ENHANCING THERMAL COMFORT OF RESIDENTIAL BUILDINGS THROUGH A DUAL FUNCTIONAL PASSIVE SYSTEM (SOLAR-WALL)

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ABSTRACT

Thermal comfort has a great impact on occupants' productivity and general well-being. Since people spend 80–90% of their time indoors, developing the tools and methods that enhance the thermal comfort for building are worth investigating.

Previous studies have proved that using passive systems like Trombe walls and solar chimneys significantly enhanced thermal comfort in inside spaces despite that each system has a specific purpose within a specific climate condition. Hence, the main purpose of this study is to design and configure a new, dual functional passive system, called a solar wall.

The new system combines the Trombe wall and solar chimney, and it can cool or heat based on building needs. Simulation software, DesignBuilder, has been used to configure the Solar Wall, and study its impact on indoor operative temperature for the base case. Using the new system, the simulation results were compared with those obtained in the base case and analyzed to determine the most efficient system design parameters and implementation method. The case that gave the best results for solar wall configuration was triple glazed glass and 0.1 cm copper as an absorber (case 11). The results show that using four units (case D) achieves longer thermal comfort levels: 15 to 24 thermal hours during winter (compared to five hours maximum) and 10 to 19 comfort hours in summer (compared to zero).

KEYWORDS

indoor environmental quality, thermal comfort, indoor operative temperature, passive systems, passive design

INTRODUCTION

Jordan, officially the Hashemite Kingdom of Jordan, has witnessed rapid population growth, and is currently home to around 8 million, with an estimated population growth rate of 3.86% in 2014, making it the fifth highest migrant population in the world (Malkawi et al., 2017). The expenditure on energy in Jordan is considered to be one of the highest in the world. It reached a record high of 19% of GDP (4.02 billion USD); however, only 4% of the total energy consumed

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is generated from renewable sources with a goal of renewables to meet 10% of energy demand by 2020, while the rest is from fossil fuels imported from neighboring countries (Hamed and Bressler, 2019).

Generally, the building sector consumes 35.3% of total energy (IEA, 2007), with maximum energy being consumed for ventilation, heating, and air-conditioning (HVAC) to ensure an acceptable level of comfort and a satisfactory Indoor Environment Quality (IEQ) (Abbassi et al., 2014, Chan et al., 2010). Since the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) established that people spend 80% to 90% of their time indoors (American Society of Heating and Engineers, 2013), many studies (De Giuli et al., 2012, Al horr et al., 2016, Heinzerling et al., 2013) established that satisfactory IEQ impact occupants' productivity and general well-being, while poor IEQ affects comfort, health, and productivity, which leads to poor performance. The IEQ is determined by four main environmental parameters: indoor air quality (IAQ), thermal comfort (TC), visual comfort, and aural comfort, where TC is considered one of the most important determinants (Al horr et al., 2016).

Like most countries in the Middle East, solar energy resources in Jordan are promising. Solar energy radiation equals 5.5 kWh/m2 and 2900 h annual sunshine as Jordan lies in the "global Sunbelt," between 29°11′ and 33°22′ N latitudes, a suitable range for solar heating and cooling systems (Hamed and Bressler, 2019, Mason et al., 2009, Jaber and Ajib, 2011). Since passive solar designs can reduce heating and cooling load, and improve comfort (Jaber and Ajib, 2011), therefore enhancement of energy efficiency standards in buildings become vital (Hammad et al., 2014), and international regulations have been constantly encouraging the integration of passive solar systems in buildings (Hu et al., 2017).

To achieve thermal comfort inside the building year round, and after an in-depth study of the Trombe Wall and solar chimney where each system works to achieve thermal comfort either in the summer or winter, this research aims to configure and develop a new, dual functional passive system combined with two passive solar systems (Trombe Wall and Solar Chimney) in terms of their concepts and mechanisms called Solar Wall. The new integrated passive system—Solar Wall—provides heating or cooling based on the season in which the system will operate and space needs.

PASSIVE DESIGN STRATEGIES

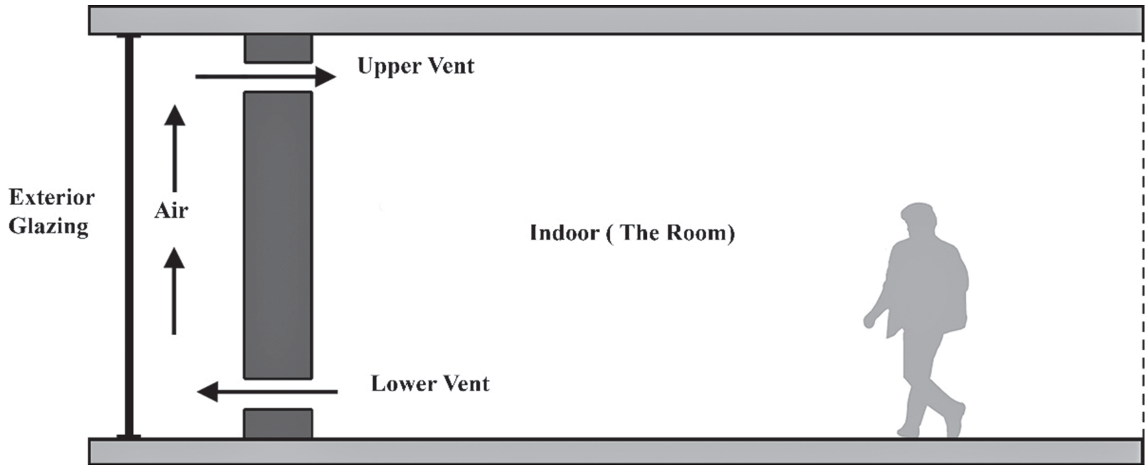
Passive design strategies use energy sources directly such as solar radiation and wind for Passive Heating and Passive Cooling, (Spacey, 2016). The main purpose of the passive solar heating system is to collect, store, and distribute solar energy(Chan et al., 2010), while passive cooling strategies provide cooling through shading, heat transfer method, and the natural ventilation system, which is the most common type of passive cooling strategy (Oropeza-Perez and Østergaard, 2018).

Passive solar heating and passive cooling mostly depends on the same mechanism where the driving force is the buoyancy effect (Chan et al., 2010). Trombe wall and Solar Chimney are passive systems that rely on the buoyancy driving force. Thus, natural ventilation and airflow can be controlled for cooling and heating the internal space by using these systems.

Trombe wall

According to Chan et al., a classic Trombe wall is composed of a massive wall painted black and an exterior glazing, with a ventilated air gap in between (Chan et al., 2010). The classic Trombe

FIGURE 1. Classic Design of Trombe wall. Source: (Chan, et al, 2010).



wall mechanism depends on a mass wall, generally built of a dark-colored material, absorbing solar radiation. The heating procedure depends on transferring heat to the inside space via conduction in a direct way by the mass wall and by convection based on the air buoyancy effect inside the cavity. Low temperature air enters the cavity from the lower vent, where it is heated before returning to the room via the upper vent, as shown in Figure 1.

Some studies indicate challenges with this design. Shen et al. (2007) reported challenges that may face this design: for example, if the mass wall has a low thermal resistance, an inverted heat flux can occur, causing heat loss. During extreme cold in winter conditions, inverse thermo-siphon phenomena may occur, and the massive wall may become colder than the indoor air temperature, causing reverses in the flow mechanism inside the cavity (Shen et al., 2007, Onbasioglu and Egrican, 2002). In the summer, researchers observed an increase in cooling energy and a risk of overheating (Stazi et al., 2012a).

Over time, modifications have been made to classic Trombe walls to improve their efficiency and overcome challenges (Hu et al., 2017, Chan et al., 2010). For example, the Trombe–Michel Wall was introduced to overcome heat flux problems from inside to outside (Shen et al., 2007). Using water as heat storage is another solution to reduce heat loss (Wang et al., 2013). Another type of Trombe wall is a zigzag Trombe wall, designed to reduce the excessive heat gain and glare of sunny days (Saadatian et al., 2012).

Some modifications have been made to improve Trombe wall efficiency. According to Hu et al., any material with high-capacity storage could be used as a mass wall, but using a small volume with high capacity, as is the case in a phase change material (PCM), is preferable (Hu et al., 2017). The energy stored in the PCM can be transferred inside more quickly than with a concrete wall (Zalewski et al., 2012). In addition, using insulation for the interior surface of the mass wall is equivalent to using infinite thickness to avoid overheating (Gan, 1998), as well as to increasing the overall efficiency of the system (Jie et al., 2007). The thickness and the number of glazing layers has a significant effect on the heat loss that occurs between the cavity wall and the outside environment (Stazi et al., 2012b).

For cavity design parameters, increasing the depth decreases the frictional pressure loss and flow resistance, thus increasing the mass flow rate (Chen et al., 2003). Gan demonstrated that the airflow rate increases as long as the channel depth and inlet width increase together (Gan, 1998). Liping and Angui suggested that an optimal ratio of channel depth to height is about 1:10 in most cases (Liping and Angui, 2006).

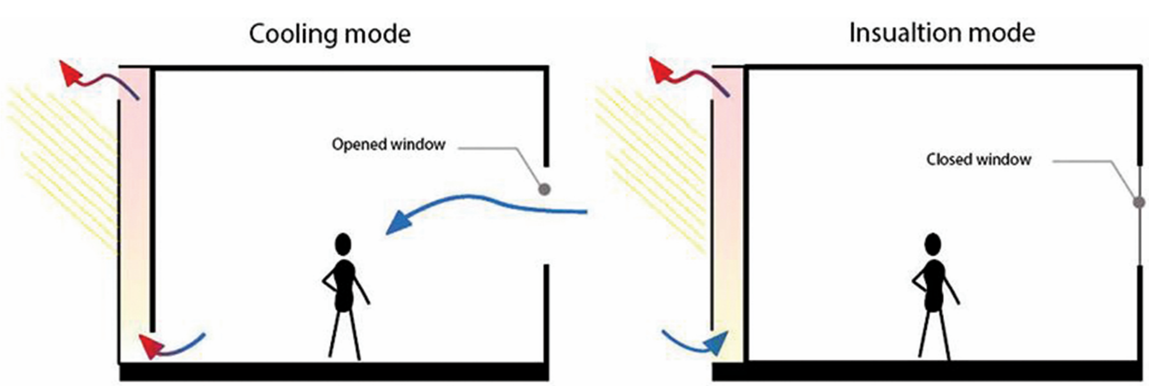
Solar chimneys

A solar chimney, also called a thermal chimney, "is a vertical shaft that utilizes solar energy to enhance the natural stack ventilation" (Etheridge, 2012). The mechanism depends on generating airflow through the cavity by converting thermal energy into kinetic energy (Chan et al., 2010). A solar chimney could be either an attached or a detached element on building walls; when attached, the chimney works like a Trombe wall.

As Figure 2 illustrates, two modes of operation (cooling and ventilation) can be applied for passive cooling purposes. In the cooling mode, warm air rises from the upper vent. Therefore, by the stack effect, an upward flow occurs, creating negative pressure on the vents at the bottom. As a consequence, cold air flows from the inlet located on the opposite side of the space. For extremely hot climates, in which natural ventilation is not appropriate, the solar chimney is not used to enhance natural ventilation and operates as thermal insulation to reduce heat gain (Miyazaki et al., 2006).

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), "natural ventilation and cooling systems are most effective in a climate where ambient temperature and humidity levels naturally fall into comfort ranges" (Indoor air quality guide, 2009). Supporting this statement, Miyazaki et al. (2006) stated that outdoor conditions in summer should not be harsh, and outdoor temperature should be below room temperature for natural ventilation to provide effective cooling. Regarding design parameters, increased height means increased exposure to the sun and thus increased heat gain (Shi et al., 2018) and an increase in the pressure difference (Ding et al., 2005). Therefore, Wei et al. suggested using the greatest possible height (Wei et al., 2011). According to Balccoco, increasing the cavity gap increases airflow (Balocco, 2002). Anderson suggested a minimum cavity width of 4.7 cm (Andersen, 1995). Bouchair (1994), meanwhile, suggested an optimum width of $W_{opt} = H/10$, where W_{opt} is the optimum width and H is the height of the chimney, and Bouchair observed an increase in effectiveness when the cavity width increased from 0.3 to 0.5 m (Bouchair, 1994).

FIGURE 2. Solar chimney passive cooling modes.



For the inlet and outlet dimensions, Bouchair suggested extending the inlet and outlet along the length of the cavity to maximize air entry (Bouchair, 1994). Based on the computational fluid dynamics (CFD) result of Li et al. (2004), the inlet and outlet area should be equal in order to realize improvement in overall performance (Li et al., 2004). Hatami and Bahadorinejad performed an experimental study on glazing design, and their results indicated that double glazing enhances performance (Hatami and Bahadorinejad, 2008). Gan and Riffat, meanwhile, suggested triple glazing in winter for maximum performance (Gan and Riffat, 1998).

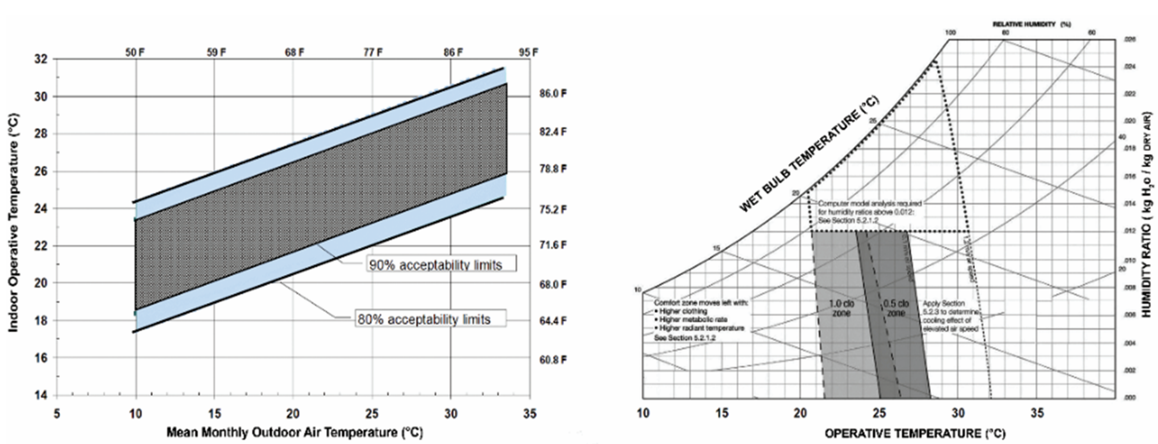
Some studies have shown that solar chimneys have a direct effect, and that they are more effective regarding indoor temperature, especially in hot a climate in which the outside nighttime temperature is lower than the daytime temperature (Bouchair, 1994). H.-Y. Chan et al. highlighted the cooling efficiency of solar chimneys in a hot climate with an ambient temperature of 32–40°C and indicated they can reduce indoor temperature by 1.0–3.5°C (Chan et al., 2010).

Thermal comfort (TC)

Thermal comfort has been discussed since the 1930s (Taleghani et al., 2013). It was identified as the most important contributors to the overall IEQ acceptance in workplace (Wong et al., 2008, Lee et al., 2012). According to ASHRAE Standard 55-2013, thermal comfort is "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. Another definition of the thermal comfort zone for human occupancy is as "a range of operative temperatures that provide acceptable thermal environmental conditions."(American Society of Heating and Engineers, 2013).

Two models to determine the comfort range were introduced by ASHRAE: the predicted mean vote (PMV)/predicted percentage dissatisfied (PPD) model and the adaptive thermal comfort model (Figure 3). The adaptive model is used for naturally ventilated buildings, while the PMV/PPD model can be applied in air-conditioned buildings. According to the PMV/PPD model, acceptable thermal comfort can be achieved by controlling a set of environmental parameters: air temperature (°C), relative humidity (%), radiant temperature (°C), airspeed (M/s), metabolic rate (met), and clothing insulation (clo). For the Adaptive model, mean

FIGURE 3. ASHRAE comfort models, A: Adaptive model B: PMV model.



outdoor air temperature and operative temperature are the only parameters needed to measure the comfort range (American Society of Heating and Engineers, 2013).

METHODOLOGY

The research consisted of a simulation study of a passive system (Solar Wall). A full factorial experimental design will accrue where the simulation process will run for all possible combinations for suggested variations design parameters. The simulations were performed using DesignBuilder and a one-hour time step. The software uses realistic weather data with both clear and overcast days, and it can calculate the amount of solar energy reaching the system instantaneously in each time step during the simulation process.

A new operation mechanism will be configured. Some design parameters will be considered as fixed based on the recommendations from literature, like system height and length, cavity width, absorber material, vent size and location, and insulation material and thickness, while others will be considered as variation design parameters to be tested and validated, like absorber thickness, system glazing type, and system size of the facade area.

Design parameters

As Figures 4a and 4b illustrate, the solar wall will be designed as a four meters high box, at maximum possible height, capturing maximum heat gain and increasing the pressure difference inside the cavity as clarified and suggested by (Shi et al., 2018, Ding et al., 2005, Wei et al., 2011), the cavity dimensions are a half meter by a half meter as recommended by (Chen et al., 2003, Balocco, 2002, Bouchair, 1994, Andersen, 1995) to increase the mass flow rate; thus,

FIGURE 4A. Solar-wall design configuration.

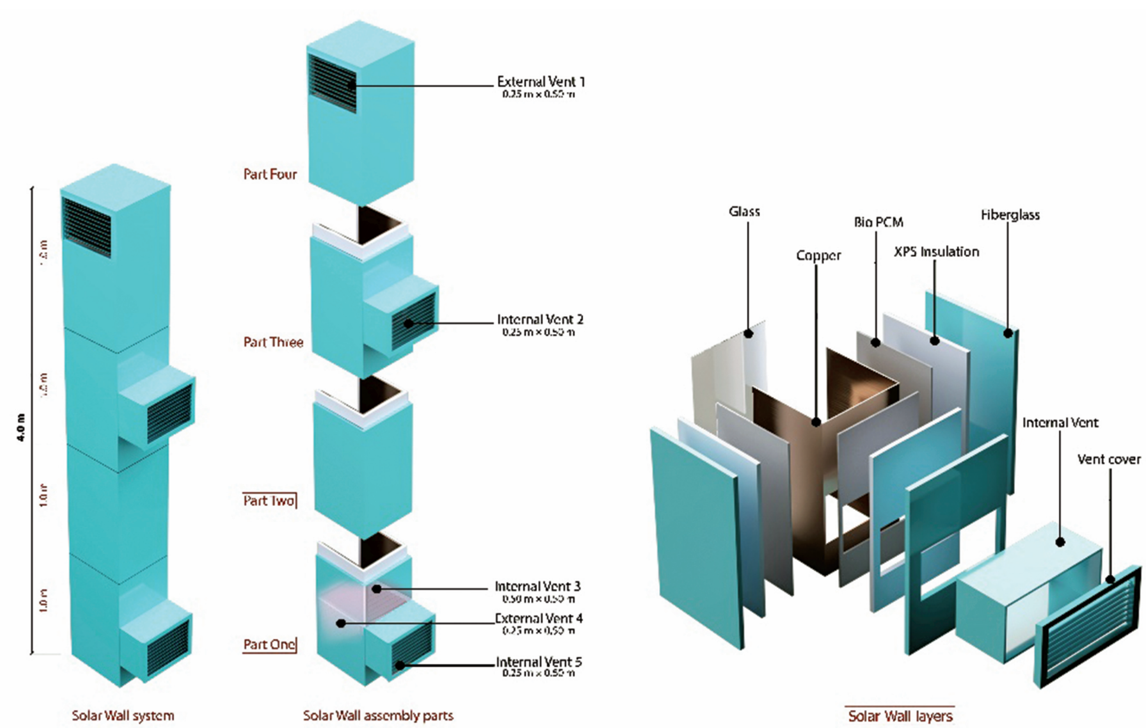
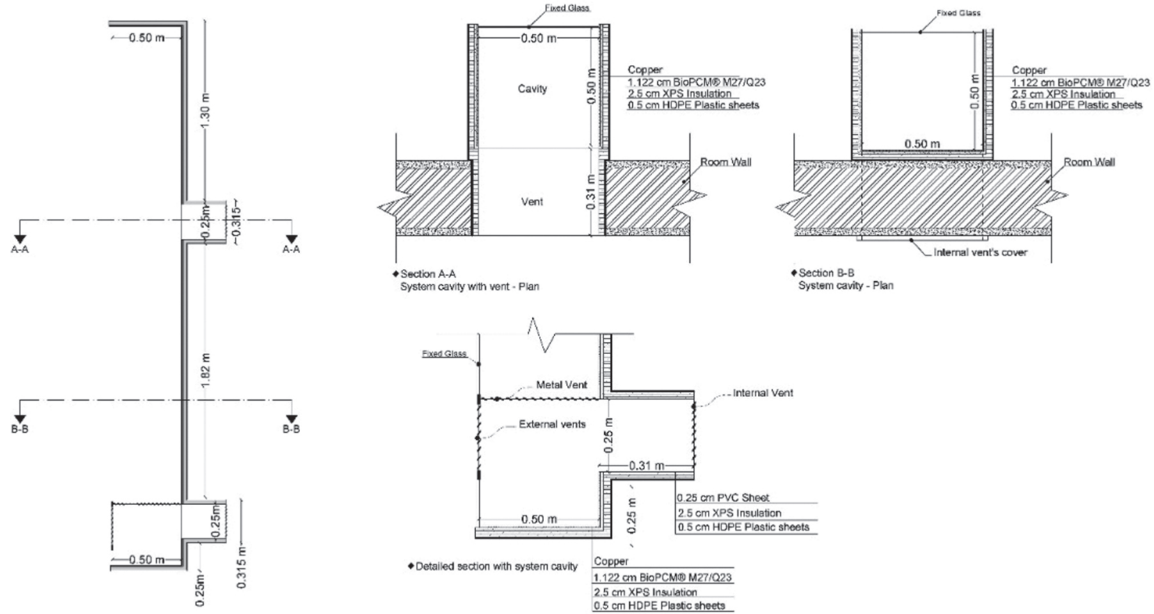


FIGURE 4B. Solar-wall design details; sections and plans.



increasing the efficiency. The design has five vents, two connected to the wall of the adjacent space, one on the upper east side of the system, one on the southern side, and one inside the system itself. The size of the inlet and outlet are equal and extend along the length as suggested by (Bouchair, 1994, Li et al., 2004).

In terms of system materials, Copper and PCM will be chosen and combined as the main absorber material instead of brick or heavy concrete as used in a Trombe wall. To maximize the absorption area, copper and PCM will be used in the inner eastern and western parts of the system in addition to the part attached to the space. All parts will be insulated with 2.5 cm (XPS) polystyrene before the last external layer to minimize heat loss and prevent heat conduction towards the building's inner space and thus prevent overheating as clarified by (Gan, 1998). The XPS layer functions to direct the heat flux towards the system's cavity, thus improving system efficiency. High-density polyethylene (HDPE) sheets were used as an external layer to cover the system and give it the final appearance.

PCM was chosen for its unique characteristics, as shown in Table 1: small volume with high capacity, heat transfer speed, and suitability for interior spaces and desert regions as explained by the researchers (Hu et al., 2017, Zalewski et al., 2012, Raj and Velraj, 2010). Copper is chosen to combine with PCM because of its high connectivity, which allows it to absorb the maximum solar radiation. The new combination will be utilized in two different modes; daytime and night. As explained in As Figure 5, during the daytime mode, the copper transfers a part of the absorbed heat to the inner air within the cavity, and the remaining heat is stored inside the PCM. During the night mode, as there is no source of energy from the sun, Copper will work as a heat exchange to transfer the absorbed heat from the PCM to the air inside the cavity which keeps the system running all the time.

To reach the optimal design configuration, a series of sensitivity studies on glazing type and thickness of copper (absorber) were combined into 15 different cases as presented in Table

FIGURE 5. Heat flux inside solar wall during daytime and night.

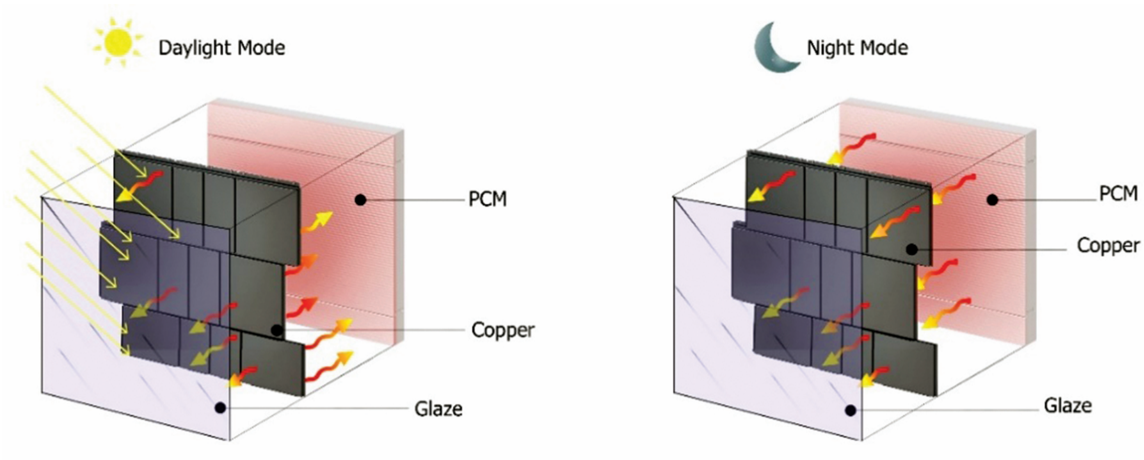


TABLE 1. PCM specifications used in Solar-Wall system.

Type	BioPCM® M27/Q23
Melting Point (°C)	23
Conductivity (W/M-K)	0.20
Specific Heat (J/Kg-K)	1970
Density (Kg/M^3)	235
Number of points on the curve	16

2. Copper was selected as a variation variable to examine the effect of its thickness, as it is first used in combination with PCM as a heat absorber in a passive system. Apart from studying the impact of glass layers to reach the ideal glazing type suitable for Jordan's climate, the glass plays an important role in thermal insulation in addition to its effect on the amount of heat gain. The best case with a positive effect on indoor operative temperature was selected to configure the solar wall system.

After reaching the best configuration for the solar wall, and to achieve the best thermal comfort design solution, four cases were combined as presented in Table 3. Each case represents a ratio from the south wall: one system (12.5%), two systems (25%), three systems (37.5%), and four systems (50%).

The system is designed to be portable and easy to handle with minimum labor required during the installation process. The system is composed of four pieces, which can be easily assembled on site and allow it to be installed by attaching it directly to the targeted space with minimal effect on the exterior envelope, as shown in Figure 6 and Figure 8. The system can be anchored to the external wall using simple wall ties, with two vents (0.315 × 0.565 m) penetrating the external wall towards the targeted space. The system's net weight is about 156 kg. The outer layer of the system is made of a HDPE plastic sheet, due to this material's strength and light weight. The system is able to be used as a passive retrofitting technique to improve

TABLE 2. Sensitivity study regarding absorber thickness and glazing type Case.

Case #	Glazing	Copper thickness	System specification (Fixed)
Case 1	Single glaze	0.10 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 2	Single glaze	0.25 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 3	Single glaze	0.5 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 4	Single glaze	0.75 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 5	Single glaze	1.0 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 6	Double glaze	0.10 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 7	Double glaze	0.25 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 8	Double glaze	0.5 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 9	Double glaze	0.75 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 10	Double glaze	1.0 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 11	Triple glaze	0.10 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 12	Triple glaze	0.25 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 13	Triple glaze	0.5 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 14	Triple glaze	0.75 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation
Case 15	Triple glaze	1.0 cm	Geometry 0.5*0.5*4m, PCM, 2.5 cm insulation

TABLE 3. Cases of the system to wall ratio.

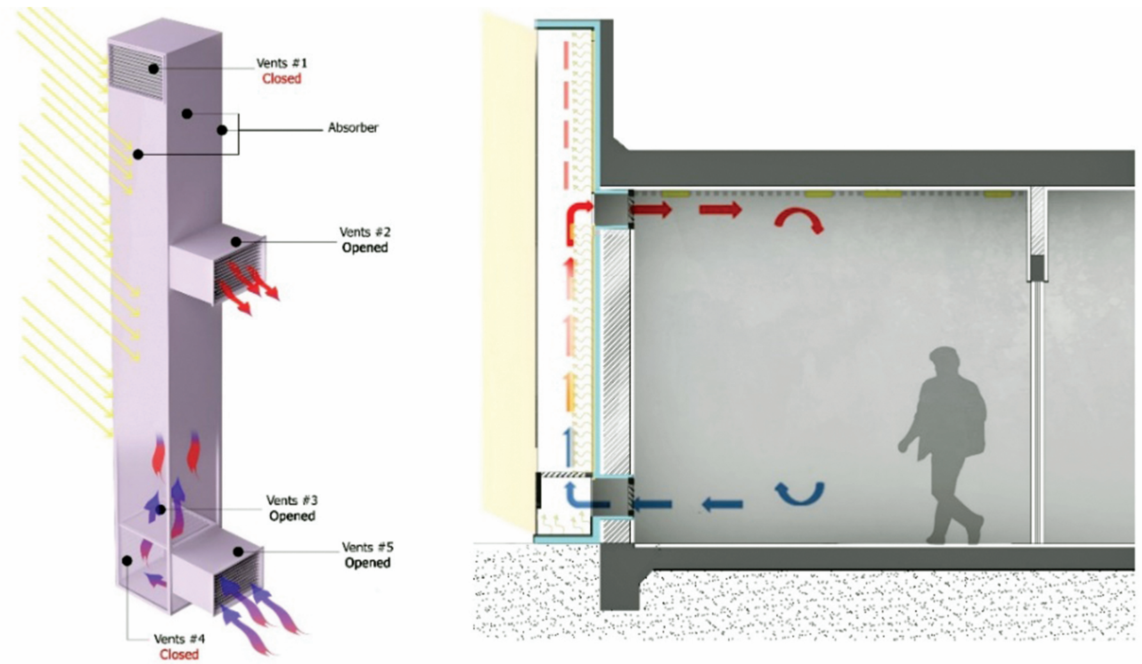
Case #	Number of units	System to wall ratio
Case A	One unit	12.5%
Case B	Two units	25%
Case C	Three units	37.5%
Case D	Four units	50%

the thermal performance of the existing space; alternatively, it could be integrated within the new design.

Winter season, heating mode

As Figure 6 displays, upper vent number one and vent number four are closed, and vents two, three, and five are open. The copper layer absorbs the largest amount of solar energy and heats the air inside the cavity. Due to the air buoyancy effect, the heated air rises to the top and enters the room, allowing the cold air to be pulled into the cavity due to the difference in pressure. Throughout the day, this system helps raise the temperature of the internal air.

FIGURE 6. Operation mechanism during winter season.



The investigated days were selected based on Amman, Jordan's, weather data. The days with the maximum and minimum outdoor dry-bulb temperature in winter months were selected. Based on weather data, January 15th had the minimum outside dry-bulb temperature, around 2.5 °C. While December 16th had the maximum at around 16.2 °C, as shown in Figure 7.

Summer season, cooling mode

During the summer or when the internal temperature is above the thermal comfort level, the mechanism is inverted. The solar wall reduces the air temperature inside the space by extracting the hot air at the top of the room. The process relies on rising hot air inside the cavity and

FIGURE 7. Dry-bulb temperature for winter months.

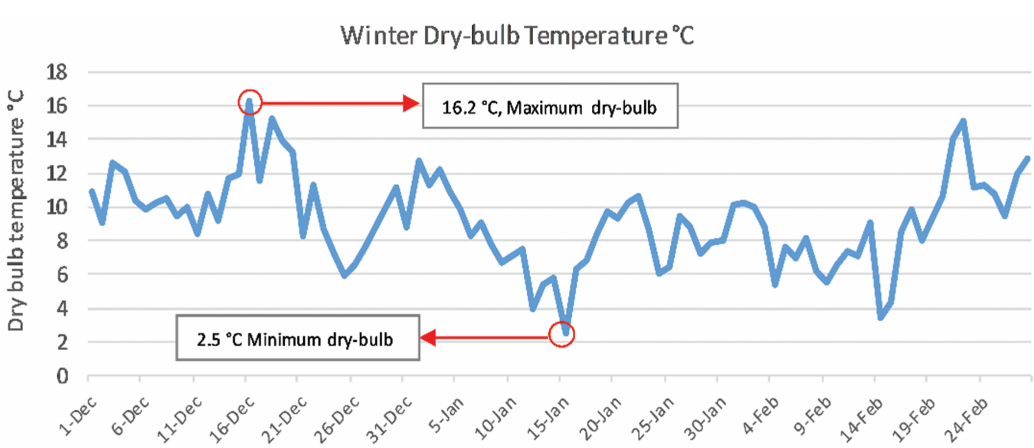
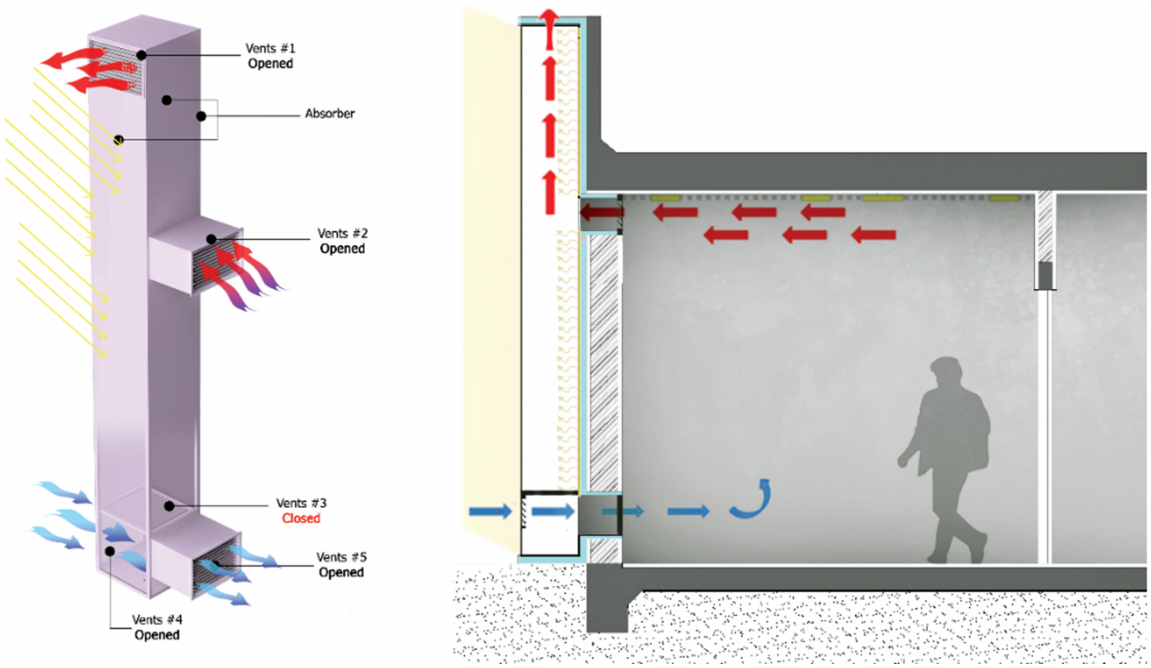


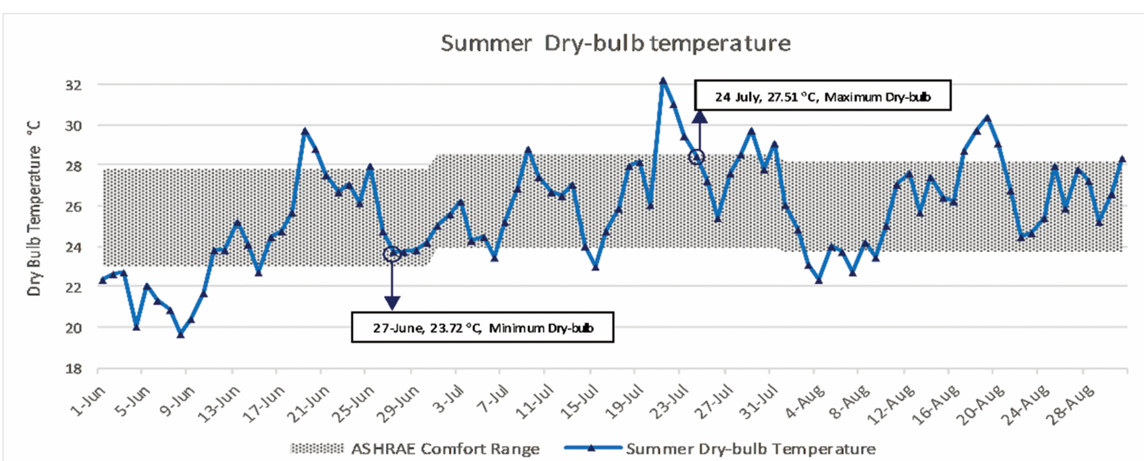
FIGURE 8. Operation mechanism during summer season.



creating negative pressure inside the upper part of the room. Then, the hot air at the top of the room will be suctioned, allowing the cold air to enter the space through the lower vent. In addition to the potential cooling process, this operation helps increase the rate of air exchange inside the space, thus enhancing natural ventilation, as shown in Figure 8.

According to ASHRAE, when the dry-bulb temperature falls within the comfort range, it will be appropriate for natural ventilation. Therefore, the maximum and minimum dry-bulb days within the ASHRAE comfort range will be selected for investigation. Based on weather data and using the ASHARAE adaptive model, the maximum dry-bulb day was July 24th at around 28.43 °C, and the minimum was June 27th, at around 23.72 °C (Figure 9).

FIGURE 9. Dry-bulb temperature for summer months.



Simulation software—DesignBuilder

The DesignBuilder simulation program will be used in this study to test different scenarios to reach the ideal design solution for a solar wall system. DesignBuilder is an energy simulation software, with an added CFD module, with a comprehensive user interface to the EnergyPlus dynamic thermal simulation engine, and it's chosen by various professionals such as architects and building service engineers (Al-Hafith et al., 2017, Liang et al., 2017). A primitive variable is a numerical method employed by DesignBuilder CFD which implies the solution of a set of coupled non-linear second-order partial differential equations known as the Navier-Stokes equations (de la Torre and Yousif, 2014).

DesignBuilder provides comprehensive energy simulation with a three-dimensional interface. It can provide CFD calculations for both internal and external conditions of a building for every possible situation and takes into consideration a wide range of environmental factors depending on hourly weather data. The accuracy of the DesignBuilder in energy simualtion has been validated by the Building Energy Simulation TEST (BESTest) procedure developed by the International Energy Agency, and considered by the American Department of Energy and the international community to evaluate building energy simulation programs capabilities (de la Torre and Yousif, 2014, Taleb and Sharples, 2011).

DesignBuilder validity as a CFD simulation software has been proven by many researchers based on field experiment results (Baharvand, Hamdan, and Abdul 2013; Evola and Popov 2006; Bangalee, Miau, and Lin 2013). It has also been compared to other widely respected CFD software, such as Phoenices (School of Built and Natural Environment of Northumbria University 2011). In this study, the CFD modeling by DesignBuilder was conducted to ensure that the mechanism of the proposed system works as planned. The CFD model was based on the K-e Turbulence model, a non-uniform rectilinear Cartesian grid with 0.1-m spacing. All temperatures and flow-boundary-condition data for building components were imported directly from the EnergyPlus simulation results. The building was simulated under free-floating temperature without using mechanical heating or cooling equipment.

For accurate results, the simulation software was set to perform an annual energy simulation with 30 steps per hour. The simulation software produces energy and comfort analysis for the building throughout the year. However, running an annual simulation in two-minute increments provides the solar wall the time required to work and reach the desired heat capacity. During this time, the software considers the loss of efficiency that occurs overnight or the overheating during some days. Therefore, the results presented in this research were selected to illustrate the effectiveness of the system during cooling and heating seasons in detail.

Outline of investigated case

A three-dimensional model of the investigated space was created using DesignBuilder software. The southwest room within the building was selected as the main study area. The building construction details followed a typical Jordanian building's U-values and specifications. Figure 10 and Table 4 shows the investigated space layout and parameters, while Table 6 provides the construction specifications. Table 5 explains the solar wall parameters and specifications used in the simulation software.

RESULTS

In this section, the impact of various modifications on the solar wall system regarding absorber material thickness and glazing type is presented along with thermal comfort

FIGURE 10. 3D model and plan for the investigated space (living room) within the building layout.

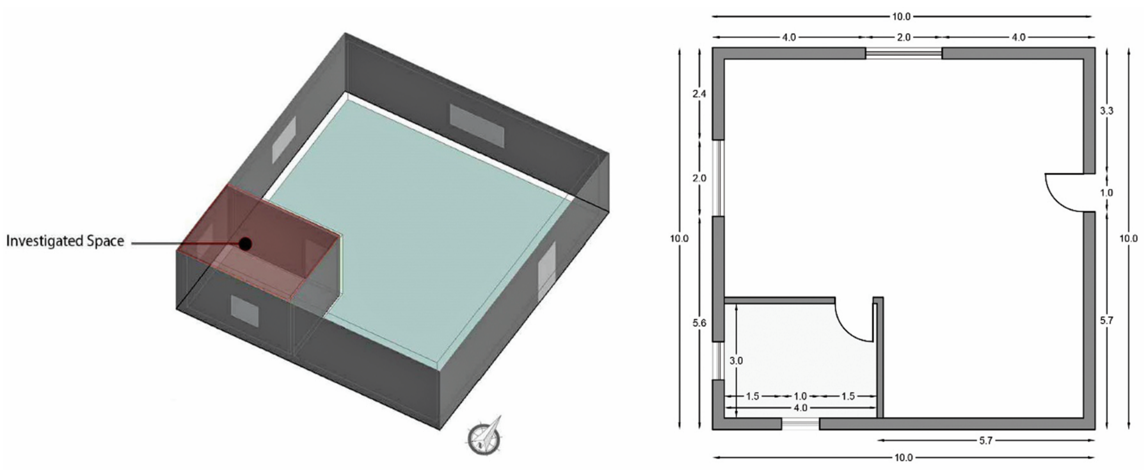


TABLE 4. Investigated space (living room) parameters.

Parameter	Description	
Building area	100 m^2	
Shape	Square, 10*10 m	
Living space area	12 m^2	
Building height	3 m	
Parapet height	1 m	
Living space shape	Rectangular 3*4 m	
Orientation of living space	Long axis east-west	
Windows	Two windows. South, West	
Windows size	Four windows	
Windows size	Two windows: Width = 1.5 Height = 1	
	Two windows: Width = 1.0 Height = 1	
Airtightness	0.05 ac/h	
Lighting	Fluorescent	25mm diam
	Power density	10.20 W/m^2
	Control	Stepped = 1 step ON/OFF dimming day lighting control
HVAC System	Heating	Off
	Cooling	Off
	Natural Ventilation	On within ASHRAE limitations
Occupancy	Person	5

TABLE 5. Solar wall simulation parameters and specifications.

Variables	Type	Value	Thermal conductivity W/M-K
System geometry	Total height	400 cm	—
	Cavity gap	50 cm	—
	Vents size	50 cm width	—
		25 cm length	—
Absorber Material	Copper Thickness	(0.1–1.0) cm	384
	PCM Thickness	1.12 cm	0.2000
Insulation	XPS Extruded Polystyrene–CO_2 Blowing Thickness	2.5 cm	0.0340
Glazing Type	Single Clear	0.6 cm	
	Double Clear	(0.6—0.6—0.6) cm glass—Air—glass	
	Triple Clear	(0.3—0.6—0.3) cm glass—Air—glass	

TABLE 6. Investigated space construction specification.

Component	Thickness	U-Value	Layers	Thickness
External wall	0.26 m	1.736	Cement Plaster	0.03
			Block	0.20
			Cement Plaster	0.03
Internal wall	0.16 m	1.690	Cement Plaster	0.03
			Block	0.10
			Cement Plaster	0.03
Roof	0.28 m	2.004	Cast Reinforced concrete	0.10
			Block + cast reinforced concrete	0.15
			Cement Plaster	0.03
Floor	0.35 m	1.4	Gravel-based Soil	0.20
			Sand	0.05
			Cast Reinforced concrete	0.10
Windows	N/A	1.4	Sliding, Single clear glazing	0.06
		5.881	Aluminum Framing	0.05

assessment regarding system ratio from the south wall. The evaluation is based on ASHRAE Standards, which defines acceptable ranges of environmental parameters to obtain acceptable thermal conditions.

As many as 15 cases were combined at the design level for the solar wall. Among the suggested cases, Case 11 showed that using triple glazing with 0.1 cm copper yielded the best results. This case study yielded the highest positive impact of operative temperature in both winter and summer. Four cases at the implementation level were conducted to study the impact of using more than one system, and Case D, four systems, showed the best result regarding thermal comfort. Based on the ASHRAE Standard, 15 and 24 thermal hours in the comfort range were achieved in winter during the investigated days, whereas in the base case, without the solar wall, the comfort hour was observed only zero to five hours. In the summer, 10 and 19 comfort hours were observed, while the base case showed zero for both days.

DISCUSSION

As the Green Building movement is growing worldwide, the main purpose of the study was to develop a dual functional passive system, called a solar wall. Passive design uses energy sources directly such as solar radiation and wind and provides thermal comfort at the lowest possible energy consumption. The study combined the Trombe wall and solar chimney and used simulation software called DesignBuilder to configure the Solar Wall, and determine its impact on indoor operative temperature for the base case. The results obtained from the simulations are satisfactory.

Various studies have indicated that it is possible to maintain occupant thermal comfort while achieving energy efficient designs and the results of this study coincide well with these findings. As mentioned earlier, Jordan spends considerably on energy consumption. What is noteworthy is that only 4% of the total energy consumed is generated from renewable sources, while the rest is from fossil fuels, which has an adverse effect on the environment. According to the report titled Transition to Sustainable Buildings—Strategies and Opportunities to 2050, if no action is taken to improve energy efficiency in the building sector, energy demand is expected to rise by 50% by 2050.

Jordan has a vast resource of solar energy as it lies in the earth-sun belt area. As Jaber and Ajib, 2011, stated, passive solar designs can reduce heating and cooling loads, and improve comfort, therefore enhancement of energy efficiency standards of buildings becomes vital.

Considering the current trend where international regulations constantly encourage the integration of passive solar systems in buildings, this study evaluated a dual functional passive system called Solar Wall for the Jordanian climate using a simulation study. The new system combined the Trombe wall with solar chimneys that can cool or heat based on the requirement of the structure.

Previous studies and experiments have proved that the incorporation of phase-change materials (PCM) with construction layers is an attractive solution to minimize the massive energetic consumption related to building conditioning. This study combined 15 cases of the design levels for the solar wall and tried a novel approach to combine copper with PCM as the main absorber material instead of brick or heavy concrete. A positive trend in operative temperature is observed when the copper thickness was decreased and layers of glazes were increased. Hence, a better system was discovered.

Sensitivity study for solar wall configuration

Figures 11, 12, 13, and 14 illustrate the effect of using the suggested solar wall system for indoor cooling and heating purposes in the investigated space. Results indicate a positive trend in the operative temperature as copper thickness decreased and layers of glazes increased. The reduction of copper thickness helped to increase the delivery of absorbed heat from the sun to cavity air during the daytime, thus increasing the amount of heated air inside the cavity. Also, the reduction of copper thickness helped to increase the amount of absorbed heat inside the PCM layer, thus increasing the system efficiency at night. The use of triple-glazed glass was more efficient in reducing the heat loss between the cavity and outside environment due to its lower U-value than double or single glaze, which is consistent for Gan and Riffat (Gan and Riffat, 1998), where they suggest using triple glass to get maximum performance. Figure 15 illustrates the effect of the solar wall system by CFD slice on selected days in winter and summer.

FIGURE 11. Effect of solar wall heating mode on January 15th.

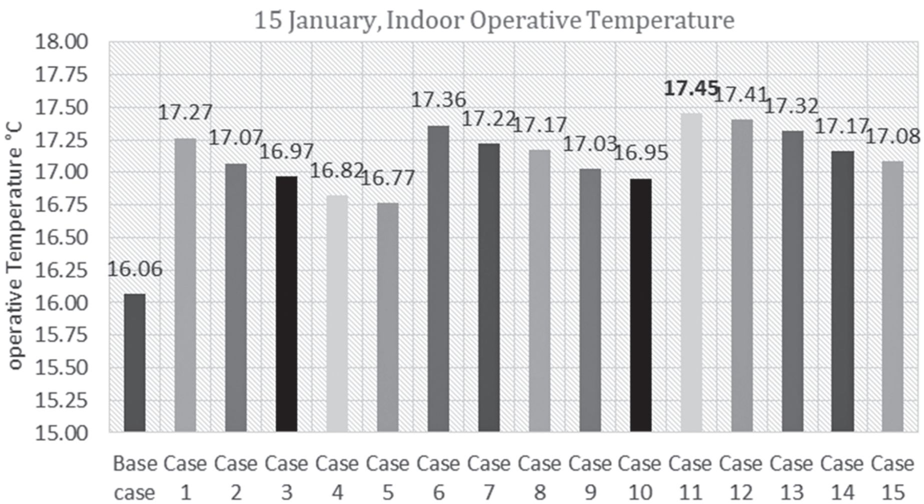


FIGURE 12. Effect of solar wall heating mode on December 16th.

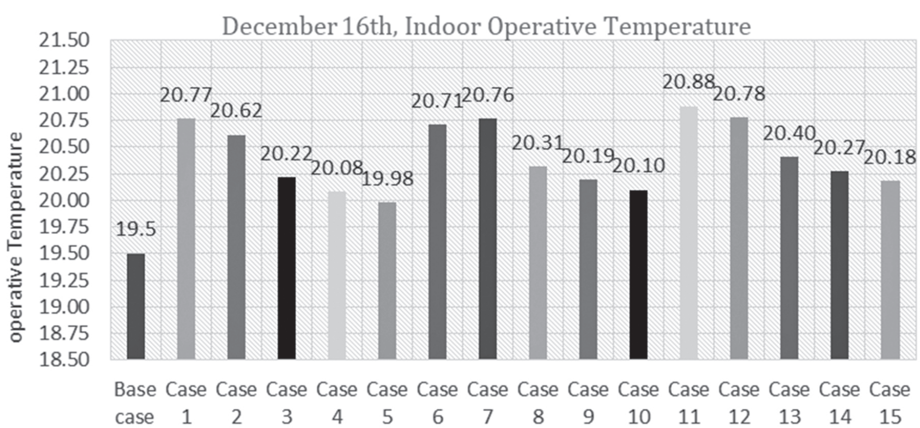


FIGURE 13. Effect of solar wall cooling mode on June 27th.

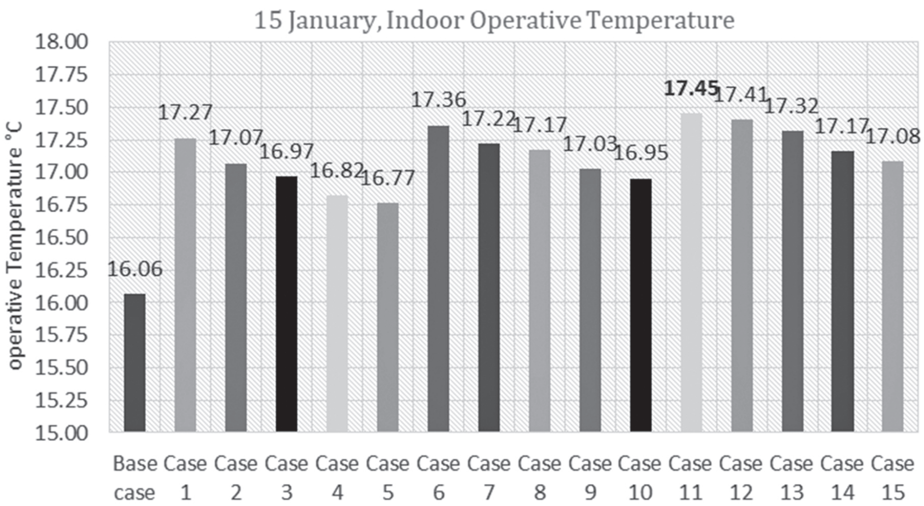


FIGURE 14. Effect of solar wall cooling mode on July 27th.

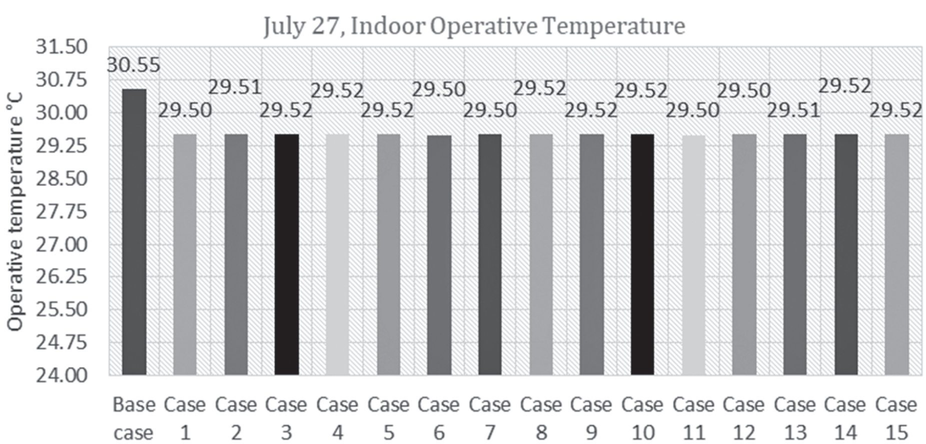
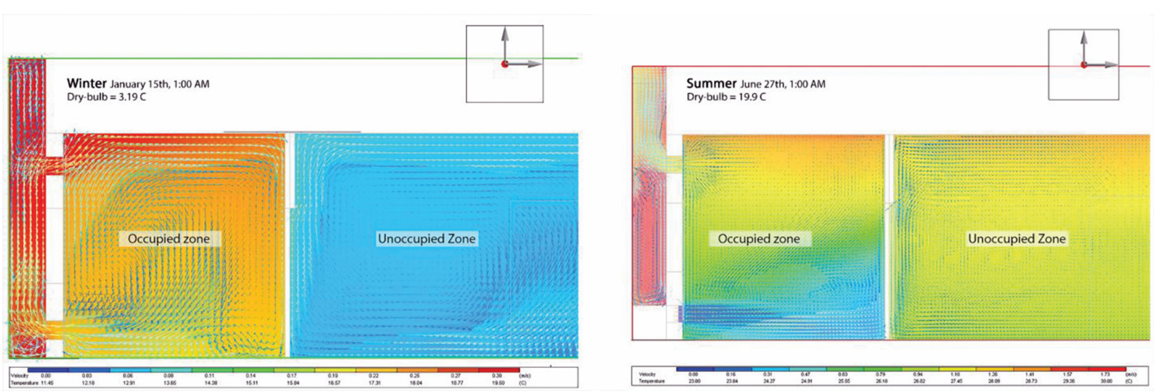


FIGURE 15. CFD slice for investigated case in winter and summer.



By comparing the results to the current thermal condition of the investigated space (base case) using the solar wall in winter helped in increasing operative temperature and decreasing it in summer. Overall, Case 11 (triple glass and 0.1 copper thickness) has a maximum impact on indoor operative temperature. In winter, an increase of approximately 1.4 °C in the operative temperature is observed during the investigated days. While in summer, there is a decrease of 1.05 °C to 1.72 °C in the operative temperature.

Thermal comfort assessment regarding system ratio

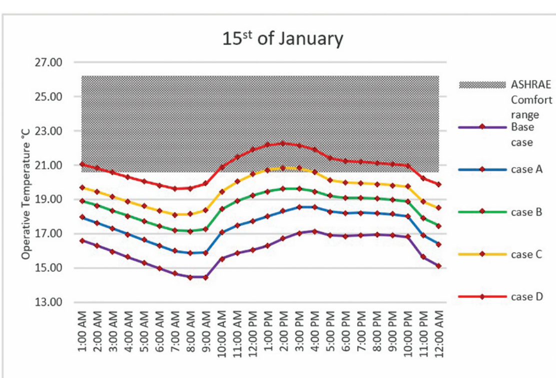
Heating mode

Figures 16 and 17 present indoor operative temperatures against the ASHRAE comfort range for the investigated winter days (January 15, December 16). The ASHRAE comfort ranges were determined based on the PMV model. Increasing the number of units in the investigated space, as presented in cases B, C, and D, had a significant effect on indoor operative temperature. Increasing the absorber mass area helped increase the amount of heated air inside the cavity and the amount of absorbed heat in the PCM layer. The larger area absorber mass means higher efficiency for heating consistent with (Hu et al., 2017) the relationship between absorber mass and system efficiency. The PCM layer helped extend the system's heating operation in the night, which reflected on the heating efficiency during the day; adding four systems (case D) on January 15 turned out to be more efficient. In case D, the temperature was in the comfort range for 15 hours, whereas the base case comfort range was zero hours. In addition, on December 16, cases C and D had a full day of thermal comfort. The results showed a contradiction with (Jaber and Ajib, 2011) a study about the ideal ratio of the absorber mass. The impact of increasing the number of units continued to be useful and effective despite the ratio exceeding 37% from the facade area.

Cooling mode

The thermal comfort range during summer is determined based on the ASHRAE adaptive model. Figures 18 and 19 present the indoor operative temperature inside the space against the ASHRAE comfort range for the investigated summer days. Increasing the number of units, as in case of B, C, and D, had a significant effect on indoor operative temperature at night and in

FIGURE 16. Indoor operative temperature against ASHRAE comfort range for investigated winter days.



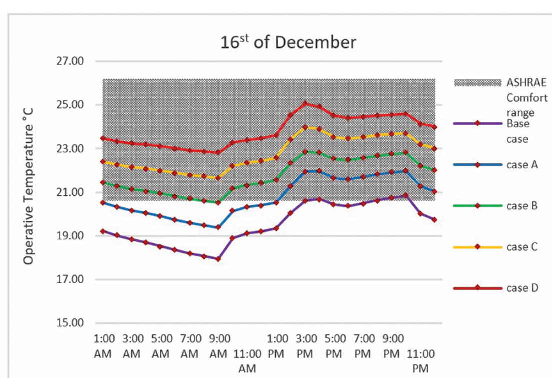


FIGURE 17. Indoor operative temperature against ASHRAE comfort range for investigated—highlighted numbers are within ASHRAE comfort zone.

Winter 15-January							Winter 16-December						
Day	Dry-bulb	Base case	Case A	Case B	Case C	Case D	Day	Dry-bulb	Base case	Case A	Case B	Case C	Case D
1:00 AM	3.19	16.63	17.96	18.92	19.69	21.05	1:00 AM	12.9	19.22	20.52	21.46	22.41	23.47
2:00 AM	2.487	16.31	17.65	18.65	19.45	20.83	2:00 AM	12.228	19.02	20.33	21.3	22.27	23.34
3:00 AM	1.738	15.98	17.32	18.36	19.17	20.58	3:00 AM	12.582	18.84	20.17	21.16	22.15	23.24
4:00 AM	1.142	15.65	16.98	18.05	18.88	20.32	4:00 AM	13.758	18.69	20.04	21.06	22.09	23.18
5:00 AM	0.693	15.32	16.65	17.76	18.61	20.07	5:00 AM	14.207	18.52	19.9	20.95	21.99	23.11
6:00 AM	0.293	15	16.32	17.47	18.36	19.84	6:00 AM	13.987	18.36	19.75	20.82	21.89	23.02
7:00 AM	0.048	14.68	16	17.2	18.12	19.62	7:00 AM	14.117	18.2	19.6	20.7	21.79	22.92
8:00 AM	0.413	14.5	15.88	17.16	18.13	19.66	8:00 AM	14.858	18.07	19.5	20.62	21.72	22.87
9:00 AM	1.368	14.48	15.92	17.28	18.39	19.93	9:00 AM	15.203	17.94	19.39	20.53	21.65	22.81
10:00 AM	2.468	15.57	17.07	18.43	19.44	20.88	10:00 AM	15.145	18.89	20.14	21.16	22.21	23.27
11:00 AM	3.517	15.88	17.49	18.91	20.04	21.47	11:00 AM	15.362	19.12	20.32	21.34	22.36	23.4
12:00 PM	4.362	16.06	17.73	19.23	20.45	21.9	12:00 PM	15.958	19.22	20.41	21.43	22.44	23.48
1:00 PM	4.958	16.33	18.02	19.48	20.73	22.18	1:00 PM	16.458	19.34	20.53	21.56	22.59	23.63
2:00 PM	5.252	16.73	18.32	19.62	20.85	22.26	2:00 PM	17.63	20.04	21.29	22.33	23.45	24.54
3:00 PM	5.197	17.06	18.57	19.65	20.82	22.17	3:00 PM	19.017	20.61	21.95	22.85	23.98	25.06
4:00 PM	4.738	17.17	18.57	19.48	20.58	21.91	4:00 PM	19.603	20.68	21.97	22.8	23.9	24.92
5:00 PM	3.935	16.93	18.3	19.2	20.15	21.43	5:00 PM	19.39	20.45	21.64	22.52	23.54	24.51
6:00 PM	3.293	16.87	18.21	19.1	19.99	21.24	6:00 PM	18.945	20.36	21.59	22.47	23.46	24.4
7:00 PM	2.893	16.93	18.23	19.1	19.96	21.2	7:00 PM	18.593	20.49	21.7	22.57	23.53	24.45
8:00 PM	2.493	16.95	18.21	19.07	19.91	21.14	8:00 PM	18.193	20.63	21.82	22.67	23.61	24.51
9:00 PM	2.093	16.91	18.14	19	19.85	21.07	9:00 PM	17.845	20.75	21.91	22.75	23.67	24.56
10:00 PM	1.693	16.82	18.02	18.9	19.75	20.98	10:00 PM	17.493	20.84	21.97	22.81	23.71	24.59
11:00 PM	1.293	15.64	16.91	17.94	18.89	20.24	11:00 PM	17.145	20.03	21.27	22.2	23.19	24.15
12:00 AM	0.893	15.14	16.41	17.48	18.5	19.89	12:00 AM	16.793	19.75	21.02	22.01	23.03	24
Comfort Hours		0	0	0	4	15	Comfort Hours		5	11	23	24 (All day)	24 (All day)

the morning. Increasing the absorber mass area helped increase the amount of absorbed heat in the PCM layer, which extended the operation of the solar wall as a chimney during night-time. The efficiency of the system during the night-time was remarkable due to the decrease in dry-bulb temperature in comparison to the air temperature inside the room.

This difference in the night-time temperature was more suitable for cooling by natural ventilation than daytime, as (Bouchair, 1994) mentioned in his study. During the day, especially at noon, increasing the system units had no effect. The systems were suspended to lose one of the operating conditions for cooling by natural ventilation set by ASHRAE in (Indoor Air Quality Guide, 2009). The dry-bulb temperature was above the internal air temperature inside

FIGURE 18. Indoor operative temperature against ASHRAE comfort range for investigated summer days.

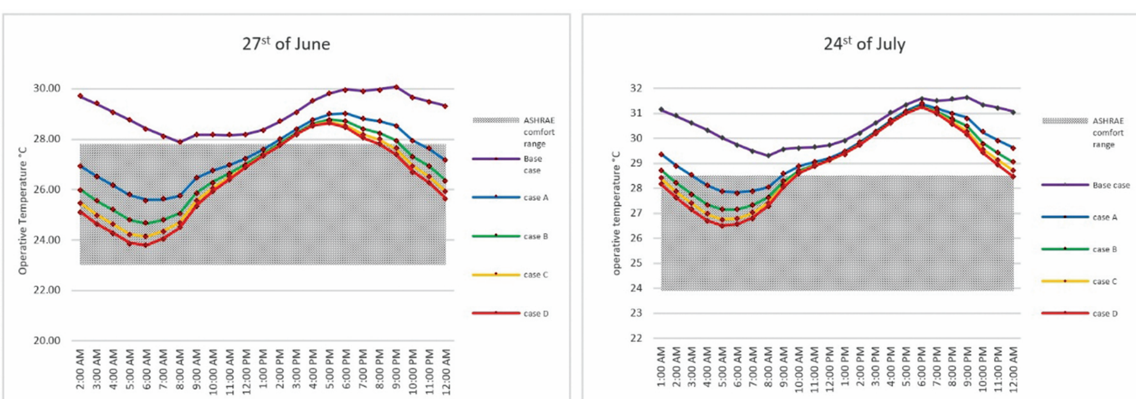


FIGURE 19. Indoor operative temperature against ASHRAE comfort range for investigated summer—highlighted numbers are within ASHRAE comfort zone.

Summer 27-June							Summer 24-July						
Day	Dry-bulb	Base case	Case A	Case B	Case C	Case D	Day	Dry-bulb	Base case	Case A	Case B	Case C	Case D
1:00 AM	19.94	29.95	27.39	26.52	26.02	25.69	1:00 AM	25.235	31.14	29.37	28.73	28.39	28.17
2:00 AM	19.19	29.69	26.94	26.02	25.48	25.13	2:00 AM	24.283	30.89	28.92	28.21	27.85	27.61
3:00 AM	18.59	29.39	26.53	25.36	25.01	24.65	3:00 AM	23.542	30.62	28.52	27.78	27.4	27.14
4:00 AM	18.25	29.07	26.16	25.19	24.63	24.27	4:00 AM	23.093	30.33	28.11	27.36	26.96	26.7
5:00 AM	18.1	28.76	25.78	24.8	24.24	23.88	5:00 AM	22.9	30.02	27.88	27.15	26.76	26.51
6:00 AM	18.67	28.42	25.59	24.66	24.14	23.8	6:00 AM	23.262	29.75	27.84	27.15	26.8	26.56
7:00 AM	19.92	28.14	25.61	24.8	24.35	24.06	7:00 AM	24.375	29.51	27.89	27.32	27.01	26.82
8:00 AM	21.48	27.89	25.75	25.06	24.7	24.48	8:00 AM	25.978	29.29	28.05	27.64	27.42	27.29
9:00 AM	23.18	28.18	26.45	25.86	25.55	25.36	9:00 AM	27.678	29.58	28.57	28.27	28.13	28.04
10:00 AM	24.78	28.17	26.74	26.3	26.07	25.94	10:00 AM	29.327	29.63	28.88	28.71	28.65	28.62
11:00 AM	26.17	28.15	26.98	26.65	26.49	26.41	11:00 AM	30.772	29.64	29.06	28.93	28.9	28.89
12:00 PM	27.37	28.2	27.25	27.02	26.93	26.9	12:00 PM	32.02	29.73	29.22	29.12	29.11	29.14
1:00 PM	28.31	28.37	27.59	27.42	27.36	27.35	1:00 PM	33.013	29.92	29.46	29.39	29.39	29.4
2:00 PM	28.91	28.69	27.98	27.82	27.76	27.74	2:00 PM	33.607	30.23	29.84	29.78	29.77	29.76
3:00 PM	29.15	29.08	28.4	28.25	28.2	28.2	3:00 PM	33.903	30.62	30.27	30.21	30.2	30.2
4:00 PM	29.1	29.51	28.77	28.62	28.56	28.55	4:00 PM	33.897	31.01	30.72	30.65	30.64	30.64
5:00 PM	28.64	29.81	28.99	28.78	28.68	28.63	5:00 PM	33.438	31.36	31.11	31.04	31.02	31.01
6:00 PM	27.78	29.97	29.02	28.71	28.55	28.45	6:00 PM	32.532	31.6	31.38	31.3	31.27	31.26
7:00 PM	26.68	29.9	28.81	28.41	28.19	28.06	7:00 PM	31.38	31.51	31.2	31.09	31.03	31
8:00 PM	25.48	29.97	28.71	28.24	27.97	27.8	8:00 PM	30.128	31.55	31	30.78	30.66	30.58
9:00 PM	24.28	30.09	28.53	27.95	27.61	27.4	9:00 PM	28.88	31.64	30.83	30.49	30.29	30.16
10:00 PM	23.08	29.66	27.94	27.31	26.95	26.72	10:00 PM	27.628	31.35	30.24	29.81	29.57	29.42
11:00 PM	21.88	29.49	27.62	26.91	26.51	26.26	11:00 PM	26.38	31.22	29.92	29.41	29.12	28.93
12:00 AM	20.63	29.33	27.15	26.36	25.92	25.64	12:00 AM	25.128	31.07	29.63	29.04	28.7	28.48
Comfort Hours		0	15	16	18	19	Comfort Hours		0	5	8	9	10

the room, which meant that cooling by natural ventilation would not be appropriate. Thus, the remaining system worked as an isolated system only for the internal walls away from direct sun. For both investigated days, adding four systems (case D) was the most effective—June 27 had 19 hours in comfort range; July 24 had 10; the base case had zero.

CONCLUSION

The third International ASHRAE Conference on Efficient Building Design focused on the latest research and development to improve building design and state-of-the-art technologies in building material and HVAC Equipment Technologies. Topics such as Alternative Energy Use in Buildings; Energy Efficiency, Comfort, and Climate; Energy Conservation Strategies; Indoor Air Quality and Thermal Comfort, etc. were discussed at length and number of presentations on new concepts and advances in HVAC design and industry were presented. In short, the focus was on environment-friendly energy-saving designs.

Continuing with the global trend, this paper also presented a new design for a dual functional passive system, a solar wall that combined a Trombe wall and a solar chimney. The main objective of this research was to enhance thermal comfort within spaces by using a solar wall system to provide heating or cooling based on the needs of the space. A new design criterion, new mechanism, and operating conditions were set. According to Energy Saver, the US Department of Energy's (DOE) consumer resource on saving energy and using renewable energy technologies at home, passive solar design takes advantage of a building's site, climate, and materials to minimize energy use. A well-designed passive solar home first reduces heating and cooling loads through energy-efficiency strategies and then meets those reduced loads in whole or part with solar energy.The simulation results of the suggested system show an increase in the number of hours in which thermal comfort was achieved. Increasing the thermal comfort hours means less energy consumption and more productivity for the space occupants. However, the proposed system was tested only on the southern facade of the building, which experiences direct solar radiation. Investigations for the possibilities of implementing the system on other facades of the building should be carried out.

The system was designed using four pieces that can be easily assembled on the site, with the weight of each piece ranging from 24 to 28 kg and the weight of the glass for each piece of the system being 11 kg. All this helps make it a portable system that is easy to carry and move. The outer layer of the proposed system is a HDPE plastic sheet, which may affect the building's external appearance. Further investigation of the system appearance should be carried out while maintaining or improving its appearance.

Future Studies

Further studies should investigate the different variables of the systems in order to make use of their ultimate potential. Additional studies should also consider the Life Cycle Assessment (LCA) or Life Cycle Cost (LCC) analysis for the suggested system and investigate its effect on multi-story buildings in addition to its influence on thermal comfort in different regions and climate. The typology of the system and the buildings and relation to each other should be studied also.

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