

Parametric investigation of solar chimney with new cooling tower integrated in a single room for New Assiut city, Egypt climate

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Abstract Houses in Egypt are often designed without taking the climate into account sufficiently. Consequently, new houses often have a poor indoor climate, which affects comfort, health and building efficiency. In hot and arid climates, passive cooling system employs non-mechanical procedures to maintain suitable indoor temperature. Thus, they have been increasing the influence of the traditional cooling concepts but with new technology. Therefore, these conditions encourage such a concept to enhance natural ventilation with evaporative cooling and save energy in the New Assiut city. In the present study, the effect of solar chimney parameters on wind tower parameters was numerically investigated as a second phase of the new integrated model. All the detailed mathematical equations and system description are presented in phase one. A numerical simulation is implemented in Transient systems simulation program-Conjunction of multizone infiltration specialists program softwares. The parametric studies of the integrated system in phase two were studied to achieve high performance with new compact small design especially for the hottest days in the summer season. The temperature and airflow rates are predicted iteratively taking into account the zone pressure and the pressure drop in the evaporative cooler component. The result shows that the system achieves nearly at least close to 80 % acceptable comfort range according to Adaptive Comfort

Standard of American Society of Heating, Refrigerating and Air-Conditioning Engineers with optimum ventilation rate 414 m³/h for the hottest day. The findings show that the system achieves high performance in the hottest day with small solar chimney dimension and is easy to integrate in the building envelope than the proposed system before parametric studies in phase one.

Keywords Passive cooling · Solar chimney · TRNSYS-COMIS · Parametric investigation

Abbreviations

ACS	Adaptive comfort standard
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
ACH	Air change rate per hour
COMIS	Conjunction of multizone infiltration specialists program
TRNSYS	Transient systems simulation program
TESS	Thermal energy system specialist library of TRNSYS 16

Introduction

Buildings consumed large amount of energy for its operation [1]. As architects and engineers continue to search for better ways to improve both the indoor environmental quality and energy efficiency of buildings, cooling buildings using natural ventilation continues to be an approach that provided air movement and cooling. One method for increasing the air movement through a building is by implementing solar chimney within a design [2]. The

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application of solar chimney with evaporative cooling tower has attracted extensive attention due to its unique advantages [3]. Passive evaporative cooling is one of the most efficient and long recognized ways of inducing thermal comfort in predominantly hot dry climates. Historically, evaporative cooling was used extensively in traditional architecture throughout the world's hot arid countries [4–6]. Many researches have been conducted on using natural ventilation and evaporative cooling strategies for producing cool air and the effect of using a solar chimney on thermal-induced ventilation in buildings; Marefat and Haghigi put forward a new solar system employing a solar chimney together with an evaporative cooling cavity. The numerical calculation showed that this integrated system with the proper configurations was capable of providing good indoor conditions during the daytime in the living room even at a poor solar intensity of 200 W/m^2 and a high ambient air temperature of $40 \text{ }^\circ\text{C}$ [7]. Alemu et al. developed an integrated model incorporating passive airflow components into a coupled multizone ventilation and building thermal model. This model allows an assessment of a combination of passive features such as solar chimney and wind induced earth–air tunnel for both natural and hybrid ventilation systems at the design stage [8]. A lot of awareness is ongoing worldwide on solar energy utilization [9]. Several researchers are being conducted in studying optimization and parametric investigation for the solar chimney with passive cooling; Bassiouny et al. [10] studied some geometrical parameters such as chimney inlet size and width to predict the flow pattern in the room as well as in the chimney. It can be concluded that increasing the inlet size three times only improved the Air change rate per hour (ACH) by almost 11 %. However, increasing the chimney width by a factor of three improved the ACH by almost 25 %, keeping the inlet size fixed. Sudaporn et al. [11] experimentally investigated the effect of using a vertical chimney with and without a wetted roof to enhance indoor ventilation. They reported that the solar chimney can reduce the indoor temperature by $1\text{--}3.5 \text{ }^\circ\text{C}$ depending on the ambient temperature and solar intensity. In addition, spraying water on a roof along with solar chimney use can further reduce indoor temperature by $2\text{--}6.2 \text{ }^\circ\text{C}$. Tawit et al. [12] studied a transparent roof used, with an attic room underneath, to create the driving force that induces natural ventilation in the building. They studied different chimney inclination angles and heights for a two floor building. They analyzed the flow streamlines inside the space as well as in the attic room and the vertical chimney. The results showed that, increasing the inclination angle of the roof from 15° to 60° improved the ACH. Harris et al. [13] computationally analyzed the effect of inclination angle on the induced ventilation rate. They reported that the optimum angle for a maximum flow rate

was 67.58° from the horizontal. This gives an increase in the ventilation rate by almost 11 % compared to the vertical chimney.

Finally, the effect of roof solar chimney inclination angle on natural ventilation was studied in single room. The authors found that the optimum absorber inclination varies from 40° to 60° with latitude ranging from 20° to 30° . Further, they reported that the air flow rate was 10 % higher at an angle of 45° compared to 30° and 60° . In their results, they quoted that the highest flow rate (190 kg/h) was obtained for the inclination angle of 45° at noon time for an air gap of 0.3 m and inlet height of 0.3 m. Moreover, the optimum inclination at any place varies from 40° to 60° , depending upon latitude [14]. As a result, there are limitations for the past literatures that studied the effect of different solar chimney parameters on wind tower parameters. Advantage of two system integration is not optimized yet.

Therefore, the main objective of this paper is parametric investigation of the proposed system to improve the system performance and achieve small compact design with high priority to thermal comfort especially in hot period. This was done by understanding the effect of each parameter of solar chimney and wind tower on the sensitivity of the system performance under the steady-state conditions using Conjunction of multizone infiltration specialists program (COMIS)-Transient systems simulation program (TRN-SYS) software. This development system is used in a room of a single zone to study the performances and the advantages of an integrated system using the combination of different parameters that achieves compact and high-performance system.

Description of the passive system

The performance of solar chimney integrated with the evaporative cooling wind tower is studied in phase one during the summer season of the New Assiut city. This proposed system achieves comfort during the hottest days of the summer season with 95 % of indoor temperature below the upper range of 80 % acceptable comfort range [15, 16]. This study is based on case study building measurement for indoor environment and review for the present climate problem in the Egyptian housing [17, 18]. The performance of the system is to provide desired comfortable conditions and suitable ventilation rate, depending on several parameters such as the ambient conditions (temperature, solar radiation, relative humidity, wind speed and wind pressure coefficient). The following dimensions and specifications are applied to the model: The system is located in the New Assiut city, having a 27.30°N latitude position and 31.15°E longitude position. The solar chimney

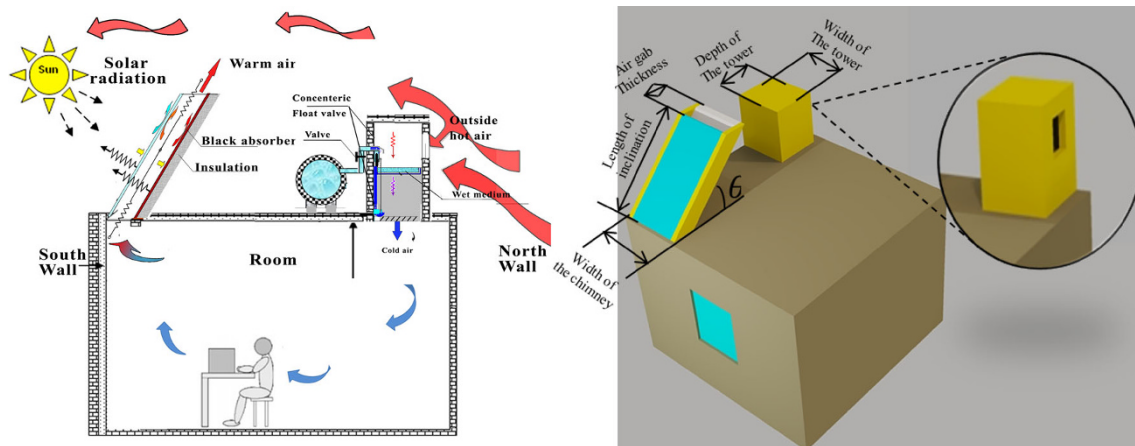


Fig. 1 Schematic diagram of solar chimney with evaporative cooler wind tower

oriented to the south. The calculations were carried out for a single zone with a dimension of $4.0 \text{ m} \times 4.0 \text{ m} \times 3.125 \text{ m}$ ($L \times W \times H$). Nevertheless, for the new proposed system, the inclination length of the chimney was 2 m on the inclined angle, and the height of the cooling tower was 1 m in order not to extend the vertical height above the building according to Egyptian Building Regulation Law. Also, assume the maximum width of the tower and the chimney is equal 1 m. This helps to apply easily in the Egyptian building envelop. Therefore, the parametric studies are done under these ranges and conditions. Figure 1 shows the schematic diagram of the proposed system.

The system is being developed with a solar chimney and a small evaporative cooling wind tower. The evaporative pad provides a large water surface and the pad is wetted by dripping water from the above source. The EC works by a concentric float valve, which opens when the water level is low in the collecting grill, allowing more water to enter. When the water level returns to the full level, the valve is shut automatically. The developed model is implemented in the COMIS-TRNSYS simulation software. This direct evaporative cooling tower used a component no. 506d-Thermal Energy System Specialist library of TRNSYS 16 (TESS) library which uses wet medium at the top, and this component was assembled and validated by a Thermal Energy System Specialists, USA and was modified in 2004. The present model includes special airflow component which need simultaneous prediction of temperature and airflow rates. In the developed multizone ventilation model, a building is idealized as a system of zones, openings and ducts linked together by discrete airflow paths. Zones are represented by nodes. Chimney and evaporative cooling channels are represented by ducts for resistance and pressure drop calculations. A hydrostatic condition is assumed in zones and the flow rate in each link is defined as a function of zone pressure, which results in a system of nonlinear equation solver, defined by the mass

conservation for each zone [19]. The mathematical equations of the integrated system are discussed in detail with full description of the system in the published paper [16].

Methodology

System investigation is started by understanding the effect of each parameter of solar chimney and wind tower on the sensitivity of the system performance during the steady-state condition in the first and the second stages. Figure 2 shows the flow chart of the parametric studies procedure.

The parametric studies used the critical outdoor condition for the summer season to study the parametric investigation during the steady state, so that the outdoor input temperature is $38 \text{ }^\circ\text{C}$, relative humidity is 17 % and solar radiation is 600 W/m^2 . Important parameters of the steady-state stage that helps to achieve indoor thermal comfort are chosen to be studied in the next stage (3rd stage) using real weather data of the New Assiut city in TRNSYS-COMIS model [20, 21], so that the third stage aims to study different parameters that achieve compact and high-performance system. Real weather data were taken from the typical meteorological year (TMY) data sets which were derived from the 1961–1990 National Solar Radiation Data Base (NSRDB) [20].

Then, the results of the final stage of parametric studies were analyzed and compared with the proposed system before parametric studies according to the comfort range of Adaptive comfort standard (ACS) and American society of heating, refrigerating and air-conditioning engineers (ASHRAE) psychrometric chart. Thus, investigation was done for the important dimension parameters of solar chimney and wind tower, while other performance parameters, such as absorptance–transmittance of the absorber, discharged coefficient, length between inlet and outlet, heat transfer coefficient, etc., are kept constant in this model.

Fig. 2 Flow chart of parametric studies procedure

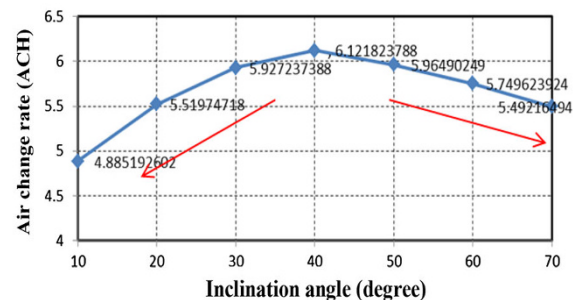
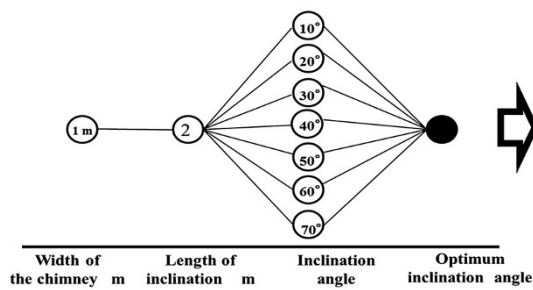
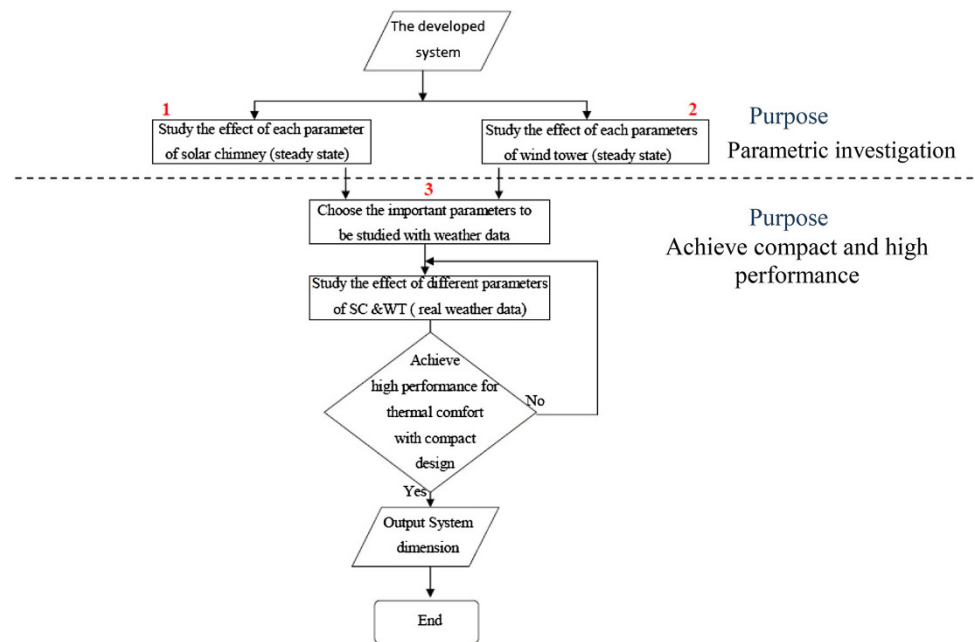


Fig. 3 Parametric studies structure of inclination angle and its result

The ventilation model is integrated in the conventional thermal model to have strong influence on the system performance using TRNSYS-COMIS program. The detail of thermal and ventilation models is based on the mathematical calculation [15].

Parametric studies

The inner flow pattern as a result of varying the chimney inclination angle was predicted and presented in Fig. 3 at different angles: 10°, 20°, 30°, 40°, 50°, 60° and 70°. As can be noticed from Fig. 3, there is a noticeable effect of the chimney inclination angle on the space air flow pattern. These variations of air flow rate are dependent on the intensity of solar radiation, surface azimuth angle of the chimney and surface title with the horizontal. The small inclination angle of 10° showed a high flow resistance and sudden flow with low absorption of solar energy. Once the chimney inclination angle increases

until 40°, the flow speed increases in the room and the chimney. The optimum flow pattern can be seen for inclination angle 40°. On the other side, as the chimney inclination angle increases to 70°, the indoor air flow decreases another time. This is due to less absorption of solar energy.

Figure 4 shows the variation of chimney air gap on indoor temperature and air change rate. The results show increasing indoor air change rate with increase in air gap thickness from 0.1 to 0.4 m. On the contrary, the increase in the air gap after 0.4 m has no effect on indoor cooling temperature and air change rate. This is because, when the air gap increase, convective heat transfer coefficient decreases. According to the calculation of temperature prediction in the solar chimney, the convective heat transfer coefficient is inversely proportional to the air gap thickness. With the air gap 0.1 m, the chimney has high resistance that decreases the flow. Therefore, the parameters that need to be studied for air gap using real weather data are 0.2, 0.3 and 0.4 m.

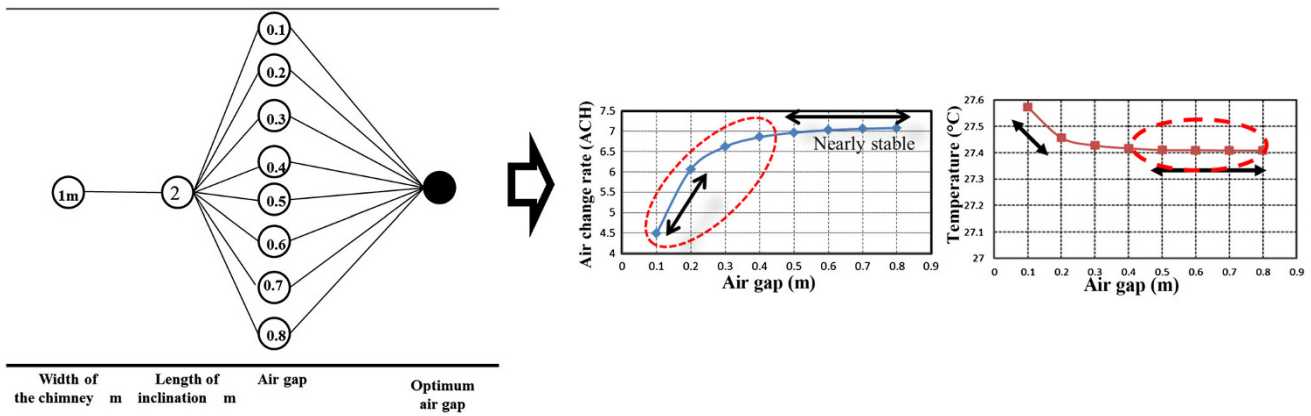


Fig. 4 Parametric studies about structure of air gap and its result

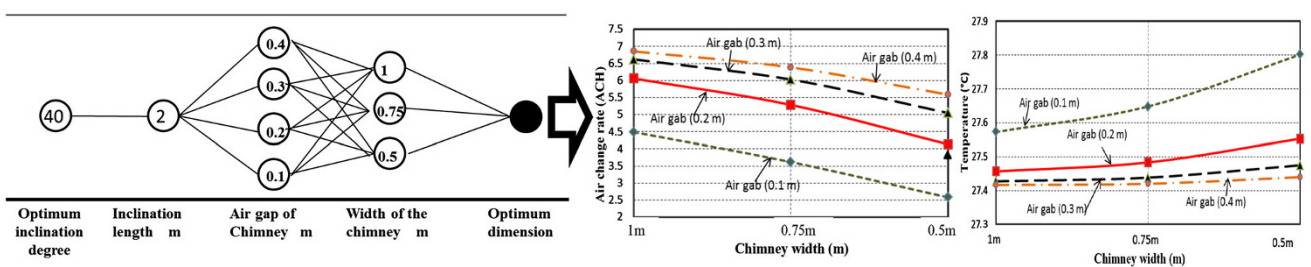


Fig. 5 Parametric studies about structure of chimney width and air gap combination and its result

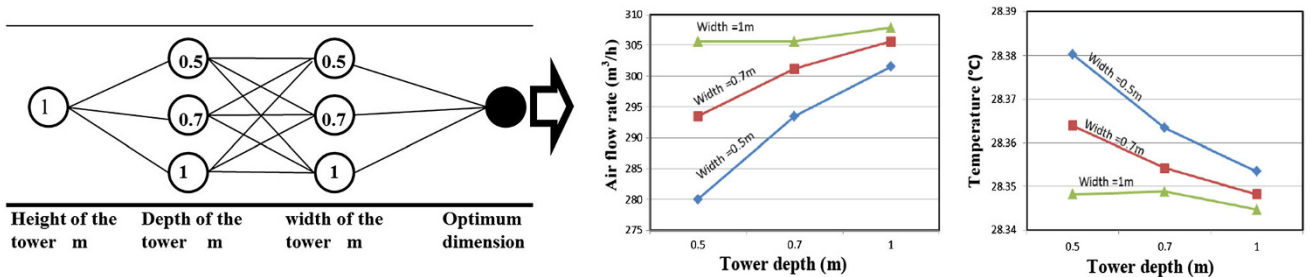


Fig. 6 Parametric studies about structure of tower dimension and its result during steady-state condition

Figure 5 shows the variation of indoor temperature and air change rate due to the combination of different chimney width and air gaps. It is concluded from the developed system, 1 m for chimney width achieves good indoor air flow rate and CO₂ concentration during day time according to ASHRAE Standard for four occupants, while more than 1 m achieves more than the occupants need for indoor ventilation rate with increase in indoor temperature. Different combinations of chimney width 1, 0.75 and 0.5 m with the different air gap width are needed. It is clear that indoor temperature increases when the chimney width equals 0.5 m with different air gap dimensions. In addition, a chimney width of 0.5 m did not support indoor thermal comfort due to increase of indoor temperature. Therefore,

the chimney widths of 1 m and 0.75 m is important to be studied using real weather data.

Figure 6 shows the effects of different tower depth and width on indoor temperature. When the dimension of the tower decreases, less air from outside enters the tower with a few layers of air having contact with the wetted pad surface and this causes decrease in the evaporation rate of air with low outlet cooling energy from the chimney. Therefore, indoor temperature increased especially for tower depth and width equals 0.5 m. While, the performance of the system increased with dimension equal 1 m, 0.7 m for tower depth and 1 m for tower width. This causes decrease indoor temperature and more cooling is achieved. Therefore, it is better to choose 1 and

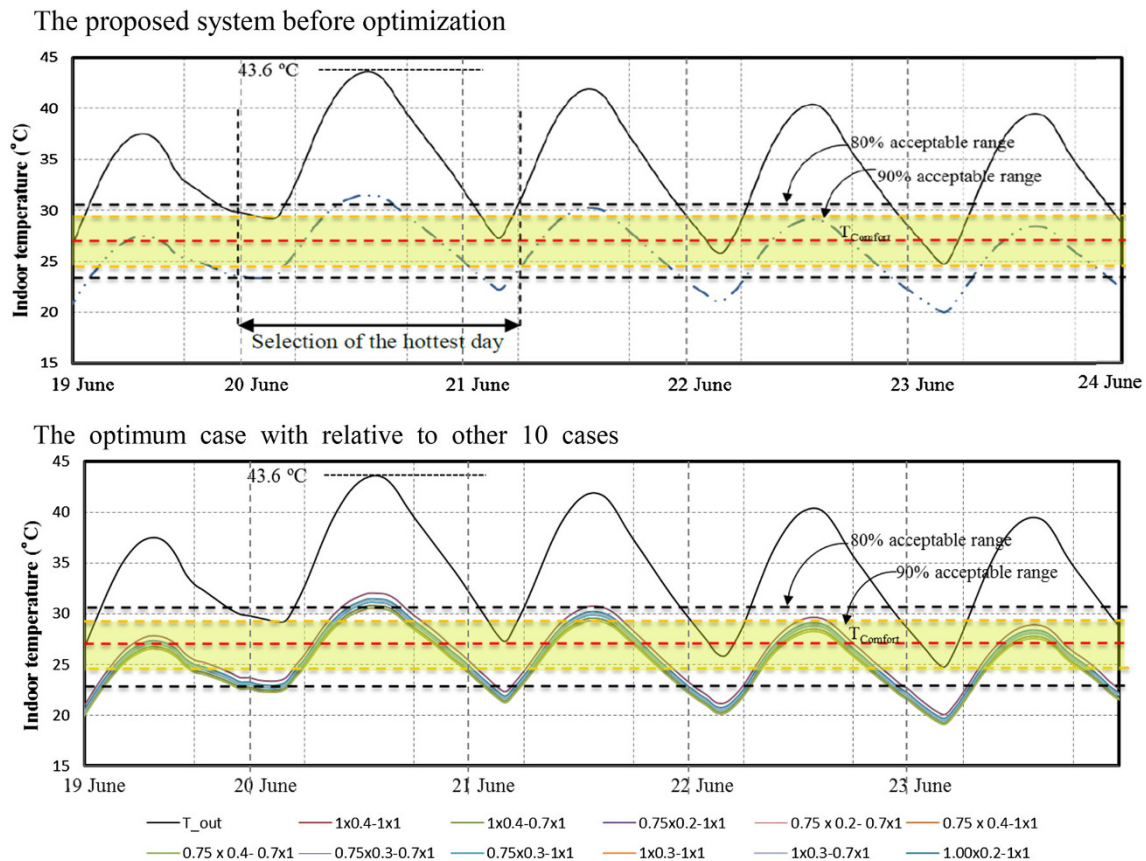
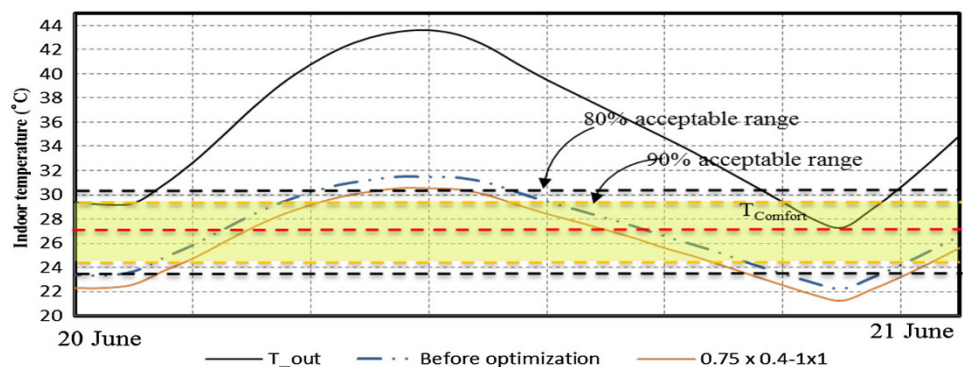


Fig. 7 Indoor temperatures for different system dimension with relation to outdoor temperature

Fig. 8 The difference between the proposed system before and after parametric studies during the hottest day



0.7 m for tower depth and 1 m for tower width to simulate real weather data.

Based on the study of each parameter of solar chimney and wind tower in the first and second stages on indoor temperature and air change rate, important parameters are chosen to be simulated in order to achieve compact and high-performance design. These parameters are 1 and 0.75 m for chimney width, 0.2, 0.3 and 0.4 m for air gap, and 1 and 0.7 m for depth and 1 m for width of the tower. Therefore, 11 cases are needed to be simulated using real weather data (typical) for the hottest days in the summer season from 19th June until end of 23rd June.

Result and discussion

Figure 7 shows the proposed system before parametric studies and the 11 cases after parametric studies. The result shows only one optimum case with dimension 0.75 m × 0.4 m for solar chimney and 1 m × 1 m for wind tower achieves a minimum close to the upper range of 80 % acceptable comfort range. By selecting the hottest day (June 20th) and comparing the simulation result before and after parametric studies, the difference between before and after parametric studies is nearly 1.5 °C (Fig. 8).

Figure 9 shows the effective ventilation rate for the system after parametric studies. It is clear that increasing the ventilation rate ($>414 \text{ m}^3/\text{h}$) inside the room causes indoor air temperature to increase. Also, low ventilation rates ($<414 \text{ m}^3/\text{h}$) cause indoor air temperatures to increase. Therefore, the optimum ventilation rate is $414 \text{ m}^3/\text{h}$, which achieved the optimum indoor air temperature.

By calculating the carbon dioxide concentration in the room from the resulted air change rate based on the mathematical equation [22], the indoor concentration is $<1,000 \text{ ppm}$ especially during daytime according to ASHRAE comfort criteria [23] with high indoor air change rate than the system before parametric studies as shown in Fig. 10. It is clear that the maximum difference (%) in CO_2 concentration before and after parametric studies is 7.8 % with average 3.1 %.

Assume a maximum occupant load of four people staying in the room with no air exchange from other room.

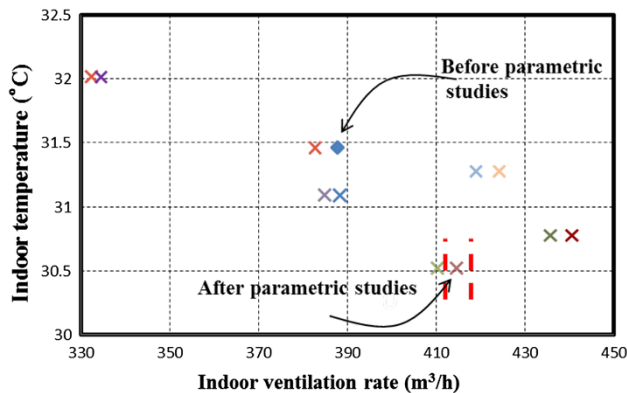


Fig. 9 The effective ventilation rate in the system

This concentration is calculated based on the flow rate in the room, CO_2 generation rate per person (23.8) according to Egyptian body surface area (1.84 m^2) [24] with metabolic rate = 1.2 and outdoor CO_2 concentration (380 ppm). This helps to understand the performance of the integrated system on one single zone with assuming maximum occupant load.

Conclusion

The present study aimed at investigating the effect of solar chimney and wind tower parameters on indoor ventilation rate and temperature pattern. Then, important parameters are optimized in order to achieve compact and high-performance design. Important conclusions are drawn from the numerical operations of the system:

- The system achieves the upper range of 80 % acceptable range during the hottest days with the effective ventilation rate equal to $414 \text{ m}^3/\text{h}$ for a room of volume 50 m^3 .
- The system achieves compact design with dimension $0.75 \text{ m} \times 0.4 \text{ m}$ for the solar chimney and $1 \text{ m} \times 1 \text{ m}$ for wind tower.
- The optimized system achieves the acceptable CO_2 concentration (not exceed 1,000 ppm) according to the ASHRAE standard especially during daytime.
- The priority of the system is to apply in the hot days of the summer season. So the system could apply during daytime for the summer season. While, it can be controlled during night time when indoor temperature becomes very low (less than the lower range of 80 % acceptable range).

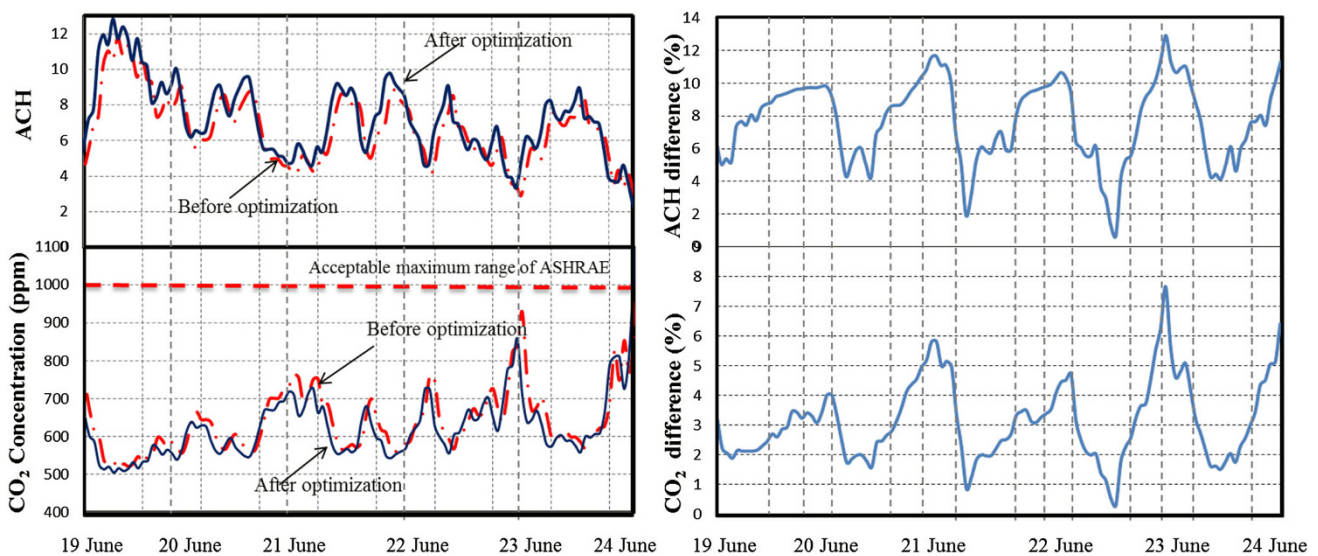


Fig. 10 The CO_2 concentration and ACH of the proposed system before and after parametric studies on 19, 20, 21 and 22 June

This proposed compact system could be an economical and practical passive alternative to the conventional air-conditioning systems in hot and dry climates with no pollution released or energy consumed. Finally, these results are for the integrated system in the living room of the top floor. They will not be extended to another stage without further simulation. The results of this study help to build a real model in Egypt, so that the performance of the real model will be investigated during the summer condition of New Assiut city with internal load.

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Conflict of interest The authors declare that they have no competing interests. All the authors approved the final manuscript.

Author's contributions All authors read and approved the final manuscript.

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