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Optimization and Performance Analysis of Trombe Walls in Hot-Arid Climates Using DesignBuilder Simulation

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ABSTRACT

Extreme climates are defined by high solar radiation, sharp hourly temperature variations, and low humidity, factors that present significant challenges while also offering opportunities for energy-efficient building design. This study utilizes DesignBuilder simulation to assess enhancements to the Trombe wall system to improve indoor thermal comfort. The research centers on optimizing critical parameters, including wall orientation, material selection, glazing characteristics, and ventilation configuration, to achieve effective heat retention during winter and improved heat dissipation in summer. By selecting appropriate air gap widths, ventilation opening areas, and wall materials for seasonal performance, simulations were conducted to evaluate the thermal behavior of Trombe walls. To reduce overheating risks and enhance cooling potential, the study also explores the integration of phase change materials (PCMs) and air gaps alongside natural ventilation systems. The results indicate that a properly designed Trombe wall can maintain indoor temperatures within a comfortable range, significantly reducing reliance on mechanical cooling systems. The study further demonstrates the effectiveness of combining Trombe walls with conventional passive cooling techniques to address the specific challenges of hot, dry climates. Utilizing Energy Plus simulation and analytical tools, this research supports the development of sustainable building designs that emphasize energy efficiency, improved thermal comfort, and reduced carbon emissions.

1. INTRODUCTION

Hot arid zones are characterized by wide temperature fluctuations, high solar radiation, and very low humidity. These factors create significant challenges in achieving indoor thermal comfort. The Trombe wall, a passive solar heating and cooling system, holds potential for effective adaptation in such conditions. This study investigates the optimization of Trombe wall design to improve both thermal comfort and energy efficiency in buildings located in hot, arid climates.

Simulations conducted using DesignBuilder indicate that indoor temperatures can remain within comfortable ranges while reducing reliance on mechanical heating and cooling systems. These results underscore the potential of Trombe walls as a sustainable solution for enhancing thermal comfort in buildings located in hot arid climates, contributing to improved energy efficiency and lower carbon emissions [1].

Adaptations include the use of high thermal mass materials, advanced glazing systems, and insulation to control heat gain and loss effectively. Shading devices, operable vents, and phase change materials (PCMs) support seasonal flexibility by enabling heat retention during winter and promoting heat dissipation during summer. Furthermore, incorporating Trombe walls alongside traditional passive cooling methods such as cross-ventilation and evaporative cooling, can significantly enhance indoor thermal regulation [2].

This study examines the effectiveness of ventilated Trombe walls in providing passive heating and cooling to enhance indoor climatic conditions while minimizing reliance on external energy sources.

This study employs experimental simulations to evaluate the performance of ventilated Trombe wall designs across a range of semi-arid climate conditions. Research indicates that vented Trombe walls can significantly reduce indoor temperature fluctuations, offering a practical low-tech solution for thermal regulation in off-grid areas. Implementing such passive systems may improve living conditions and reduce dependence on conventional energy, aligning with sustainable development goals in remote and resource-constrained regions. Figure 1 illustrates the morning and evening operation modes of the proposed Trombe wall during both winter and summer seasons [3].

To achieve optimal thermal performance, and maintain indoor comfort, it is essential to optimize the Trombe wall design, and regulate the operation of air vents, and shading devices. During winter daytime, when solar radiation is high, the air vents located between the thermal mass, and the glazing should remain closed to create a greenhouse effect within the air layer, and increase the internal temperature. Shading devices should not be considered when optimizing solar heat gains. Ventilation openings in the massive wall should be activated only when the air layer temperature exceeds the indoor temperature and space heating is needed (Figure 2(a)). At night, both shading elements and air vents must remain closed to prevent heat loss from the interior to the outside environment (Figure 2(b)). In summer, the ventilation system should remain closed during the day, and a shading device should be used. The more opaque the shading material, the lower the solar heat gains; lighter colors, on the other hand, reflect more incoming solar radiation (Figure 2(c)). To cool the air layer at night, air vents should be opened both at the glazing surface and the shading device [4]. Under these conditions, a DVTW system may also enhance cross-ventilation within the building. This can be achieved by opening the top vent at the glazing and the bottom vent at the thermal mass, allowing warm indoor air to exit. Cross-ventilation is further supported through an opening on the north-facing opposite fade, which helps cool the interior spaces (Figure 2(d)). These seasonal adjustments demonstrate that ventilation is a key factor in the thermal performance of the Trombe wall [5, 6].

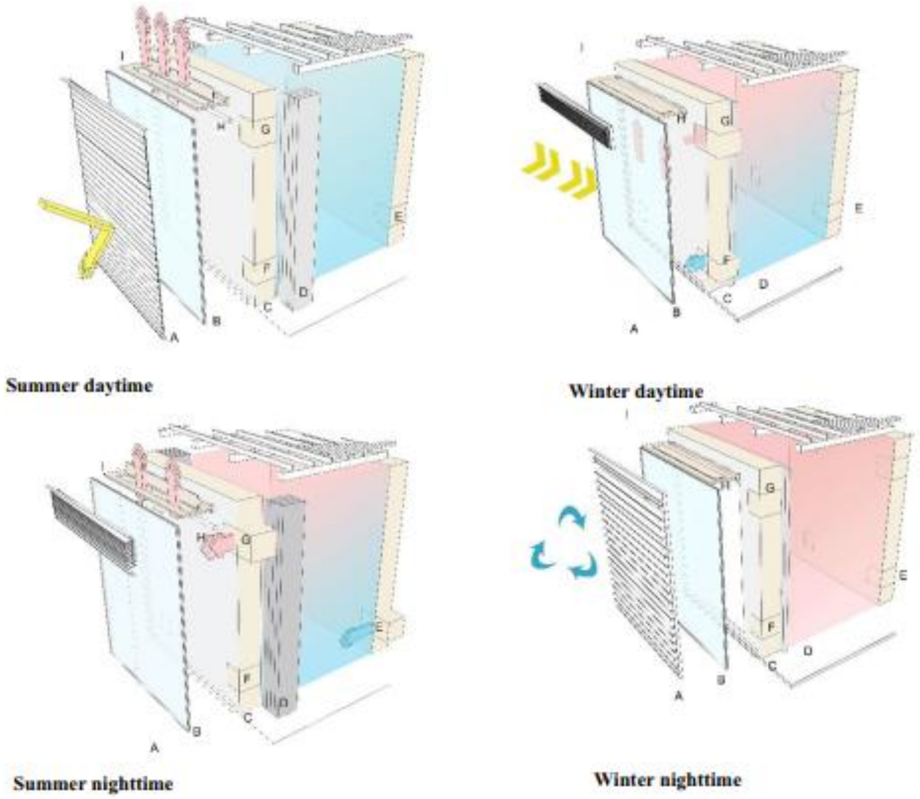


Figure 1. A rammed earth wall with wooden shutters, a glass panel, a wool insulation panel, a lower vent for north cold air, lower and higher vents for the Trombe wall, a wool curtain, and a top vent for the Trombe wall [3]

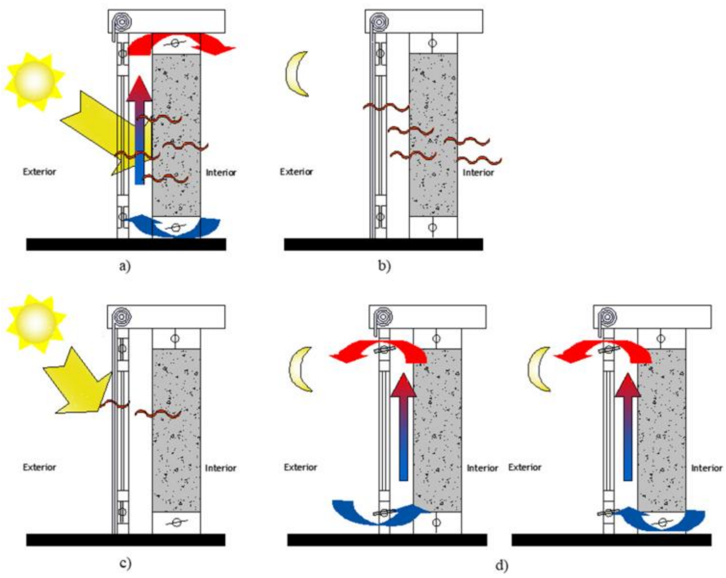


Figure 2. Operating modes for the Trombe wall are: (a) winter (daytime periods), (b) winter (nighttime periods), (c) summer (daytime periods), and (d) summer (nighttime periods) [7]

2. LITERATURE REVIEW

By integrating these methods, Trombe walls in hot arid zones can effectively mitigate temperature extremes, providing a sustainable and energy-efficient solution for thermal comfort.

Phase change materials (PCMs) have gained significant attention for enhancing the thermal performance of Trombe walls, particularly in regions with large day-night temperature differences. This literature review examines selected key studies on PCM integration into Trombe wall systems, with a focus on energy efficiency, thermal comfort, and environmental impact. The work of Su et al. [8] focused on experimental results demonstrating the effectiveness of PCMs in preventing overheating during summer while ensuring adequate heating in winter. Findings indicate a notable reduction in peak indoor temperatures in hot climate conditions. Cabeza et al. [9] found that integrating PCMs into building envelopes reduced peak heating and cooling loads by up to 30%, resulting in significant energy savings for buildings utilizing Trombe wall systems. Kim and Park [10] employed several simulation tools, including Energy Plus. Their findings emphasized the importance of site-specific design in maximizing thermal performance. As a passive solar design strategy, the Trombe wall has gained recognition for its ability to improve thermal comfort and reduce energy demand in residential buildings, particularly in hot, arid climates [11]. Table 1 summarizes key studies on Trombe wall adaptations for such regions, focusing on thermal performance, energy efficiency, and design optimization. Refer to Table 1 for detailed comparisons.

According to Saadatian et al. [12], sustainable design and green buildings offer innovative approaches to addressing energy and environmental challenges. Within this context, Trombe walls are recognized as a sustainable architectural solution for heating and ventilation. This review article examines the application of Trombe walls in buildings, outlining their configurations, technological components, and operational principles. The advantages and limitations of this passive design strategy are highlighted, and several potential areas for future research are also identified.

Zhang et al. [13] highlighted that air layer-involved envelopes (ALIEs) have become an integral part of modern building design, offering considerable potential to enhance thermal performance. Air layers serve various purposes, including ventilation, attic space, or added insulation. This study reviews recent literature on the design and application of internal air layers within building envelopes, focusing on walls, windows, and roofs. It classifies key structural features, driving mechanisms, functional impacts, and the advantages associated with different ALIE configurations. Based on the reviewed studies, air layer systems are broadly categorized into three types: mechanical ventilation, natural ventilation, and fully enclosed systems. The paper concludes by identifying current research gaps and proposing directions for future studies involving air layer technologies in building envelopes.

Table 1. Literature review on performance-enhancing Trombe wall adaptation

Thermal Performance of Trombe Walls in Hot Arid Zones	Misra and Ghosh [14]	The Trombe wall's ability to regulate indoor temperatures, by storing heat during the day and releasing it at night was highlighted to the pronounced temperature fluctuations characteristic of hot, arid regions.
	Hu et al. [15]	Trombe walls have been shown to improve comfort in hot climates by reducing indoor temperature fluctuations by up to 10°C.
	Xiao et al. [16]	The study's findings indicate that, when properly optimized and integrated with advanced materials and technologies, Trombe walls offer a cost-effective and sustainable solution for reducing building energy consumption while enhancing indoor thermal comfort.
Design Modifications for Hot Arid Zones	**Material Selection**	
	Sadineni et al. [17]	In hot, arid climates, it has been discovered that employing high thermal mass materials, such as stone or concrete, enhances the efficiency of heat storage and release.
	Aliwi and Kamoo [18]	Adobe's superior thermal performance and local availability made it a viable option for Trombe walls in arid regions.
	Glazing and Shading	
	Pourghorban and Asoodeh [19]	The significance of low-emissivity or double-glazed glass in reducing heat loss and improving solar gain efficiency was emphasized.
	Ghamari and Sundaram [20]	Emphasized how shading devices, such as overhangs and movable louvers, can aid in preventing summertime heat.
Energy Efficiency and Sustainability	**Energy Savings**	
	De Gracia and Cabeza [21]	Trombe walls have been shown to reduce heating and cooling loads in residential buildings in arid regions, resulting in energy savings of up to 25%.
	Omrany et al. [22]	Trombe walls have been shown to improve energy efficiency in hot climates when combined with other passive strategies, like green roofs.
	Carbon Footprint Reduction	
	Zarzycki and Decker [23]	It has been discovered that by lowering dependency on fossil fuel-based energy systems, Trombe wall adaptation helps to reduce carbon emissions.
Performance Simulation and Optimization	Li [24]	Trombe wall designs were optimized using simulation tools such as Energy Plus, emphasizing the importance of location-specific adjustments to maximize system performance.
	DesignBuilder Studies [25]	The impact of Trombe wall parameters, including material qualities, glazing, and vent placement in hot, arid regions is simulated by recent research using DesignBuilder.

Trombe wall adaptation for residential buildings in hot, dry climates requires careful consideration of ventilation, shading, glazing, and materials. The role of Trombe walls in improving thermal comfort and reducing energy consumption has been extensively explored. However, challenges related to overheating and aesthetic integration persist. Enhancing the performance of Trombe walls in hot climates remains a promising direction, particularly through the adoption of advanced technologies such as phase-change materials and smart control systems.

3. METHODS FOR TROMBE WALL DESIGN IN HOT ARID ZONES

To achieve thermal comfort in hot-arid regions characterized by significant daily temperature fluctuations, Trombe wall design must account for both heating and cooling needs. Table 2 outlines effective construction techniques for Trombe walls adapted to the specific climatic conditions of these regions.

Table 2. Methods for Trombe wall parameters

Orientation and Placement	South-Facing Orientation	Reduce summertime exposure and increase wintertime solar gain [25].
	Shading Technique	Use vegetation, pergolas, or overhangs to block summer sunlight at high angles without blocking winter sunlight at low angles.
Material Selection	Thermal Mass	For efficient heat storage and release, use high thermal mass materials like adobe, stone, or concrete [26].
	Back Wall Insulation	To optimize solar heat absorption, use dark, absorbent materials for the rear wall [27].
Glazing Design	Double or Low-E Glazing	Control solar gain during the day and minimize heat loss at night [28].
	Selective Coatings	To reduce overheating and maximize heat absorption, use glazing with solar control features.
Methods for Ventilation	Operable Vents	Install vents at the top and bottom of the Trombe wall to control airflow. Winter: Close vents to trap heat inside. Summer: Open vents to allow heat dissipation and support night flushing [29].
	Natural Ventilation	For better airflow, incorporate cross-ventilation systems.
Regulate Overheating and Shading	External Shading Devices	Use adjustable louvers or external blinds to control excessive solar gain in summer [30].
	Reflective Surfaces	Apply reflective coatings or paint to surrounding surfaces to reduce heat absorption.
Advanced System	Phase Change Materials (PCMs)	Embed PCMs in the wall to enhance heat storage and release capacities [31].
	Smart Control Systems	Automate vent operations and shading devices using temperature and solar sensors [32].
Cavity Dimension Optimization	Cavity Width	For efficient air circulation without resulting in undue heat accumulation or resistance, the cavity's width should be between 10 and 200 cm. Wider cavities can lower the Trombe wall's thermal efficiency, while narrow ones may restrict airflow [33].
	Cavity Height	The stack effect is improved by a taller cavity, which increases heat transfer and natural ventilation. To ensure consistent air circulation, make sure the height matches the wall's measurements.

4. RESEARCH METHODOLOGY

Several procedures were implemented to achieve the study's primary objective. Initially, a theoretical review was conducted to assess the impact of Trombe walls on thermal comfort, specifically operational temperature, Predicted Percentage of Dissatisfied (PPD), and Predicted Mean Vote (PMV), and to evaluate potential energy savings through reduced heating and cooling loads. Subsequently, data were collected from a selected residential case study in Mosul, Iraq. The thermal comfort and energy consumption of the building were analyzed using DesignBuilder Simulation V7. In the first simulation phase, the Trombe wall was introduced and compared to a baseline case without it to examine its effect on thermal comfort and energy efficiency. In the second phase, variations in the air gap, and ventilation opening percentage of the Trombe wall were tested to analyze their influence on air velocity and temperature (Figure 3).

4.1 Investigating DesignBuilder validation

DesignBuilder is a specialized software tool used for building energy performance simulation. Its reliability is typically assessed through various validation methods, with empirical validation being the most critical. One of the most widely accepted approaches for validating energy simulation software involves comparing simulated results with actual measurements obtained from real buildings [34]. In this study, indoor conditions within the case study building were monitored over a one-week period 30/8/2023 to 6/9/2023, during which temperature, relative humidity, and air quality data were collected at regular intervals using a GM8903 multifunctional portable hot wire anemometer. The device was placed at the center of the room, 1.5 meters above the floor and 2.2 meters away from the exterior window, as illustrated in Figure 4. The instrument was connected to a personal computer to enable continuous data recording at 5-minute intervals throughout the day. These empirical values were then compared to the outputs generated by DesignBuilder, to validate the model's accuracy. EnergyPlus, through DesignBuilder simulation, was employed to compare software-based results with field measurements from the case study. The differences between measured and simulated results, Figures 5 and 6, remained within a 10% margin, demonstrating the model's high level of accuracy and reliability [35]. This confirms the software's feasibility for exploring alternative design scenarios with strong alignment between simulation outputs and real-world performance.

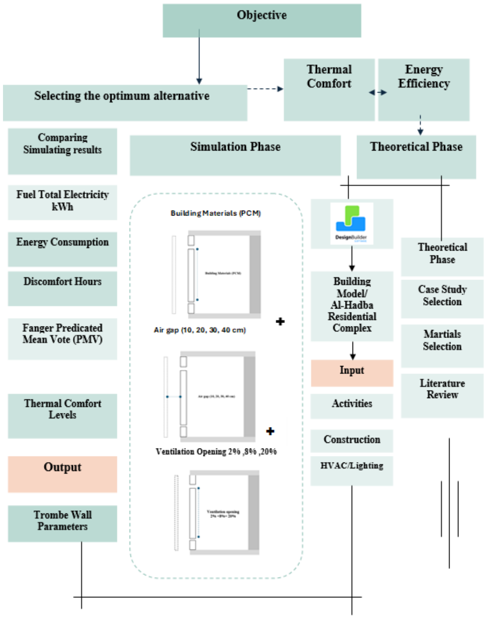


Figure 3. Research methodology framework

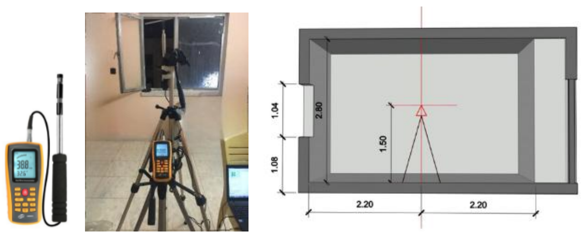


Figure 4. (a) Hot Wire Anemometer GM8903 wind velocity hotwire, (b) Setup of field measurements, (c) Position of the "wind velocity sensor" in the case study room

4.2 Practical implementation guidance of the Trombe wall

Optimal ventilation configuration: To improve natural airflow and increase the efficiency of both heating and cooling, increasing the vent opening size from 15% to 20% may be considered.

- The best results will be obtained by placing top vents near the ceiling and lower vents close to the floor.
- For narrow Trombe walls, prioritize vent size over cavity width, as airflow is more responsive to vent dimensions.

Material and surface selection: For the storage wall, use high thermal mass materials (such as brick or concrete) to retain solar heat during the day and release it at night.

- On the wall surface, apply selective, dark-coloured coatings to lower emissivity and boost solar absorptance.

Dust mitigation measures: Reduce clogging from sand and dust by installing washable or detachable mesh filters at vent ports.

- To reduce dust adhesion, use hydrophobic coatings or tilted glazing.
- Make sure there is convenient access for regular vent and glazing cleaning.
- Include automated vent dampers that have the ability to shut down in the event of a sandstorm or heavy particulate matter.

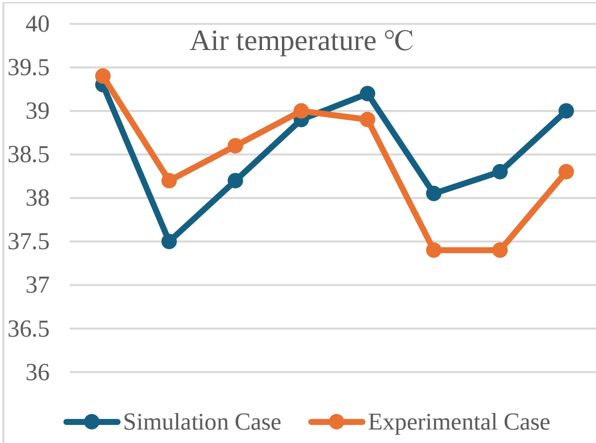


Figure 5. Comparison of the results of simulation and experimental measurement in terms of air temperature

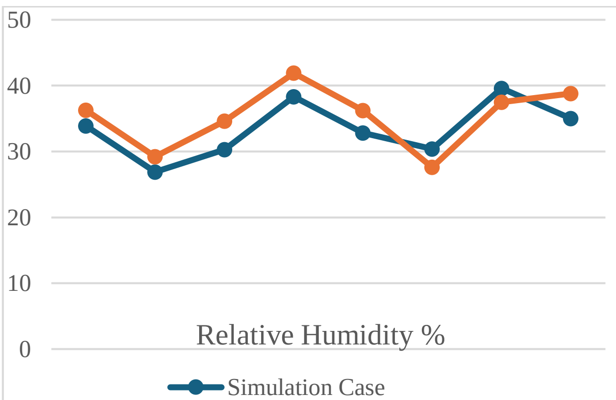


Figure 6. Comparison of the results of simulation and experimental measurement in terms of relative humidity

Table 3. The climate data for Mosul city all over the year

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Nov.	Oct.	Dec.	Year
Record high °C (°F)	19.96	25.2	31.52	35.72	40.97	48.33	51.48	49.38	45.18	39.92	30.47	28.37	51.4
Average high °C (°F)	13.3	15.6	19.72	25.52	32.19	38.69	42.94	42.71	37.83	30.51	21.62	15.24	28
Daily mean °C (°F)	10.08	12.2	16.38	21.73	28.59	34.74	38.5	38.26	33.69	26.8	18.26	12.09	24.3
Average low °C (°F)	6.43	7.87	11.24	15.65	22.57	27.61	30.41	30.71	26.84	20.99	13.89	8.49	18.6
Record low °C (°F)	-4.2	-7.35	0	4.2	8.4	19.96	22.06	22.06	17.86	12.61	4.2	0	-7.35
Average precipitation mm (inches)	85.46	57.4	93.69	89.26	62.93	2.69	0.8	0.56	5.08	57.31	57.25	63.58	48
Average precipitation days (≥ 1.0 mm)	9.17	7.83	10.03	10.88	8.31	0.77	0.28	0.19	1.24	7.54	6.59	7.73	5.88
Average relative humidity %	63.3	58.8	53.24	45.89	33.81	21.16	17.6	18.62	21.32	32.63	46.06	58.44	39.2
Mean monthly sunshine hours	8.15	8.96	11.4	13.53	14.68	15.2	14.95	14.19	12.83	8.99	8.69	8.15	11.6

Orientation and Placement: To optimise solar exposure, position Trombe walls ±15° towards the sunny south.

- During the winter, stay away from areas with a lot of shade from surrounding structures or vegetation.
- Make sure that no interior finishes, furniture, or curtains are blocking the vent locations.

4.3 Empirical study

4.3.1 Climate outlines: Mosul, Iraq

Mosul, Iraq, falls under the 'subtropical steppe climate' category based on the Köppen climate classification, denoted by the symbol 'BSh'. This classification reflects the city's significant seasonal temperature variation. The period from May to September is particularly hot, with July showing average high temperatures between 32.7℃ (90.9°F) and 42.9℃ (109.2°F). Summers are typically hot, dry, and mostly clear, while winters are relatively cool and partly cloudy. Throughout the year, temperatures generally range from 38°F to 109°F, rarely dropping below 31°F or exceeding 114°F. From November to March, average temperatures decrease notably, ranging between approximately 2.2℃ (36°F) and 7.2℃ (45°F), as detailed in Table 3.

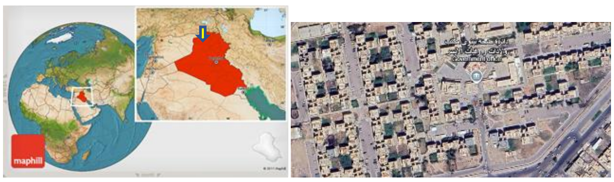


Figure 7. On the right is the location of Mosul City, Iraq, on the left is the case study building location

4.3.2 Field study: Al-Hadba compound, Mosul city

Three stories of public housing units in the Al-Hadba district were selected to examine the performance of natural ventilation in apartments representative of multi-story residential buildings located in hot-dry climates, Figure 7 and Figure 8. Detailed information about the residential complex is provided in Table 4.

4.4 Comprehensive parameter optimization for Trombe walls in hot-arid climates

This investigation performed extensive optimization of parameters through DesignBuilder CFD simulations to identify, in hot arid regions, the best Trombe wall design combinations. The following parameters were systematically altered to see their effects on thermal performance, airflow rates, and energy demand.

Table 4. Architecture properties of Residential complex (Al-Hadba district, Mosul City)

Parameters	Description/Value
Residential complex content	56 blocks of 3-story low-cost apartments
Coordinates	36°24'10.63"N, 43° 9'50.08"E
Selected block in which the field measurements were made	Block No. 42
Orientation of selected case study block	170° (South)
Unit layout	135 m², 3-bedroom unit with store, living room, kitchen and utility space
Type of roofing	Cement mosaic tiles
Shading system	Not available

The primary factor influencing the natural ventilation performance of small Trombe wall systems is the ventilation opening percentage. Simulation results under hot and dry conditions indicate that optimal annual thermal performance is achieved with a 20% ventilation opening and an air cavity width of 40 cm.

Figure 8. View of case study building

4.5 Building simulation

The DesignBuilder V7 GUI integrated with Energy Plus calculation engines to run the simulation [36]. The DesignBuilder was selected for its load profile, large material library, and flexible geometry input. In contrast to separate Energy Plus engines, it also incorporates control procedures to guarantee the accuracy of results. Once the simulations ran their course through Figures 9-12, the Design-Builder program then went ahead to simulate the consumption of heating and cooling of the building for the purpose of assessing performance. The thickness and materials were applied on the Trombe wall so as to enhance energy efficiency as well as comfort for the user. Specifications for the original wall-building materials simulated are given in Table 5.

Table 5. Parameter optimization for Trombe walls in hot-arid climate

Parameter	Range Explored	Optimal Adaptation	Reasoning
Ventilation Opening (%)	2%, 8%, 20%	20%	Reduced heating and cooling demand by 22% and 6%, respectively, through optimised airflow and cooling
Air Gap Width	15 cm – 40 cm	40 cm	Efficiency of natural convection and space utilisation should be balanced
Glazing Type	Single, Double, Low-E	One Clear Glass (τ ≥ 0.75), single	Greater solar gain for winter heating; dust resistance is favoured over delicate coatings
Orientation	South	South	Maximum winter solar gain without overly high summer gains
Control Strategy	Automated, manual, and fixed vents	Manual with input from the occupants	Affordable; favoured for real-world adaptive ventilation situations

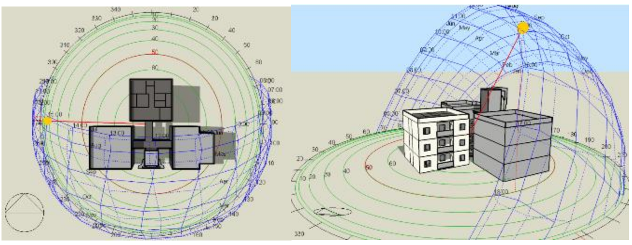


Figure 9. a) Left: Layout, b) Right: Axonometric view of the simulated apartment

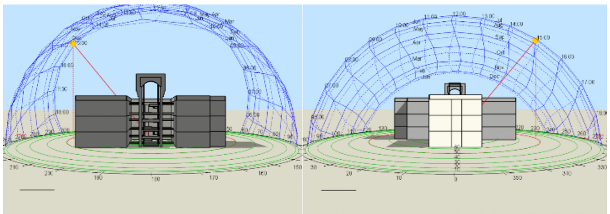


Figure 10. a) Left: Front Elevation, b) Right: Back elevation of the simulated apartment

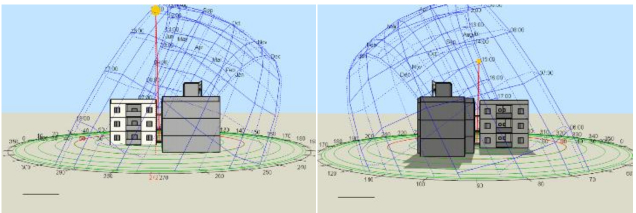


Figure 11. a) Left: Right elevation, b) Right: Left elevation of the simulated apartment

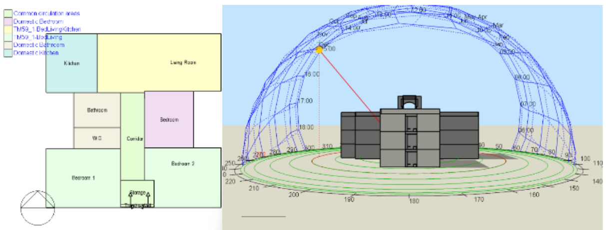


Figure 12. a) Mater plan, b) South façade showing the location of the Trombe wall

4.6 Building materials specifications

Evidence from previous studies suggests that the heat flux performance of a wall can be enhanced by varying material types and thicknesses based on their thermal properties, as shown in Table 6. In this study, selected alternative wall materials with air gaps were evaluated for thermal performance and integrated into the base case model of the "Al-Hadba Residence Project." The model was developed using multiple techniques and material layers, focusing on the modulation of the south-facing opaque wall according to manufacturer specifications in terms of size, thickness, and thermal characteristics.

Table 7 presents the input parameters for the base scenario without the Trombe wall. These initial values were used to simulate and assess the performance of the baseline model before introducing the Trombe wall parameters.

Table 6. Base case's construction layers

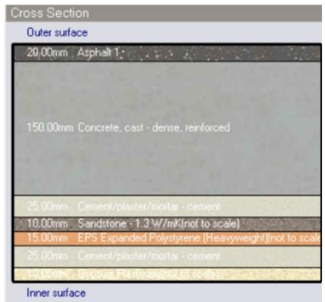
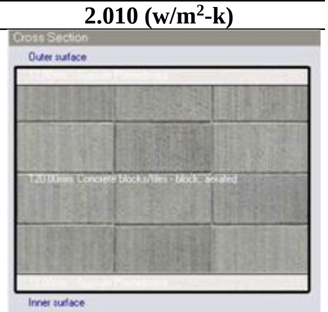
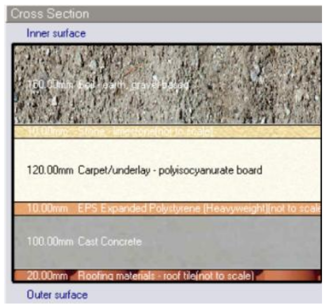
Structural Layer	
• External Wall • Cement/Plaster/Mortar-Plaster-0.12 cm • Concrete block-25.0 cm • Plaster Dense-0.12 cm	
U-Value (w/m²-k)	**1.852 (w/m²-k)**
• Roof Layers • Paving tiles • Concrete, Reinforced-15.0 cm • Cement/Plaster/Morter-25.0 cm • Sand-stone – 1.0 cm • EPS Expanded polystyrene-2.0 cm • Cement/Plaster/Morter-25.0 cm • Gypsum Plasterboard	
U-Value (w/m²-k)	**2.010 (w/m²-k)**
Internal Partitions • Gypsum Plasterboard-1.2 cm • Concrete block/tiles-block, aerated-12.0 cm • Gypsum Plasterboard-1.2 cm	
U-Value (w/m²-k)	**2.281 (w/m²-k)**
Ground Floor Layers • Compacted Soil - 15.0 cm • Stone and gravel - 10.0 cm • Polyethylene sheeting-12.0 cm • Extruded polystyrene (XPS)-10.0 cm • Cast Concrete-10cm • Tiles-2 cm	
U-Value (w/m²-k)	**3.686 (w/m²-k)**

Table 7. Design parameters for input simulated builder for the residential building case study

Simulation Data	**DesignBuilder Inputs**		
	Residential building (Al-Hadba district, Mosul City)		
Building Activity	**Occupancy**	Density	0.117 people/m²
		Clothing	1Clo/Winter-0.5 Clo/Summer
		Metabolic rate	Resident activity
		Occupancy factor	0.5

	Occupancy schedule	8:00 am to 12 pm /5 days per week
	Cooling Setpoint	27°C
External Walls	Ordinary concrete block with Gypsum plaster with the Interior faces	
Glazing	Single Clear glass	
Lighting System	Fluorescents	
HVAC	Split unit & Natural Ventilation	
	Coefficient of performance for heating systems **(COP)**	0.85
	Coefficient of performance for heating systems **(COP)**	1.8
Location	Iraq, Mosul City	
Orientation	South Facade	
Time Steps	The simulation has been conducted throughout the year (2023).	
CFD Simulation Time	15th of July 2023	
DesignBuilder simulation parameters		
Mesh Type	Unstructured mesh This approach allows for greater flexibility in addressing complex geometries, such as small vents, narrow apertures, and the air gap between the Trombe wall and the glazing	
Mesh Refinement Levels	Global Mesh Size (all mesh elements' basic sizes) 0.1 to 0.25 meters for the Trombe wall cavities and indoor air volumes	
Local Refinement Zones	**Near-wall areas (glass and Trombe wall surface):** 0.01 to 0.05 m **Openings**/vents: 0.01 to 0.05 m **Air gap** between the wall and the glazing is a finely tuned mesh that captures flows generated by buoyancy	
Mesh Growth Rate	Typical Value: 1.2 to 1.4	
Boundary Layer Mesh (Wall Treatment)	5–10 layers with a continuing increasing thickness Depending on the turbulence model, the first layer thickness is determined by the Y+ value for natural convection, which ranges from about 20 to 100	
Mesh Quality Control	Minimum Cell Quality: > 0.2 Skewness Limit: < 0.9	

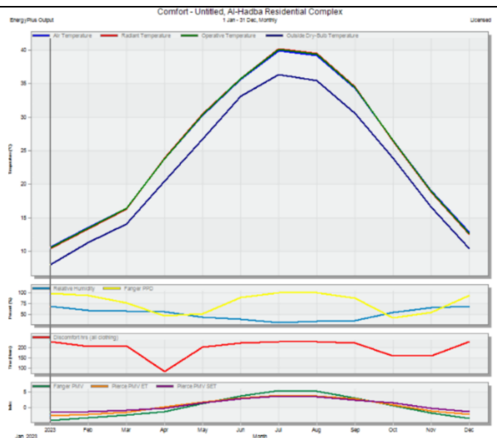
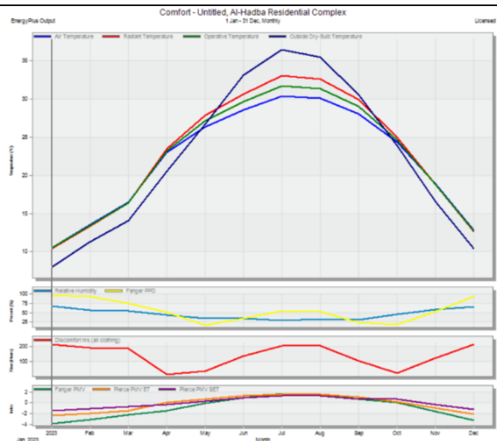
5. RESULTS DISCUSSION

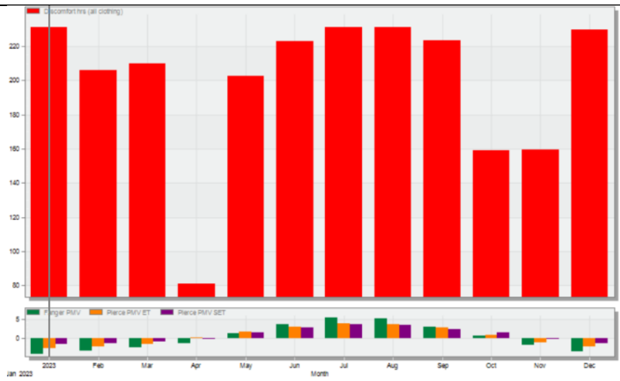
5.1 Thermal comfort results

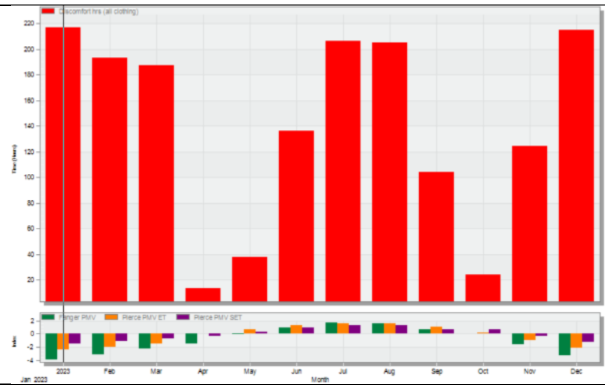
DesignBuilder has a powerful Energy Plus engine to analyze thermal comfort in building design to the fullest. It facilitates the assessment of occupant comfort in various circumstances by simulating different environmental parameters.

As shown in Table 8, thermal comfort outcomes from DesignBuilder simulations include key performance indicators. The first section of Table 7 compares the base case with an alternative configuration that incorporates a Trombe wall, focusing on Highest Air Temperature (AT), Highest Operative Temperature (OT), and Outside Dry-Bulb Temperature (OD-BT). In July, the base case recorded a peak operative temperature of 40.04℃. In contrast, the Trombe wall adaptation reduced this value by more than 9℃. Therefore, during the hottest month of the year, the operative temperature in the modified case reached approximately 31.66 ℃, demonstrating the Trombe wall's effectiveness in mitigating indoor heat buildup.

Table 8. Thermal comfort output for the base case and alternative case with Trombe wall

Output Analysis	
	
Thermal Comfort Parameters / Highest Annual Average (July/August)	
• **Highest Air Temperature (AT)** • **Highest Operative Temperature (OT)** • **Outside Dry-Bulb Temperature (OD-BT)**	
AT: 39.93/39.20°C **OT: 40.04/39.33°C** **OD-BT: 36.37/35.43°C**	**AT: 30.33/30.01°C** **OT: 31.66/31.29°C** **OD-BT: 36.37/35.43°C**

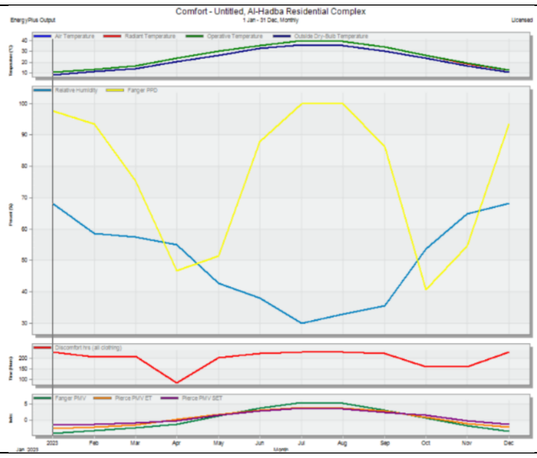


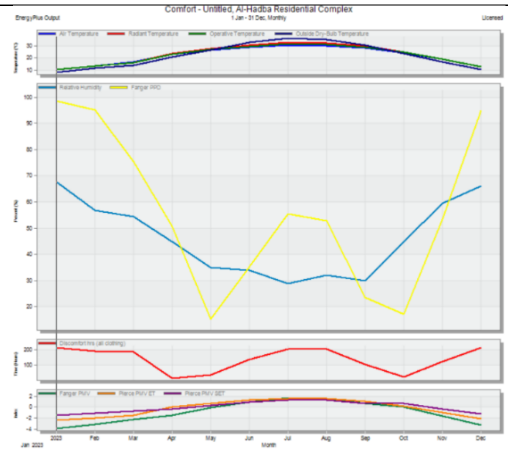


Discomfort hrs - DSH (all clothing) (July/August)

DSH:2387 hrs.

DSH:1664 hrs.

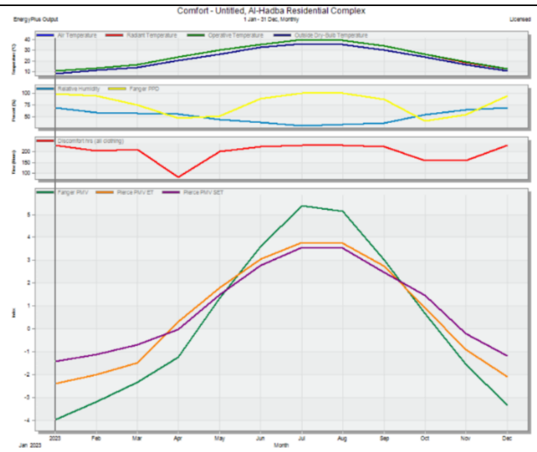


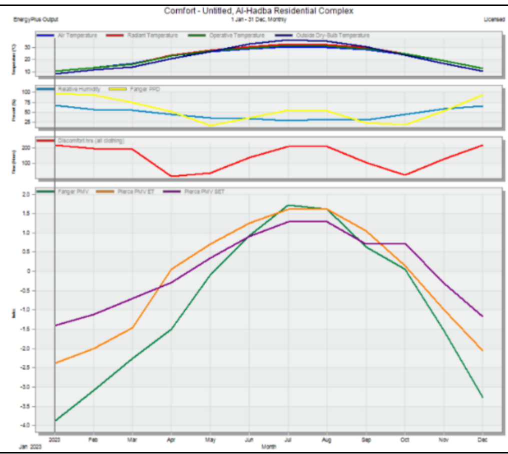


Relative Humidity / Fanger PPD (July/August)

RH: 29.98/32.93%
F.PPD: 99.90/99.900%

RH: 28.82/32.05%
F.PPD: 55.47/52.70%

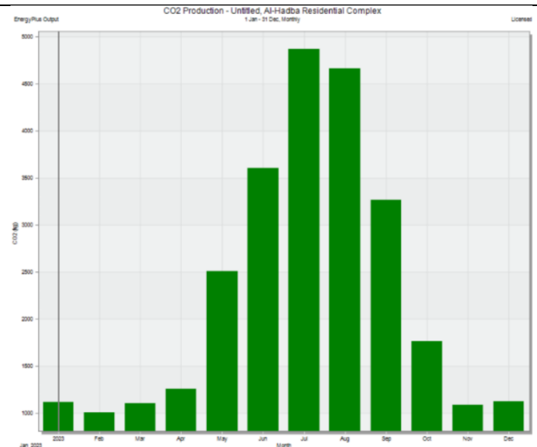


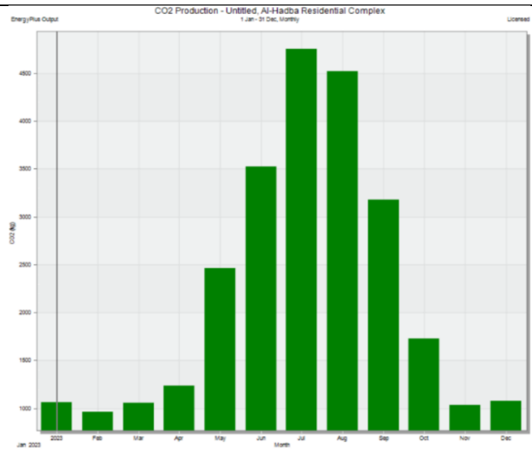


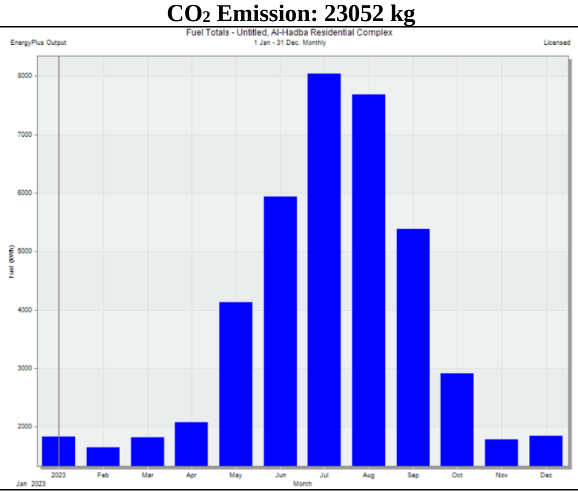
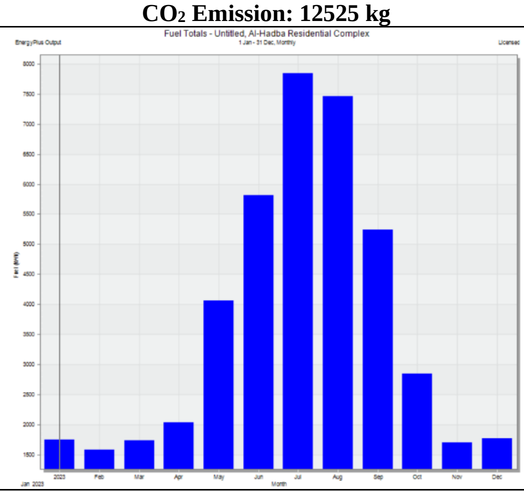
Fanger PMV (July/August)

F.PMV: 5.38/5.12

F.PMV: 1.71/1.60





Annual CO_2 Emission	
CO_2 Emission: 23052 kg	CO_2 Emission: 12525 kg
	
Average of Fuel Totals	
Fuel Total: 45102 kWh	Fuel Total: 38041kWh

The second section of Table 7 presents discomfort hours (all clothing), which refer to the number of hours during which the zone's humidity ratio and operative temperature fall outside the acceptable range defined by ASHRAE 55-2004 for either summer or winter clothing conditions. In the Trombe wall scenario, the total number of discomfort hours was calculated at 1,664, compared to 2,387 hours recorded in the base case. This represents a substantial improvement in indoor thermal comfort with the implementation of the Trombe wall system.

Relative humidity and Fanger Predicted Percentage of Dissatisfied (PPD), which together constitute key thermal comfort parameters, show poor performance in the base case. For July and August, the base case recorded relative humidity levels of 29.98% and 32.93%, respectively, with corresponding PPD values of 99.90% in both months well outside the acceptable comfort range. In contrast, the Trombe wall adaptation achieved improved relative humidity levels of 28.82% and 32.05%, with significantly reduced PPD values of 55.47% and 52.70% for July and August, respectively.

The Fanger Predicted Mean Vote (PMV), calculated according to ISO 7730, further confirms this trend. During the peak summer months, the PMV for the base case reached 5.38 in July and 5.12 in August, indicating extreme thermal discomfort. The Trombe wall configuration, however, reduced these values to 1.71 and 1.60, respectively—closer to the acceptable comfort range.

According to the simulation results from DesignBuilder, CO_2 values are used as indicators of ventilation capacity and indoor air quality (IAQ). CO_2 emissions represent the total mass emissions, calculated based on regional fuel emission factors and overall fuel consumption. In the baseline scenario, annual CO_2 emissions reached 23,053 kg. By contrast, the Trombe wall configuration achieved a reduced emission level of 12,525 kg, resulting in a total reduction of 10,527 kg.

Table 8 presents the variations in the Trombe wall air gap width, ranging from 15 cm to 40 cm, and their corresponding effects on air temperature and velocity. Different ventilation opening ratios 2%, 8%, and 20% of the wall area were applied to the Trombe wall surface. Air movement within the gap is driven by temperature differences between the inner and outer surfaces of the wall, which generate natural convection and influence airflow velocity.

5.2 Effects of various ventilation opening locations

A- Impact of 2% ventilation opening with air gaps (15 cm – 40 cm) in a Trombe wall

Table 8 presents the performance of Trombe wall configurations with a 2% ventilation opening and air gaps ranging from 15 cm to 40 cm. The results indicate that this configuration produces minimal airflow and nearly constant internal temperatures. Under hot and dry climate conditions, such a system proves ineffective for cooling. The low air velocity suggests that heat transfer occurs primarily through conduction within the wall, rather than convection in the air gap. Consequently, the airflow remains limited, and the gradual heat storage and release process fails to provide significant thermal improvement.

B- Impact of 8% ventilation opening with air gaps (15 cm – 40 cm) in a Trombe wall

The 8% ventilation opening provides at least relative ventilation for the air between the Trombe wall area to act upon. The air gap is measured between 15 and 40 cm. The proper application with good natural convection to the system is appropriate for summer ventilation openings that are at least 8 percent (as a percentage of wall area). The effect of the 8% ventilation opening on air temperature and flow was better ventilation and faster heat removal due to larger airflow rates. As shown in Table 9, the wider air gap of 40 cm is the most effective air gap on air velocity. Within the air gap, higher air velocities start from 10 cm to 40 cm, which is due to the 20% ventilation opening that greatly enhances the buoyancy-driven airflow. Slimmer gaps (15-25 cm): The chimney effect is higher but the heat retention efficiency is poor due to high air velocity. Wider gaps however tend to increase the circulation rate of the airflow and hence improve heat distribution within it. The wider air gap also enhanced the heat gain/loss balance and thus more evenly controlled the temperature. The maximum air gap temperature is lower than that of a smaller opening (say 8% opening), but it does not overheat. Improved comfort during the day rapidly evens out solar heat gain with the 20% opening.

Table 9. Comparative performance of Trombe wall configurations

Study	Vents Area (%)	Air Gap Width (cm)	Climate	Cooling Demand Reduction (%)	Thermal Comfort (PMV)	Remarks
Sadineni et al. [15]	10%	20 cm approx	Hot-arid (EnergyPlus)	12%	+0.3 PMV improvement	Focus on thermal loss minimization
Rabani et al. [37]	15%	30 cm	Yazd, Iran	18%	N/A	TRNSYS simulation and field study
This study	20%	20 cm	Hot-arid (DesignBuilder CFD)	22%	+0.7 PMV improvement	Enhanced airflow and passive gain

Table 10. Comparing ventilation openings in a Trombe wall with air gaps (15-40 cm) at 2%, 8%, and 20%

Indoor Temperature Control	2%	8%	20%
Daytime Temperature (℃)	30-35℃	25-32℃	20-28℃
Optimal Air Gap Width	15-25 cm	20-30 cm	30-40 cm
Indoor Air Quality	Lower ventilation	Good air exchange	Best ventilation
	Cold climates	Moderate climates	Hot climates
		AIR Gap 10 cm	
	0.5-1.0 m/s	0.7 - 1.4 m/s	0.9-1.8 m/s
		AIR Gap 20 cm	
Suitable for Air Velocity	0.4-0.9 m/s	0.6 - 1.2 m/s	0.8-1.5 m/s
		AIR Gap 30 cm	
	0.3-0.7 m/s	0.5 - 1.0 m/s	0.7-1.3 m/s
		AIR Gap 40 cm	
	0.2-0.6 m/s	0.4 - 0.9 m/s	0.6-1.1 m/s

C- Impact of 20% ventilation opening with air gaps (15 cm – 40 cm) in a Trombe wall

A 20% ventilation opening has a significant effect on airflow dynamics, thermal efficiency, and indoor comfort in Trombe wall systems (Table 10). The study provides a detailed analysis of these impacts across various air gap widths.

6. RESULTS

Simulation results show that, in hot and dry climates, a 20% vent opening ratio significantly enhances airflow and passive heat gains in narrow Trombe wall systems. Compared to the baseline model, this configuration reduced heating energy demand by 22% and improved thermal comfort by an average of 25%, as measured by the PMV index. In contrast, Sadineni et al. reported that a 10% vent opening in a similar context led to only a 12% reduction in heating demand. This performance gap highlights that vent sizing plays a more critical role than air cavity width in compact Trombe wall systems. Our findings indicate that larger openings promote better natural convection and heat transfer into interior spaces, especially when combined with high-performance glazing and wall materials. This contrasts with Sadineni et al.'s emphasis on minimizing heat loss through smaller vents, suggesting that vent opening percentage has a more pronounced effect on airflow regulation than cavity width in thin Trombe wall designs.

A graphical representation illustrating the relationship between cooling demand reduction and vent opening percentage is presented here. Although the Trombe wall primarily functions as a passive heating system, the data suggest that increasing the vent size, especially to 20%, can contribute to a modest reduction in cooling demand. This is probably because of better airflow and less thermal accumulation. In conclusion, the study findings confirm a positive correlation between air velocity and the increase in vent opening size. Therefore, optimizing vent configuration is essential for improving the cooling performance of Trombe wall systems. These results support and extend previous research, which demonstrated that wider vent openings allow for greater airflow and enhanced cooling efficiency, as illustrated in Figure 13.

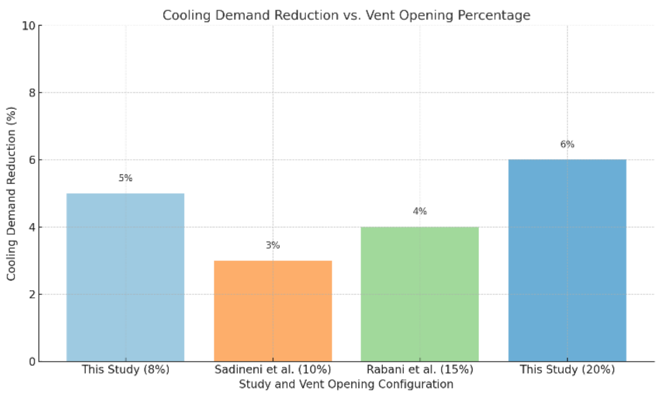


Figure 13. Cooling demand reduction vs. vent opening percentage

7. CONCLUSION

This study focuses on optimizing energy consumption, and thermal comfort in a residential building in Iraq by analyzing various Trombe wall techniques applied to the south-facing façade. Key parameters included building material selection (specifically phase change materials), air gap width, and ventilation opening size, all simulated using DesignBuilder software. A comparative analysis was performed between the baseline model without a Trombe wall and multiple alternative configurations to determine the most efficient design. As shown in Figure 14, all Trombe wall alternatives consumed less energy than the baseline case, which recorded the highest energy consumption at 45,102 kWh. Among the tested configurations, the specific technique demonstrated the best performance, achieving an annual energy consumption of 37,788 kWh.

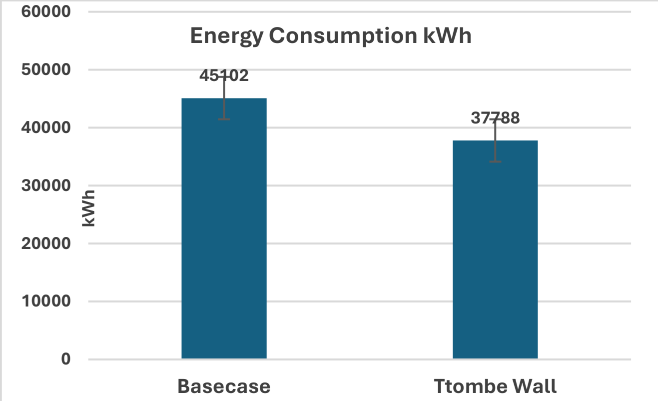


Figure 14. Comparison of energy consumption estimates for the base case and alternative case

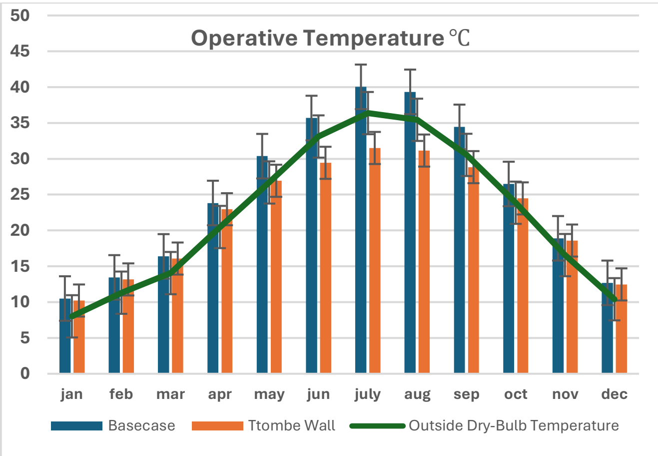


Figure 15. Comparison of operative air temperature (Internal temperature) estimates for base-case and alternative case

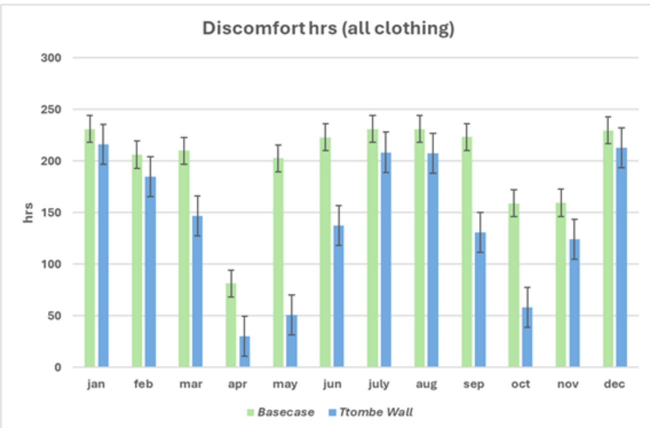


Figure 16. Comparison of discomfort hours for base-case and alternative case

Thermal comfort depends, among other things, on operative air temperature. These values are the operative air temperatures produced by the Trombe wall alternative technique during summer and winter months and are shown in Figure 15. In that case, the operative indoor air temperature was found to reduce by 8°C in June, 7°C in July, and by 8°C during the hottest month of the year, in August. Overall, the internal air temperature for operations improved over the months, supporting users in achieving comfort levels. This will significantly contribute to boosting energy efficiency.

Based on thermal comfort parameters related to discomfort hours, Figure 16 shows that the base case recorded 231, 231, and 223 discomfort hours in June, July, and August, respectively. In comparison, the Trombe wall adaptation reduced these values to 208, 207, and 130 hours for the same months. However, the annual intervention model experienced a total of 1,707 hours of overheating, exceeding the base case by more than 2,387 hours (Figure 17). These results highlight the importance of seasonal adjustment in Trombe wall operation to avoid unintended thermal discomfort.

In summary, the adaptation of the Trombe wall technique resulted in a notable reduction in discomfort hours, indicating an overall improvement in occupants' thermal satisfaction.

Figure 17. Annual discomfort hours for base-case and alternative case

The ventilation opening significantly reduces the reliance on air conditioning by enhancing passive cooling. This feature is particularly suitable for hot climates, as it prevents the buildup of hot air. According to the results, a 20% vent opening provides the highest cooling efficiency, making it an optimal configuration for such environmental conditions.

In narrow Trombe wall systems, the air gap width has a limited effect on airflow performance. Variations in air gap size between 10 cm and 40 cm do not significantly influence airflow due to the relatively small surface area of the wall, particularly when larger ventilation opening ratios (e.g., 8% and 20%) are used. In such configurations, the ventilation opening percentage emerges as the primary factor governing airflow control.

Small Trombe walls are less affected by the air gap limited buoyancy-driven flow:

- There is not enough air in the gap to lead to the development of strong convection currents in a small area of the Trombe wall.
- The gap width (10 cm to 40 cm) has less of an effect because there is not much thermal buoyancy produced by the volume of air.
- The gap width (10 cm to 40 cm) has less of an effect because there is not much thermal buoyancy produced by the volume of air.

Openings for ventilation control the movement of air

- Air velocity is more related to the opening size than the air gap at larger openings (8%-20%).

- The effect of air gap width is dominated by the larger openings which allow for faster exchange of air with the outside environment.

Thermal storage dominates in small systems

- In small Trombe walls, natural convection is of lesser importance than heat storage in the wall material (concrete, brick, or water tubes).
- The effect of air gap width on temperature and velocity is reduced by the gradual release of heat stored.

Analysis of discrepancies between simulation and potential experimental results

Differences in Trombe wall performance between simulation tools (such as DesignBuilder) and laboratory testing may occur due to various factors. Recognizing these discrepancies is essential for evaluating the accuracy of the simulation and identifying its potential limitations. At the same time, such comparisons can reveal areas where actual operating conditions diverge from theoretical predictions, offering valuable insights for improving both modeling approaches and real-world design strategies.

Limitations and future work

Several barriers in an environmental and practical sense may adversely affect the long-term performance of the Trombe wall systems in hot dry areas even though the positive simulation results are.

Future implementations could include safeguards like these to lessen this:

- Dust filters or detachable mesh at vent holes.
- The glazing surfaces could be inclined or self-cleaning with hydrophobic coatings.
- Vent controls that shut off automatically during dust storms.
- Planned maintenance schedules based on data on dust frequency in the area.

8. RECOMMENDATIONS

The study's results suggest that modifications to the Trombe wall system are necessary to improve energy efficiency and enhance occupant comfort in residential units. Further research is required to assess the long-term feasibility, durability, and overall performance of such systems. Based on the findings, the following recommendations are proposed:

- Because of the large area where the Trombe wall will be applied, its air gap width will greatly impact the efficiency of air circulation and heat transfer.
- Large ventilation openings (8%-20%) are better for encouraging airflow, given the large area of exposure.
- Chances are residential building design would contemplate energy efficiency considerations and measures.
- Now, this study deals with the Trombe wall with respect to air gaps and PCM materials only. Glazing size and type can be further studied for their effect on solar heat gain and energy loss.
- Future studies should assess the cost implications and their effects on the feasibility of the overall material life cycle.
- Evaluate carbon footprints and embodied energy of the materials for Trombe walls, that is, PCM, adobe, and concrete.
- Further studies need to be done to test Trombe wall performance in different climates (i.e. temperate and hot, arid).

Additional investigations are needed to explore the performance of the Trombe wall with sustainable or recyclable materials to enhance life cycle efficiency.

- It will be required to investigate the area for their performance in the dynamic control of heat gains by dynamic glazing and motorized louvers.

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