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Evaluation a Hybrid Passive Cooling System for a Building Using Experimental and Commercial Software (Design Builder)

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ABSTRACT

Increasing fossil fuel consumption in the building, especially in the air-conditioning sector, has increased environmental pollution and global warming. In this research, a zero-energy passive system was designed to ventilate the building and provide comfortable conditions for people in the summer. A hybrid passive system was designed for indoor cooling to minimize fossil energy use. This research was done experimentally- and analytically and by simulation. An experimental study comprising a test chamber and simulation using Builder Design software was carried out to evaluate the cooling and ventilation potential of a hybrid passive system functioning. In the experimental section, air temperature, humidity, and airflow for the outdoor environment and the output of the evaporative cooling channel were measured. These measurements were tested in August from 9:00 AM to 3:00 PM for six consecutive days. The obtained experimental data were given to Design Builder software as an input parameter, and then, the comfort conditions inside the chamber, the dimensions, and location of the air inlet valve into the chamber were examined. The findings showed that the proposed system could reduce the air temperature by an average of 10 ^{o}C and increase the air humidity by 33 %. The findings showed that the air inside the chamber was comfortable during the hottest hours of the day. Raising the valve location, increasing the area, and increasing the volumetric flow rate of the air increased the percentage of dissatisfaction. The findings showed that in addition to wind speed and air temperature, the geometrical shape of the air inlet opening contributes to indoor air comfort conditions.

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1. INTRODUCTION

Buildings consume about 40 % of global energy consumption [1-4]. All building services such as Heating, Ventilation, and Air Conditioning (HVAC) systems consume more than 60 % energy in Buildings [5], which is mainly supplied by fossil fuels [6]. Using a passive cooling system can be an alternative method to keep the house cold or reduce the air conditioner load [7]. In ancient architecture, passive techniques were used to achieve summer comfort without the need for mechanical cooling systems. Today, because of the need for an effective method to make efficient energy and biocompatible architecture, the use of natural ventilation methods in buildings has become more significant. One of the methods to create comfortable conditions in the interior is to make use of evaporative cooling in the cooling systems. Evaporative cooling is widely used as a passive cooling method in the built environment. In the system, the movement of air on a wet surface causes water evaporation through the air energy absorption, thereby reducing the temperature and increasing the amount of vapor contained in the air [8]. Evaporative cooling is one of the oldest air-conditioning techniques in dry air climates [9]. Windcatchers were used in Egypt several thousand years ago, and today, a number of them can be found in the Middle East. Some of these windcatchers have porous jars at their depths, while others use a fountain or running water [10]. To produce evaporative cooling, wet surfaces, or water spray can be used inside the windcatcher. Thus, to achieve an excellent indoor condition is a problem in the hot and dry climates. Natural cooling was used in traditional architecture. Windcatchers [11] produced evaporative cooling using a wet surface or water spray in the tower. Some researchers have proposed new evaporative cooling systems [12-15]. In an experimental study in Yazd, two windcatchers with a new design were examined and their cooling rate was compared with a traditional windcatcher [13]. One of the windcatchers was equipped with wet curtains that were suspended inside the duct and the other with wetting surfaces. The cooling performance of the two new systems was compared with that of the conventional system. The experimental results showed that the efficiency of both new units with evaporative cooling systems was better than that of the conventional unit. Further, the experimental results showed that the traditional type reduced the air temperature by 4 ^{o}C, while the windcatchers with wet surfaces and wet curtains reduced an air temperature to 11 ^{o}C and 14 ^{o}C,

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respectively, both of which reduced the air temperature more than the traditional type did.

Another researcher evaluated the performance of an evaporative cooling windcatcher with clay conduits installed within the tower. This study developed a mathematical model and analyzed the condition of air passing through the evaporative cooling column in different external conditions. The results showed that a tower of 4 m height and 0.57 m × 0.57 m cross-section produced airflow of 0.3 m^3⁄s and reduced the internal temperature by 1 t [12].

A method for increasing the airflow rate inside a building is installing a solar chimney within a design [16-21]. One study, investigated the effect of aspect ratio and slope angle of a solar chimney on its thermal performance [18]. The results showed that the highest airflow velocity was created in the solar chimney with a slope angle of 45º. This increase in airflow is 45 % higher than a vertical chimney with similar conditions. Research showed that the optimal amount of solar chimney slope to maximize the speed of airflow was dependent on the latitude of the location and varied from 40º to 60º. Using a solar chimney alone makes the room temperature 4 ^{o}C to 5 ^{o}C lower than that without this passive system. This amount is insufficient to reduce the temperature in the hottest hours when maximum temperature is 40 ^{o}C and does not provide indoor comfort conditions [21].

To increase building ventilation, the impact of a solar chimney coupled with a windcatcher was evaluated [22]. The results showed that solar chimney increased the speed of air conditioning. When the wind velocity is 1 m/s, the windcatcher alone can produce a mass flow rate of 0.75 kg/s, while with the aid of a solar chimney; , it can generate an airflow rate of 1.4 kg/s at 700 w/m^3 of solar radiation [22].

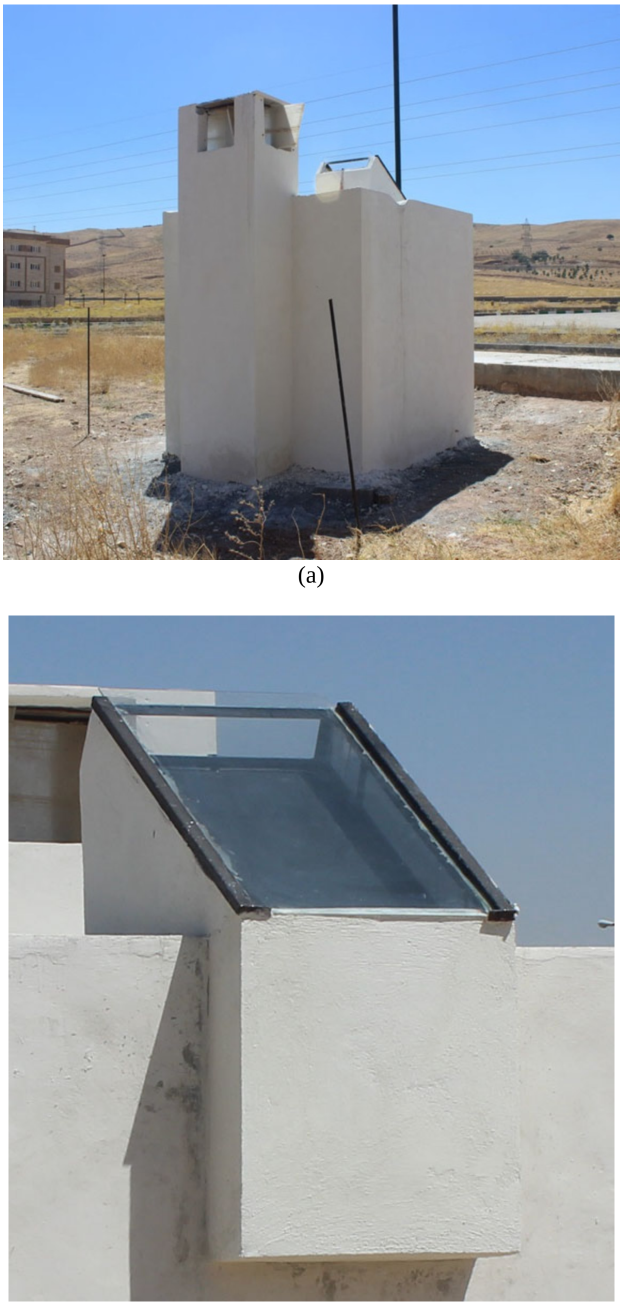
In the reviewed literature, studies have investigated the cooling performance of solar chimneys or windcatchers separately. In this research, by combining two solar chimney systems and evaporative cooling (using clay cylinders in windcatcher), an attempt was made to improve the cooling efficiency of passive systems. Therefore, the purpose of this study is to create thermal comfort conditions in the interior space without the use of energy in the summer and with the help of a new combined cooling system.

2. EXPERIMENTAL

This paper first describes the specifications of a hybrid passive cooling system that includes dimensions and size, construction site, and test time. Then, the comfort conditions inside the chamber are examined according to the geometry and position of the air inlet valve.

2.1. Functional hybrid passive cooling system design

The Hybrid Passive Cooling System (HPCS) consisted consists of two distinctive systems: the Solar Chimney (SC) and Evaporative Cooling Cavity (ECC). The ECC system was connected to the northern facade of the room (Figure 1a), and the SC system was installed in the southern facade of the room (Figure 1b). Air enters through windcatcher openings and passed passes through the clay cylinders. In this section, the air is cooled and diverted downward. The SC system creates a sufficient temperature difference between the interior and exterior by maximizing the solar energy gain and performed air ventilation in the SC and ECC systems (Figure 2).



(a)

(b)

Figure 1. a) The ECC system is installed in the northern façade, b) The SC system installed in the southern façade

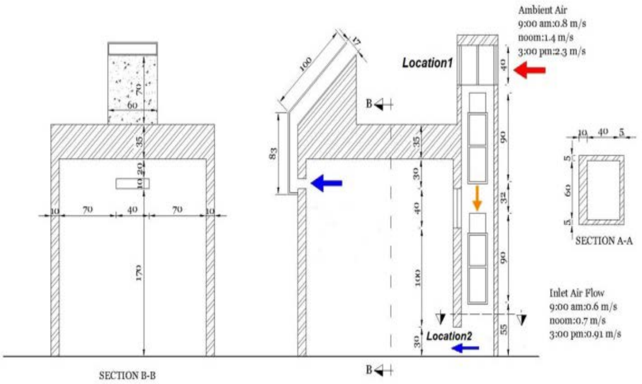


Figure 2. Cross-section of the HPCS system

2.2. Time and place of testing

The proposed hybrid system was built on the campus of Azad University, Kermanshah branch, and was tested in 2018 from August 5 to 10. According to the 10-year statistics of Kermanshah Meteorological Station, which is shown in Figure 3, August is the warmest month of the year therefore, the tests were performed at 9:00 AM, noon, and 3:00 PM. Kermanshah city has a latitude of 34°19'N. The air temperature values of Kermanshah city in August are presented in Table 1.

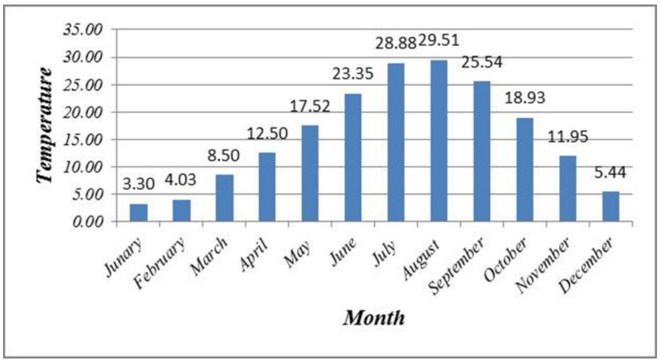


Figure 3. The average temperature of 10 years in Kermanshah city [23]

Table 1. Climate conditions of Kermanshah city (www.kermanshahmet.ir)

Average temperature (^oC)	Average humidity (%)	Average wind flow (m/s)	Average solar radiation intensity (wh/(sq.m))
29	21	2	623

2.3. Dimensions and size of the HPCS

- A room with 2 m × 2 m × 2.35 m (L×W×H) dimensions with 10 cm-thick walls and 35 cm-thick ceiling without air filtration.

- An SC with 1m height, 60 cm width, 17 cm air gap, and 45 ^oC tilt angel. The front side of the SC consisted of a 15 mm-thick glass glazing and the rear part included a 1 m-high absorber wall made of a black-painted aluminum sheet.

- A 40 cm × 10 cm air outlet of SC placed 20 cm below the ceiling.

- The ECC system with a length of 3.25 m and a 0.6 × 0.4 m cross-section. Each air inlet opening of the wind tower is 40 cm × 40 cm and the air exit opening is 30 cm × 30 cm.

- Four clay cylinders, each with diameter of 20 cm, and height of 90 cm.

2.4. The experimental measurement

To evaluate the comfort conditions, temperature, humidity, and wind speed parameters for outlet air of the tower into the chamber and outside environment were measured experimentally (Figure 2). The measuring instruments in this study are Data logger KH 50 and Flow anemometer AVM-07. The location of the Thermo-hygrometer data logger and anemometer is located in the air inlet valve from outside to inside the windcatcher (Location 1 in Figure 2) and the air outlet valve from the windcatcher to the room (Location 2 in Figure 2).

3. RESULTS AND DISCUSSION

3.1. Temperature, humidity, and wind speed in the HPCS

To assess the weather conditions inside the chamber from August 5 to 10, wind speed, air temperature, and humidity of ambient air and outlet air of the tower into the chamber; were measured. Figures 4 and 5 display the temperatures of ambient air and outlet air of the tower into the chamber, respectively, for six consecutive days at 9:00 AM, noon, and 3:00 PM. According to Figures 4 and 5, the largest difference between the outlet air of the tower into the room and the outside environment is 16.3 ^oC, which occurred on 7th August at 3:00 PM. According to the data, this system reduced the air temperature by an average of 10 ^oC and the air temperature of the outlet air of the tower to the chamber was in comfort at all hours. Figures 6 and 7 show that the lowest velocity of the air leaving the tower is on 10th August at 9:00 AM. This value is 0.33 m/s when the ambient airspeed is 0.5 m/s. The highest velocity of the air leaving the tower is at 3:00 PM on August 8th. This value is 1.1 m/s when the ambient airspeed is 1.8 m/s.

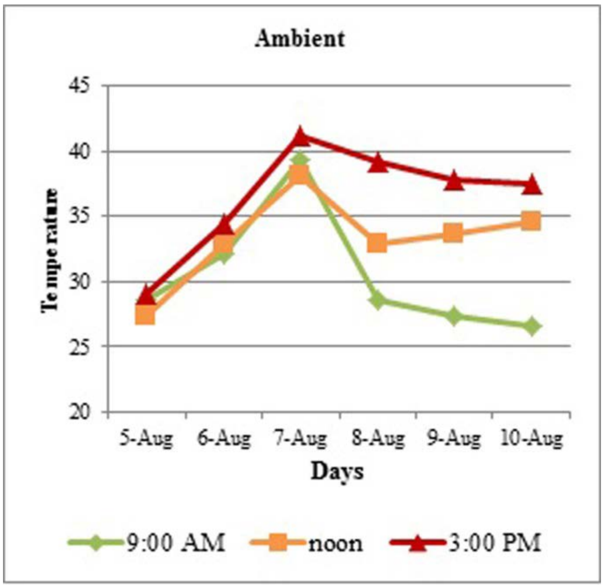


Figure 4. The ambient air temperature of ECC

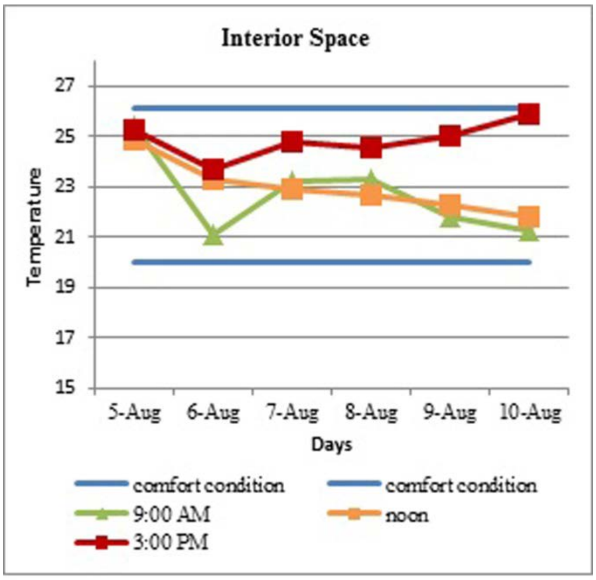


Figure 5. Interior air temperature of the ECC

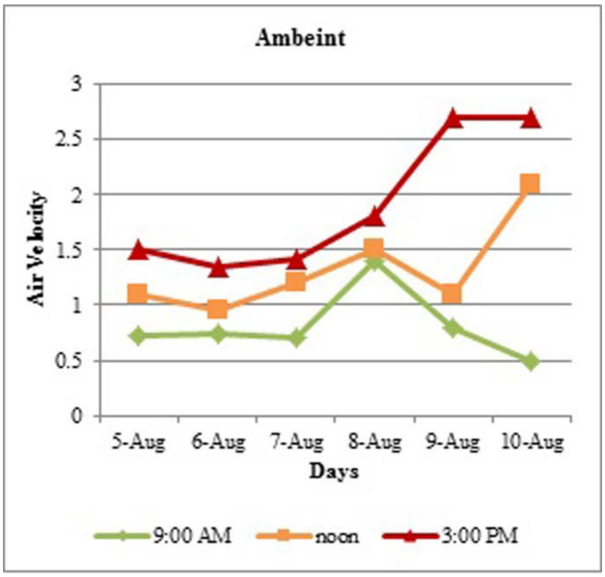


Figure 6. Ambient air velocity of the ECC

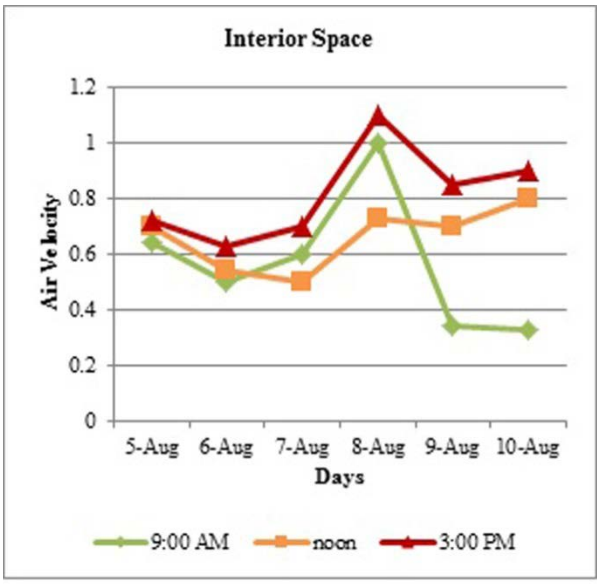


Figure 7. Interior air velocity of the ECC

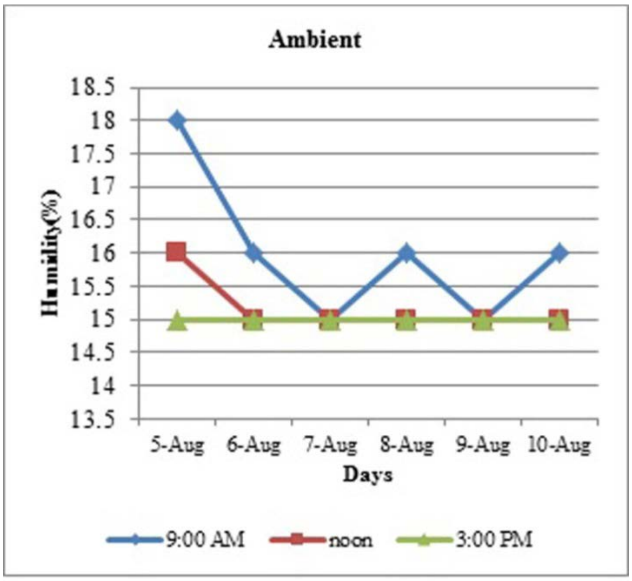


Figure 8. Ambient humidity of the ECC

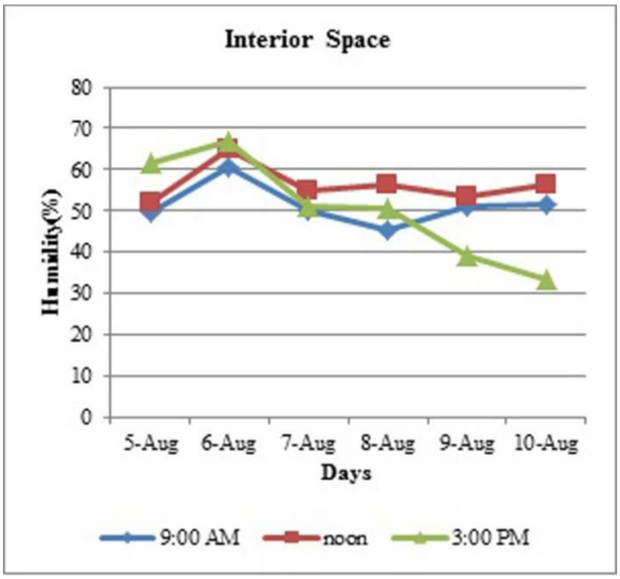


Figure 9. Interior humidity of the ECC

Based on the collected data, the highest and lowest RH values of the air leaving tower were 60.7 % and 32.6 %, respectively, at 9:00 AM when the RH value of the ambient air was 16 % and 15 %. The highest and lowest RH values of the air leaving tower were 65.1 % and 30.7 %, respectively, at Noon when the RH of ambient air was 15 %. At 3:00 PM, the highest and lowest RH values of the air leaving tower were 66.8 % and 31.3 %, respectively, when RH of ambient air was 15 %. On 24 August, the relative humidity of the room was the lowest in at all hours when the HTD system was not connected. The highest and lowest increases in the amount of RH of air using the ECC system were 50.1 % and 17.22 %, respectively, in which the highest RH was achieved at noon and the lowest RH was at 3 PM (Figures 8 and 9). Then, based on the result, the ECC system can increase RH of air by 33 % on average.

3.2. Investigating the comfort conditions inside the chamber using PMV and PPD methods

Investigating the comfort conditions inside the chamber using PMV and PPD methods, Finger's index is used to check the comfort conditions inside the chamber [24]. The average heat sensation of a large number of people for an environmental condition is called PMV, which is between cold (-3) and hot (+3) [25]. Air temperature, average radiant temperature, relative humidity, airspeed, metabolic rate, and clothing insulation are used in Fanger´s equations [24]. The input variables to the Builder Design software to check the comfort conditions inside the chamber are the ambient air temperature, outlet air temperature of the tower into the chamber, outlet air velocity of the tower into the chamber (Table 2). Also, in this research, the person's posture is assumed to be sitting and the relative rate of clothing is considered to be 0.5 [25].

Table 2. Software input parameters

The ambient air temperature (°C)	Outlet air velocity of the tower (m/s)	The outlet air temperature of the tower (°C)	Time
28.5	0.64	25.42	9:00 AM
32.1	0.7	24.86	Noon
37.53	0.8	26.66	3:00 PM

The simulation was performed in two stages. First, the air comfort conditions inside the chamber were checked at 9:00 AM, noon, and 3:00 PM, when the outlet air temperature of the tower into the chamber is maximum (Table 3).

Table 3. Check the speed, temperature, PPD, and airflow distribution pattern inside the chamber

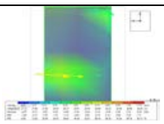
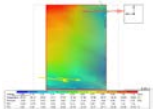
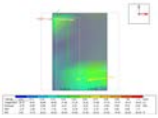
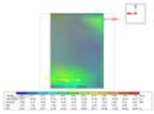
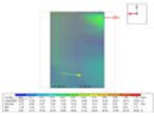
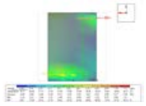
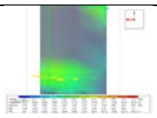
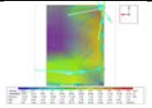
The ambient air temperature (°C)	**Outlet air velocity of the tower (m/s)**	**The outlet air temperature of the tower (°C)**	**Time**
0.62	0.11	0.2	Average wind speed (m/s)
27.6	25.9	25.73	Average air temperature (°C)
26	13	18	Average percentage of dissatisfaction (PPD)

Then, the best position of the air inlet valve in terms of height and geometry to reach the highest level of comfort at 3:00 PM was determined using the software. According to Table 3, the average air velocity and the rate of dissatisfaction with indoor air conditions at noon are 0.11 m/s and 13 %, respectively, which are lower than 9:00 AM and 3:00 PM, however, the average air temperature at 9:00 AM (25.73 °C) is the minimum.

In this study, Fanger's model was used to investigate the comfort conditions inside the chamber.

Using experimental data, the maximum temperature of the outlet air temperature of the tower into the chamber at 9:00 AM, noon, and 3:00 PM was given to Design Builder software as input parameters. Therefore, the HPCS system can provide indoor air comfort conditions in the hottest hours of the year. After determining that the chamber would be comfortable in the hottest hours using the hybrid system, in the second stage of simulation by changing the location, geometric deformation of the valve, and increasing the volumetric flow rate of the incoming air, the maximum rate of dissatisfaction of residents inside the room was checked.At this stage, the simulations took place at 3:00 PM when the weather conditions inside the chamber had the highest rate of dissatisfaction. In the pictures given in Table 4, blue indicates the lowest percentage of dissatisfaction, green the average, and red the highest percentage of dissatisfaction. First, the location of the air inlet duct valve was considered 30 cm higher. Although relocating the valve increased the inlet air velocity into the chamber, the rate of dissatisfaction increased. Then, the simulations were first performed by maintaining the valve area and the geometric deformation of the valve channel. The maximum increase in air velocity and the largest decrease in temperature occurred in the 45 × 20 valve, however, the lowest rate of dissatisfaction was in the 18 × 50 valve (Table 4).

Table 4. Check the air velocity, temperature, PPD, and distribution pattern of airflow inside the chamber by changing the height of the valve, geometric shape, dimensions, and volumetric flow rate of the air inlet duct

	The maximum percentage of dissatisfaction (PPD)	**Maximum air temperature (°C)**	**The maximum air velocity (m/s)**	
	45	28.5	0.52	Change the height of the valve from 10 cm to 40 cm
	40	28.26	0.93	30 × 30
	43.8	27.24	0.53	20 × 45
	42.9	27.62	0.53	45 × 20
	35.88	27.63	0.43	18 × 50
	43.29	27.68	0.5	50 × 18
	43.86	27.23	0.52	50 × 50
	74	27.08	3.99	Increasing the volume flow rate of the valve with dimensions of 50 × 50

Although increasing the valve area accelerated the wind speed, this change increased the percentage of dissatisfaction. At this stage, the volume flow rate of incoming airflow was increased to reduce the percentage of dissatisfaction in the 50 × 50 valve. This disturbed the airflow inside the chamber, which increased the percentage of dissatisfaction. According to the Table 5, the lowest air temperature was obtained by 50 × 50 valve, the highest air velocity in the chamber was obtained by increasing the volumetric airflow in 50 × 50 valve, and the lowest dissatisfaction rate was obtained by 18 × 50 valve.

Table 5. Optimal air valve based on the lowest percentage of dissatisfaction

The lowest percentage of dissatisfaction	**The highest percentage of dissatisfaction**	**Maximum air velocity (m/s)**	**The lowest temperature (^{o}C)**	
18 × 50	50 × 50	50 × 50 (Increase volumetric flow rate)	50 × 50	Valve dimensions (cm)
45 × 20	20 × 45	30 × 30	20 × 45	
Optimum condition: 18 × 50 valve				

4. DISCUSSION

In a new modular windcatcher design, Khani et al. showed that this system could reduce air temperature by a maximum of 13 ^{o}C. Badran also demonstrated in the design of the evaporative channel using mathematical equations that the air temperature decreased to 11 ^{o}C, while in the windcatcher designed in this study, the maximum decrease in the air temperature was 16 ^{o}C. In Badran's design, with a windcatcher height of 4 m and an ambient air velocity of 4 m/s, the air velocity of the valve to the room was 0.8 m/s. Still, in the system designed in this study, using a solar chimney, the air velocity of the tower to the chamber reached 1.26 m/s with a wind speed of 3.25 m/s. Indoor air was in the comfortable condition in the hottest hour (3:00 PM) by the HPCS system. The percentage of dissatisfaction increased upon an increase in the inlet air velocity into the chamber. Although the air velocity in the valve 18 × 50 was lower than in the 45 × 20 (the temperature is the same in both valves), the percentage of dissatisfaction was also lower in this valve.

5. CONCLUSIONS

This study aims to propose a new design hybrid passive system to create comfortable conditions inside the building for summer time. To evaluate the cooling performance of this system, the temperature and air velocity of the outside air and outlet air of the tower into the chamber were measured experimentally; then, the comfort conditions inside the chamber were examined using Design Builder software. To optimize the HPCS and reduce the percentage of dissatisfaction, the position and dimensions of the outlet of the tower into the chamber were inspected. In this study, the ECC system can increase the RH of air by an average of 33 %. Also, the increase in the area of the valve, despite the decrease in air temperature, increased the rate of dissatisfaction. Still, with the geometric deformation of the air inlet valve, the percentage of dissatisfaction decreased and provided thermal comfort conditions for the indoor air chamber. The obtained data showed that in addition to wind speed and air temperature, the geometric shape of the valve could be an effective factor in creating air comfort conditions inside the chamber.

6. FUTURE STUDY

the performance of a solar chimney integrated with a windcatcher in multi-story buildings to investigate the distribution of airflow and its cooling efficiency in existing buildings needs to be studied.

7. ACKNOWLEDGEMENT

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NOMENCLATURE

PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RH	Relative Humidity

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