L × W × H) based on the previous numerical model of solar chimneys integrated with passive cooling [7, 8]. It is located at a latitude of 27°3′N and a longitude of 31°15′ E. In terms of climatic characteristics, Assiut is located in southern Upper Egypt zone. It is characterized by hot dry summers with a maximum outdoor temperature that ranges from 41–46°C and a minimum temperature that ranges from 16–21°C in the summer months. This zone has a global radiation range of 1000 to 1125 W/m² in the summer and 650 to 800 W/m² in the winter. Outdoor climate analysis was done based on field measurements at 2-minute time interval to analyze 1-year data (2015). **Figure 1** shows the temperature and humidity patterns of 2015. Selecting 2 months for monitoring (August and September) was done to test indoor environment using passive air conditions. These periods were selected to
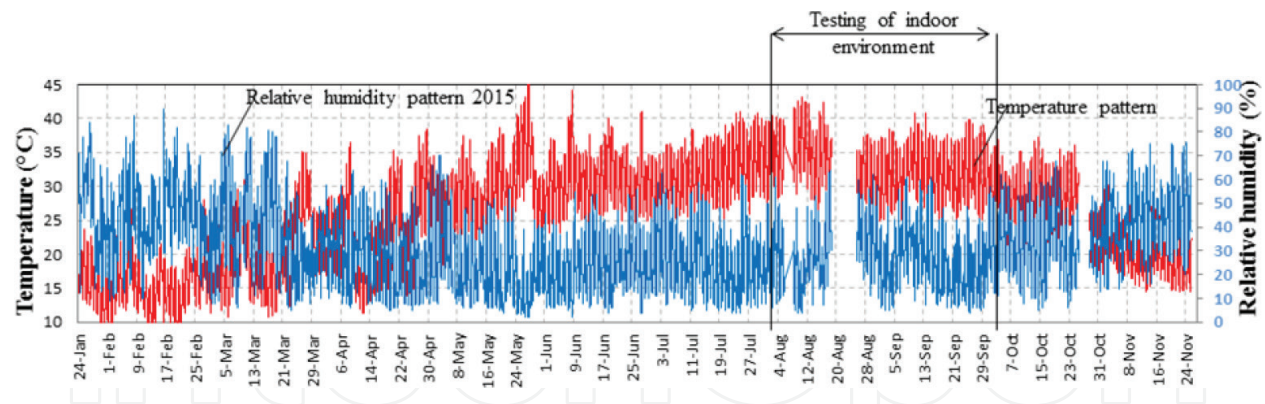
Figure 1. Temperature and humidity pattern of outdoor condition during the year of 2015.

investigate the effect of different patterns of (high/low) outdoor conditions. Also, solar radiation was measured for outdoor conditions, with a maximum solar radiation of 890 W/m² reached between 11:00 am and 1:00 pm. Solar radiation creates a temperature gradient inside the chimney air cavity that causes the driving force of air inside the chimney under the effect of stack effect.

The average solar brightness in Assiut was 12.125 h/day [16]. This encourages applying the SCPC system in this area. The overall heat transfer coefficient of the building part is calculated based on the physical properties of materials available in the local market with the same properties as the materials used in the numerical model. **Table 1** shows the characteristics of building materials. The overall heat transfer coefficients of walls, floors and roofs are 2.60, 0.797 and 0.443, respectively. The window opening is oriented towards the south and the

Building part	Material	Conductivity (kJ/h m K)	U-Value (W/m2 K)	Thickness (m)
Glass windows	Single glass	—	5.68	0.004
External walls	Common plaster + cement (coating)	1.26	2.60	0.02
	Brick	3.60		0.10
	Common plaster + cement (coating)	1.26		0.02
Roof	Insulation	0.2	0.443	0.05
	Concrete slab	4.2		0.12
	Cement plaster (coating)	4.50		0.01
Ground	Floor	—	0.797	0.10
	Insulation	0.2		0.02
	Concrete	4.2		0.10

Table 1. Description of building materials used.

Figure 2. The outer view of the room with SCPC system fixed on its roof.

door opening towards the north. **Figure 2** shows the outer view of the room with the SCPC system on its roof.

The walls of the building are made from hollow clay bricks 0.1 m thick and covered with cement from both sides with thicknesses 0.02 m and a U-value of 2.6 (W/m²K) for the wall. The ceiling is made from 0.12 m thick concrete and covered with 0.01 m thick cement on the inner side. The ceiling is covered by insulation and concrete cover with thicknesses 0.15 and 0.07 m, respectively, as shown in **Figure 3**.

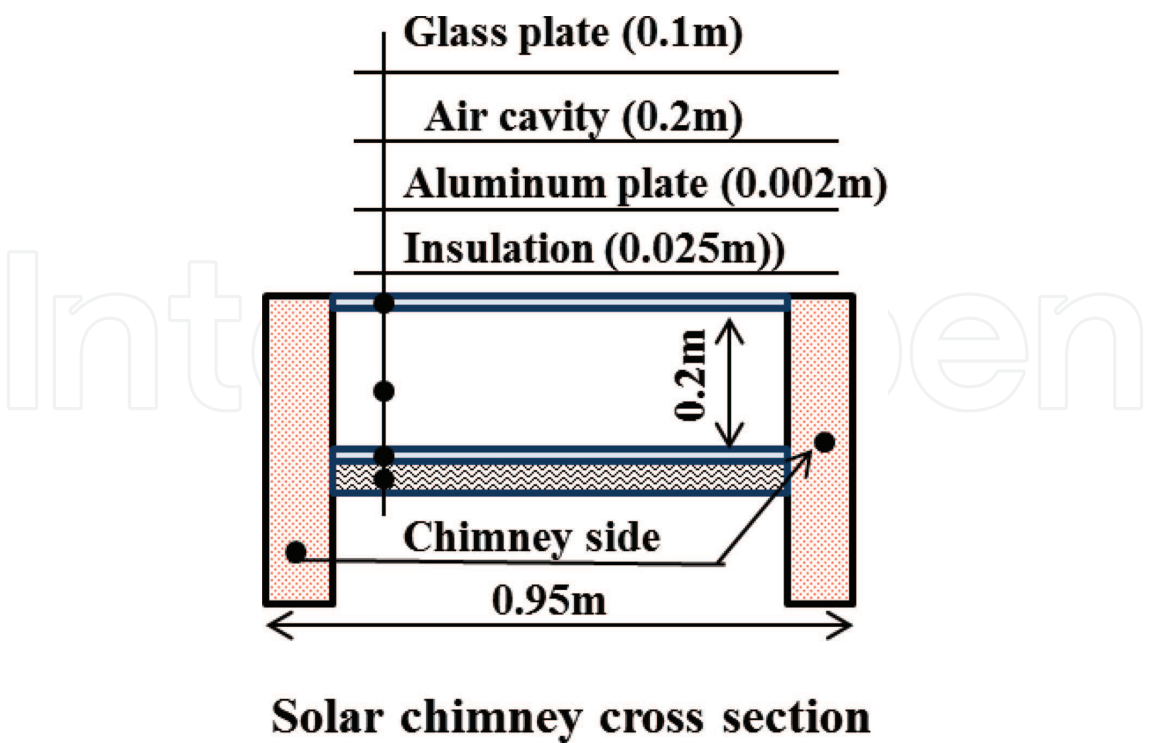**Figure 3.** The description of roof layers and their thicknesses.

Figure 4. Cross section of the solar chimney cross section.

A thermal insulation, 0.1 m thick, is installed inside the floor layer to examine the performance of the integrated SCPC system for indoor thermal comfort while excluding heat effect from the ground. The SCPC system consists of two components: the solar chimney and the short wind tower. The solar chimney was fixed on the roof of the room facing south. The SCPC system is made from widely available and conventional materials in the Egyptian market. The solar chimney is made from black aluminum with emissivity 0.95 and glass with transmissivity 0.84 and thicknesses of 0.002 m and 0.1 m, respectively, as shown in **Figure 4**. Performance of the solar chimney was examined in the first phase. The maximum airflow rate in the chimney was 0.69 kg/s during a high solar radiation of 890 W/m^2 [17, 18].
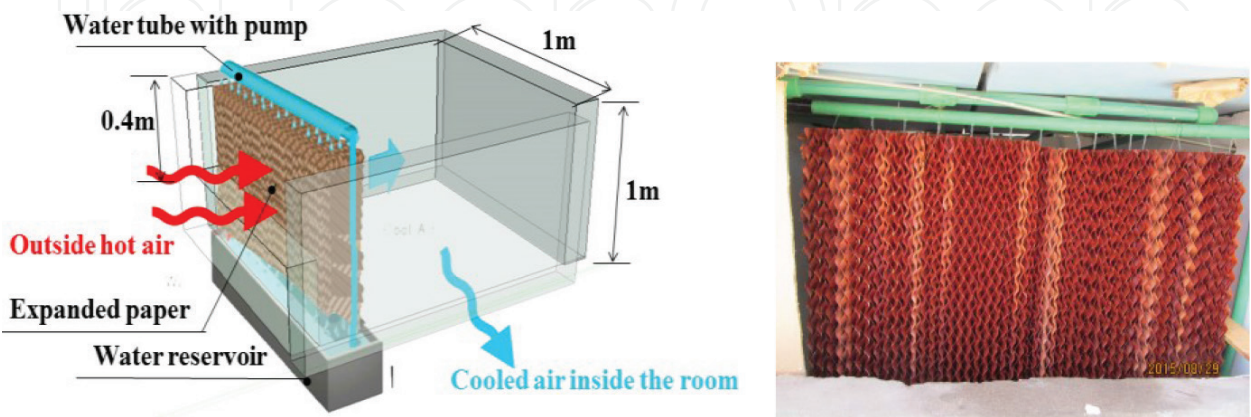

Figure 5. The description of evaporative technique in the wind tower made from expanded paper with water droplet from upper side.

The passive cooling technique was integrated inside the short wind tower with the opening facing north. The method applied in this study will depend on cooling the interior space envelope using cheap and local cooling materials without consuming much energy. The tower was built with dimensions 1 m x 1 m x 1 m (L × W × H). The wet pad in wind tower is made from 0.1-m thick expanded paper. A water tube was installed on the top of the expanded paper with small nozzles. A water pump is used to recirculate water from the water reservoir in the bottom of the pad. Water is supplied from the water tank to the bottom water reservoir using a concentric floating valve. It opens when the level of water in the bottom reservoir decreases as shown in **Figure 5**.

In order to understand the actual indoor environment after using the passive cooling system, a sample data will be presented from 2-month data monitoring as an example.

3. Comfort ventilation

Comfort ventilation is the important factor that deals directly with the human body and depends on the strategy used. It is based on the theory that high airspeed around the human body accelerates the skin's evaporation rate and, accordingly, improves the heat dissipation from the human body. This in turn shifts up the comfort upper level by providing such direct physiological cooling effect and decreases human discomfort due to skin wetness and the high humidity level [20]. In comfort ventilation strategy, two different impacts of the air velocity of the human body were determined: first, the heat exchange of the body that happens with convection; second, the evaporative capacity of the air. According to ASHRAE Standard 55 for naturally ventilated buildings, the acceptable thermal environment of indoor operative temperature ranges between 22°C and 28°C, and the comfort indoor air velocity of 1.6 m/s can be beneficial for improving comfort at higher temperatures [19]. So, new residence must have the acceptable thermal environment for all occupants. According to ASHRAE Standard 62–2001, ventilation rates depend upon the floor area, whereas the minimum ACH was 0.35, but no less than 15 CFM/person [21]. Also, passive natural ventilation standards require a minimum of three air changes for residential buildings. Finally, the comfort ventilation can easily be enhanced by appropriate building design and the system used.

4. Solar radiation and surface temperature analysis

Figure 6(a) shows the variation of daily solar radiation over time. A maximum solar radiation of 890 W/m^2 was reached between 11:00 am and 1:00 pm. Solar radiation creates a temperature gradient inside the chimney air cavity, and the warm air is less dense than cool air so it rises and creates a difference in pressure which in turn induces air movement, causing the driving force of air inside the chimney under the effect of stack effect. The main component of the solar chimney is the absorber plate, which was made of an aluminum plate painted black with 0.95 emissivity. A wind-driven protection was used at the top in order to avoid reverse flow. It is clear that the maximum surface temperature of aluminum was 86°C at 1:30 pm due to high
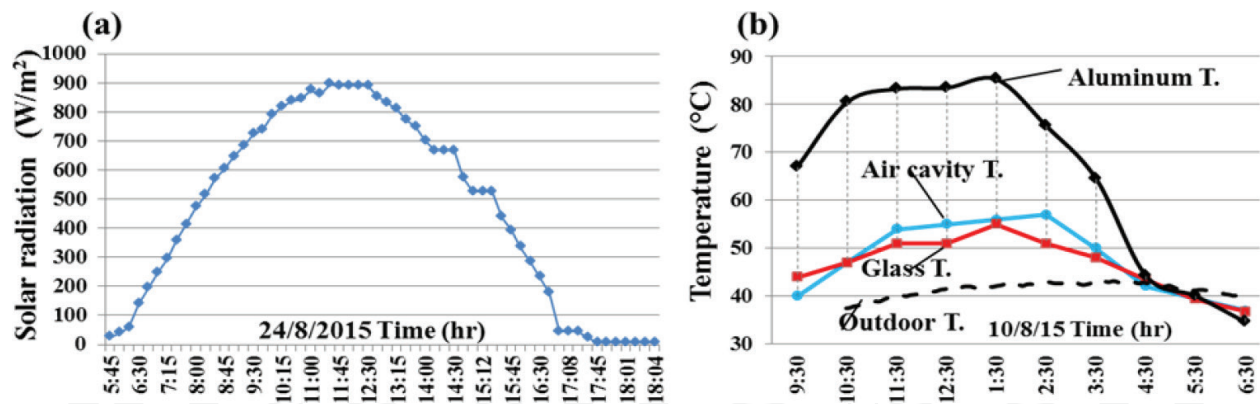
Figure 6. (a) The variation of daily solar radiation over to time. (b) The variation of different temperatures with time.

intensity of incident solar radiation in this period. Temperature was recorded in the middle of the aluminum plate. After midday, temperature started to decrease until 65°C at 3:30 pm, followed by a sharp drop of temperature due to decrease of solar intensity and high heat release without any thermal storage integrated with the aluminum plate. Also, glass surface temperature has the same pattern as aluminum temperature with 15°C higher than outdoor temperature. This affects air cavity temperature strongly. This finding is in agreement with [22].

Figure 7 shows the temperature profile of outlet air inside the chimney cavity. It is clear that the temperature of the chimney cavity increases and reaches 48°C for the highest temperature at 12:00 pm with high solar radiation. The temperature of air cavity is higher than outdoor until 4:00 pm. Then, a strong reduction of air temperature inside the cavity was reached. This is due to the decrease of aluminum surface temperature and heat release from the absorber. **Figure 4** shows the thermal images of outside chimney glass plate with the highest three temperature points on its surface at 12 pm on 13/8/2015.

Figure 8 shows the temperature distribution of three points on the upper side of the solar chimney (glass surface temperature) with an average temperature of 38°C and 36°C at 1:00 pm and 3:00 pm, respectively, due to high solar intensity. The thermal gradient of chimney surface temperature and aluminum surface temperature strongly affects the airflow through the chimney.
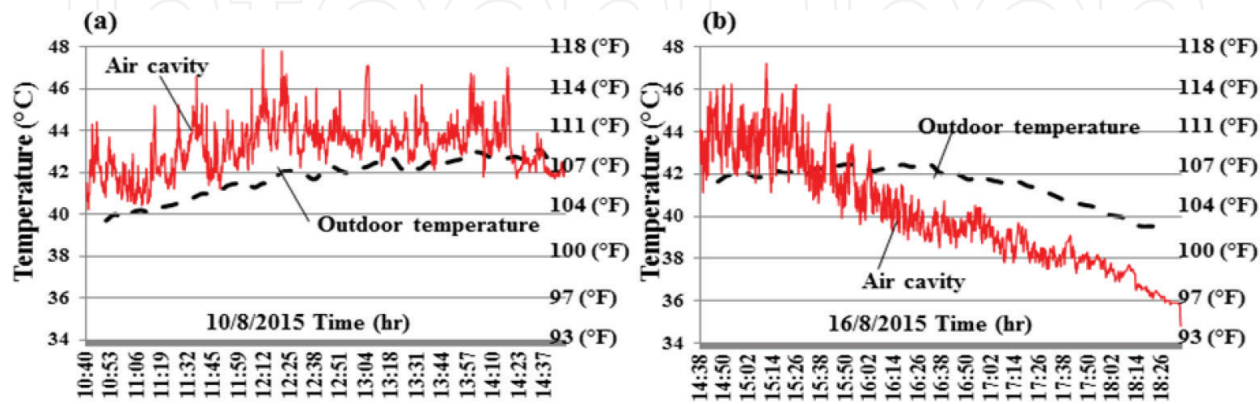

Figure 7. (a) Temperature profile of outlet air inside the chimney cavity from 10:00 am until 14:45 pm. (b) Temperature profile of outlet air inside the chimney cavity from 14:38 am until 18:30 pm.
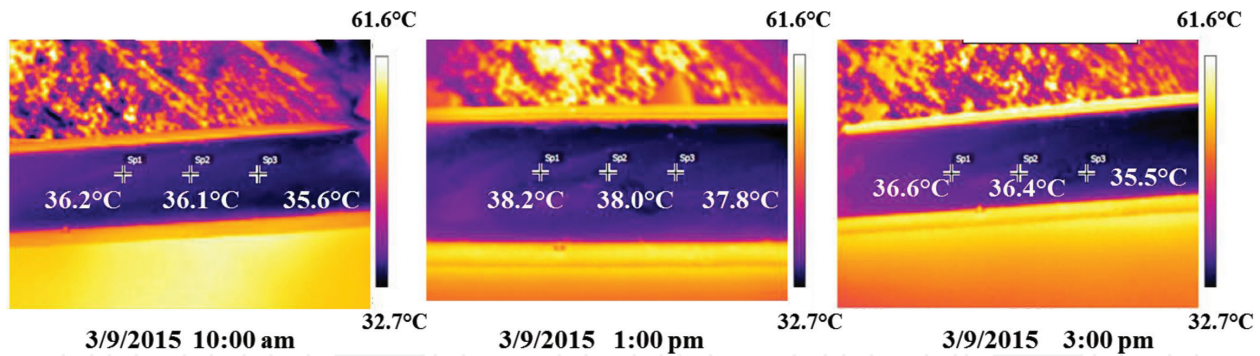
Figure 8. The variation of glass surface temperatures in the solar chimney.

Validation was done for the numerical simulation with the experimental results. The detailed model for the numerical calculation was studied, including boundary condition, geometry and material physical properties [7]. Results of chimney air temperature, cooling tower inlet temperature and aluminum surface temperature with the help of the analytical model were found in good agreement with the corresponding experimental values. The experimental results tend to be higher than analytical model by about 2% and 2.5% in average. However, the airflow at the chimney is higher than analytical model by about 40%. This indicates that the presence of outdoor high wind speed and pressure coefficient on building surfaces and chimney outlets increases airflow rate of the stack effect with a negative effect of reverse flow that occurs in the chimney for some time and decreases performance of the evaporative pad with an average difference of 6% for the indoor temperature.

Due to the buoyancy force, the outer hot air passed through the expanded paper with water droplet, and then the outdoor air temperature was reduced inside the wind tower after passing through the wet pad. A graph indicating a typical variation of indoor cooling using a cooling medium is shown in **Figure 9**. The air temperature inside the room increased gradually due to the presence of occupants inside the room and heat gained by the building. Also, the temperature inside chimney air cavity is decreased gradually due to the absence of thermal storage attaching to the aluminum plate when solar irradiation decreases gradually. Therefore, the air temperature increases in the chimney air cavity, corresponding to the increase of solar radiation.
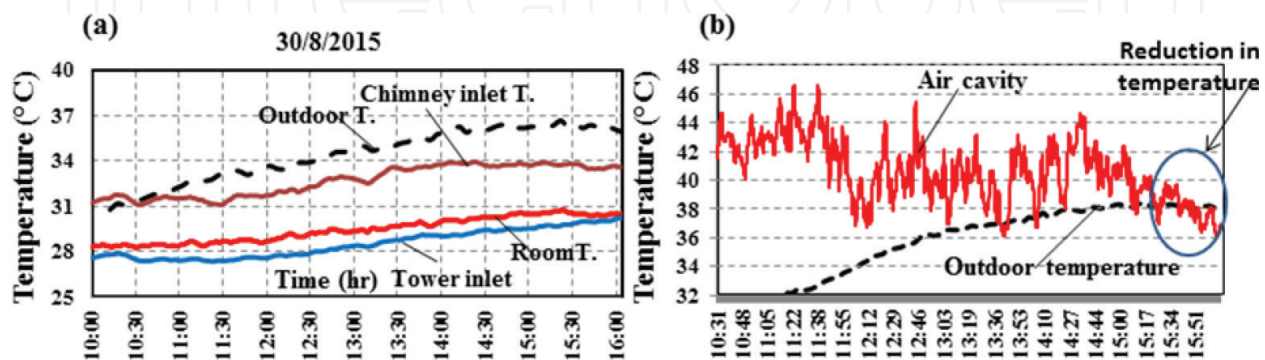

Figure 9. (a) The variation between tower inlet temperature, room temperature and chimney inlet temperature based on the cooling effect. (b) The temperature difference between chimney air cavity and outdoor temperature.
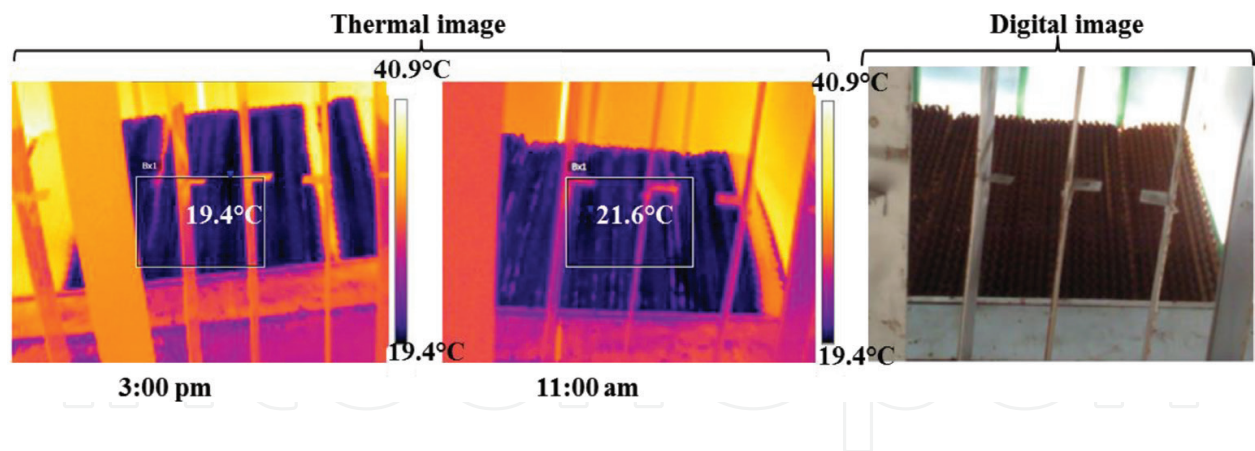
Figure 10. The variation of expanded paper surface temperatures (cooling pad).

Figure 10 shows that the minimum surface temperature of the expanded paper (cooling pad), with water droplet, was 19.4°C at 3:00 pm with an average wet bulb temperature of 22°C. The decrease of surface temperature of cooling pad strongly affects airflow temperature and causes reduction of outdoor air temperature with constant enthalpy. This demonstrates the concept of evaporative cooling. The average water consumption is 16 l/day. This is because the outdoor air that flows through the pads is cooled to a temperature close to the WBT. Then, the indoor air of the building, cooled by an evaporative cooling system, is further heated by about 1–3°C above the output air from the evaporative cooling system, depending on the airflow rate of evaporative cooling and indoor heat gained by the building. This finding is in agreement with [23, 24]. Energy consumption for this system is 18 W only.

5. Thermal comfort and CO_2 evaluation according to ASHRAE and ACS

It is observed that most of the outlet air temperatures from the wind tower are below the upper limit of the 90% acceptable range, as shown in **Figure 11**. The temperature of the outside air that passes through the wet medium can be reduced significantly with a difference 6 K ~ 7 K. Only 10% of the measured data exceeded the upper limits. **Table 2** shows the statistical analysis for indoor temperatures with a statistically significant difference = 0.024 (p level < 0.05). Therefore, the supplied air is still considered suitable to enhance indoor thermal comfort. The maximum indoor temperature was reached at 6:00 pm with a long time lag between outdoor and indoor temperatures. This is due to the effect of indoor thermal mass that impacts room cooling. This is in agreement with [23]. Reducing indoor temperature is based on the amount of water that passes inside the wet pad and the number of nozzles in the water tube.

Humidity is strongly affected by cooling the wet medium. It is observed that indoor relative humidity after using passive cooling did not rise above 57% during daytime and most of the time was below 50%, indicating that further cooling is needed. **Figure 12** shows that
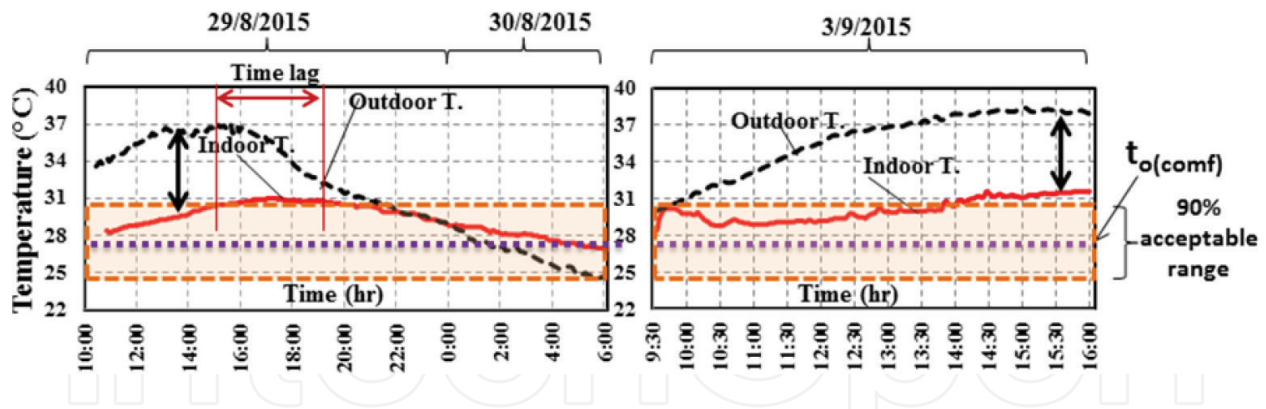
Figure 11. Temperature profile for indoor environment with a cooling technique compared to outdoor condition on the 90% acceptable range of adaptive comfort standard.

Indoor temperature	Range	Mean ± SD	Sample distribution	
			Skewness	Kurtosis
	28.3–31.7	30.1 ± 0.86	−0.63	−1.01

Table 2. The statistical analysis of indoor temperature.

room relative humidity is located within the acceptable range of relative humidity 20%~60%, according to ASHRAE Standard 2004 [19]. Arundel concluded that the optimum humidity level for minimizing adverse effects for health is between 40 and 60% [25]. Also, most of the investigated cases were very close to the summer comfort zone. This is because the air outside is so dry, typically below 10% relative humidity during daytime.

The concentration of CO_2 inside the experimental room is very low. The average concentration is 550 ppm, with three occupants staying inside the room. The lower concentration inside the room
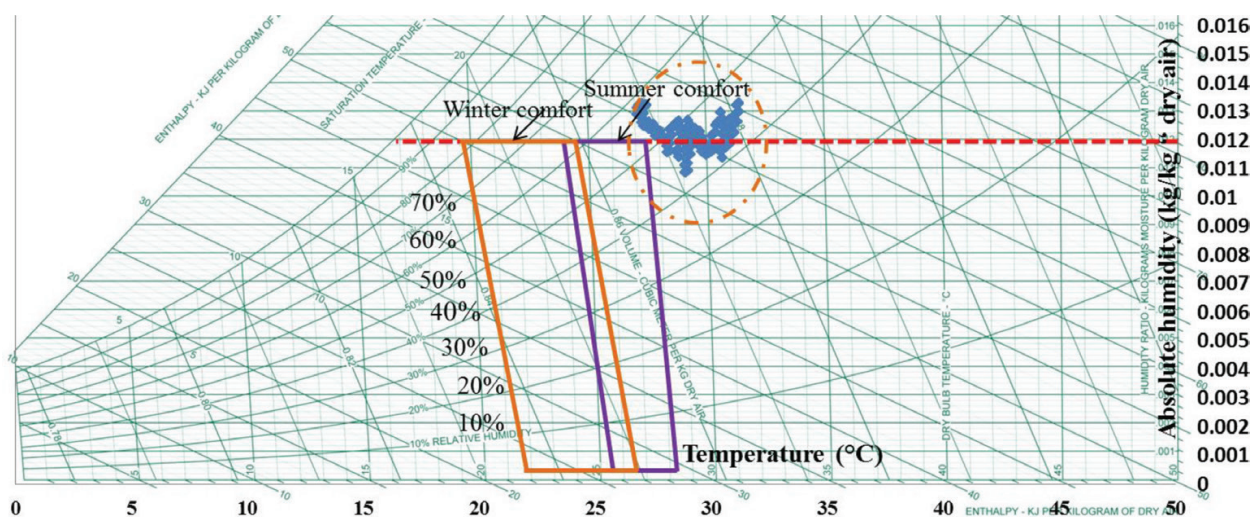

Figure 12. Temperature and humidity conditions inside the room after using the SCPC system.

is due to high airflow rate in the chimney and wind speed to a maximum of 0.69 kg/s, which affects CO_2 concentration. This helps improve the indoor air quality and achieve a safe environment according to [22]. **Figure 13** shows the variation of indoor carbon dioxide concentration.
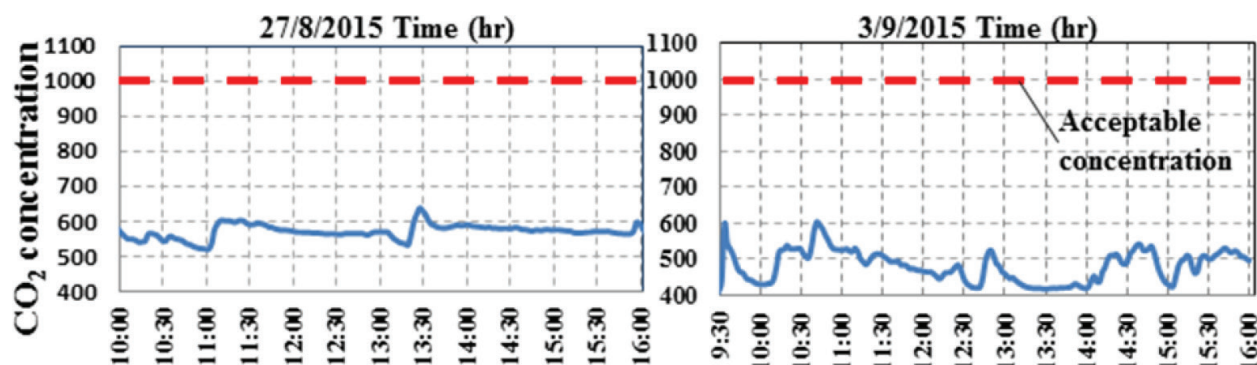

Figure 13. Indoor CO_2 concentration inside the room with SCPC system.

6. Conclusion

Using the SCPC system provides many advantages for indoor environments and achieves energy saving for cooling inside indoor room environments of hot arid regions. It is concluded that the airflow rate through a solar chimney system is greatly affected by the pressure difference between openings caused by temperature across the chimney surface. The results indicate that using the SCPC system reduced indoor temperature to be within the 90% acceptable comfort range. The SCPC system is considered a passive cooling air conditioning system that achieves a significant reduction of indoor temperature between 6 and 7 K based on the condition of the wet pad. The findings from the experimental and numerical calculations were in good agreement. Installation of the solar chimney parts and building the short wind tower are based on the available and conventional materials in the Egyptian market. The results of this research will be used to develop a new cooling system for low energy consumption (only 18 W for the water pump). The new cooling system is made of local materials and provides fresh cooled air with good indoor air quality. The materials of the system have high durability and made from normal glass, aluminum plate and standard brick for the tower. These materials are available at the local market and need simple modification in the ceiling structure of the upper flat. The system structure and materials need no specific manufacturing technology. The operation cost for the system is very low as it depends on solar radiation only. The 0.1-m thick evaporation pad in the tower can be changed nearly every 5 years with simple cleaning required every summer. This new cooling system can be integrated in the housing projects (National Housing Authority) of low-income people in new and existing cities. Adopting this system makes a significant improvement in building energy conservation.

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