buildings

MDPI

Article

Passive Ventilation of Residential Buildings Using the Trombe Wall

Khrystyna Myroniuk [1,2,3,*], Yurii Furdas [2], Vasyl Zhelykh [4], Mariusz Adamski [5], Olena Gumen [6], Valerii Savin [7] and Stergios-Aristoteles Mitoulis [1,3]

1 Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK; s.a.mitoulis@bham.ac.uk
2 Department of Heat and Gas Supply and Ventilation, Lviv Polyechnic National University, 79013 Lviv, Ukraine; yurii.v.furdas@lpnu.ua
3 MetaInfrastructure.org, London NW11 7HQ, UK
4 Department of Construction Organization and Technology, Czestochowa University of Technology, 42-201 Czestochowa, Poland; vasyl.zhelykh@pcz.pl
5 Department of HVAC Engineering, Bialystok University of Technology, 15-351 Bialystok, Poland; mariusz.adamski@pb.edu.pl
6 Department of Descriptive Geometry, Igor Sikorsky Kyiv Polytechnic Institute, National Technical University of Ukraine, 03056 Kyiv, Ukraine; gumens@ukr.net
7 Department of Heat and Gas Supply, Kryvyi Rih National University, 50027 Kryvyi Rih, Ukraine; savinvv@knu.edu.ua
* Correspondence: k.myroniuk@bham.ac.uk or khrystyna.v.myroniuk@lpnu.ua

Abstract: The article explores passive systems for regulating microclimates in residential settings, with a focus on modular constructions. It investigates the use of the trombe wall system for passive ventilation to ensure comfort and hygiene. The study examines building designs that enable effective air circulation without using mechanical systems. Furthermore, the effectiveness of the passive system of using solar energy with the trombe wall as a ventilation device in modular houses has been experimentally confirmed. Although the research confirms the effectiveness of this solar system in modular homes, there is limited documentation regarding its overall efficiency, particularly concerning the impact of the surface pressure coefficient on ventilation. The study establishes the correlations governing the thermosiphon collector's effectiveness at varying air layer thicknesses. Optimal parameters, such as maximum air consumption (L = 120 m^3h^{-1}), are identified at an air layer thickness (δ) of 100 mm and outlet openings area (F) of 0.056 m^2. These findings pave the way for improving passive systems aimed at maintaining optimal thermal and air conditions in modern homes. The findings suggest the potential for more efficient and sustainable housing solutions. Further research is essential to understand how factors like building design and wind speed affect ventilation system efficacy.

Keywords: passive ventilation; trombe wall; solar screen; modular houses; ventilation mode

check for updates

Citation: Myroniuk, K.; Furdas, Y.; Zhelykh, V.; Adamski, M.; Gumen, O.; Savin, V.; Mitoulis, S.-A. Passive Ventilation of Residential Buildings Using the Trombe Wall. *Buildings* **2024**, *14*, 3154. https://doi.org/10.3390/buildings14103154

Academic Editor: Kai Zhang

Received: 31 August 2024
Revised: 29 September 2024
Accepted: 30 September 2024
Published: 3 October 2024

1. Introduction

The environmental crisis and energy instability necessitate a comprehensive reassessment of current methodologies related to both the construction of new buildings and the operation of existing structures. Emerging trends in construction emphasize energy efficiency and environmental sustainability, propelling the rapid advancement of technologies aimed at enhancing the comfort and energy performance of living spaces.

One of the key technologies in residential buildings is natural ventilation, which is not recognized as entirely controlled but is recognized as an energy-efficient and environmentally friendly method of ensuring air exchange in rooms with the possibility of using renewable energy sources [1,2].

Several compelling factors underscore the need for in-depth exploration and the integration of natural ventilation technologies in residential buildings. The continual escalation of energy prices and the necessity to reduce environmental impact demand the identification of more effective and sustainable solutions while upholding indoor microclimate parameters. Natural ventilation, relying on convective air movement processes, emerges as a balanced and cost-effective response to this challenge, offering a means to establish a healthy and comfortable environment for building occupants.

Two primary categories of natural ventilation, both gravity-based (hinging on temperature differentials as shown in Figure 1) and wind-induced, play pivotal roles. To ensure effective natural ventilation, specialized devices such as window facades, wall grilles, and roof ventilators are employed. Each type presents distinct advantages and drawbacks, necessitating careful consideration during the design and construction phases.

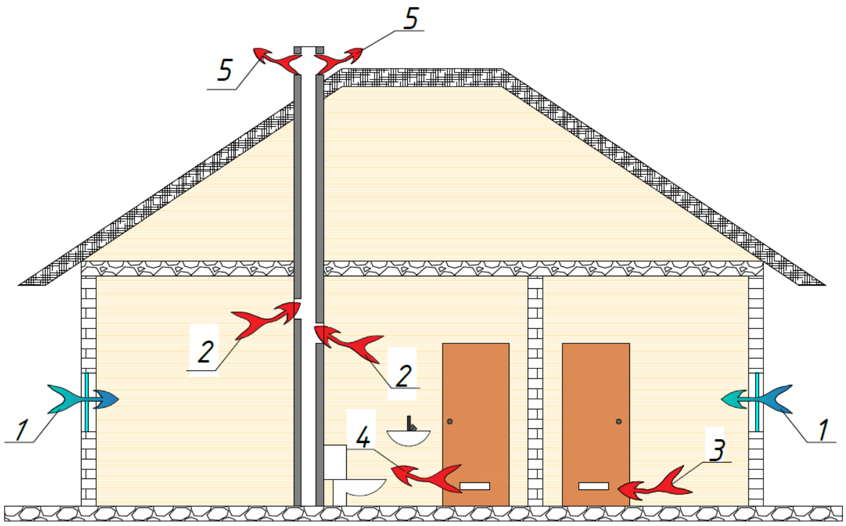

Figure 1. Principle of gravity ventilation. (Cold outdoor air enters the house through leaks or ventilation grills, while warm indoor air is removed through vertical ventilation ducts). Illustration by the authors. 1—inflow of external air; 2—exhaust air from the room; 3—transit exhaust air; 4—transit incoming air; 5—exhaust air.

A significant advantage of natural ventilation systems lies in their positive impact on the energy efficiency of buildings. In contrast to conventional mechanical systems, natural ventilation can significantly reduce electricity expenses and promote sustainable resource consumption.

Therefore, the imperative investigation of innovative technologies related to natural ventilation becomes a key focus for the scientific community. Particular emphasis is directed toward the exploration of passive ventilation systems utilizing renewable energy sources, notable for their potential integration with other engineering systems [3–8]. An example of a such system can be a passive ventilation system with a soil heat exchanger and heat recuperators (Figure 2). Such systems are effective and can be utilized year-round; however, there is a risk of condensation occurring within the ground heat exchanger, which may promote mold growth and bacterial proliferation. Therefore, manufacturers implement innovative materials to protect the internal linings of the piping in the ground collector.

An innovative technical solution involves the utilization of the trombe wall system as a combined piece of heating and ventilation equipment. The utilization of solar energy to facilitate a natural convective airflow represents an effective passive ventilation method for the premises [9–14], offering the potential for reducing electricity consumption even in instances where mechanical fans are employed [15,16]. The study of a photovoltaic (PV) Trombe wall is also of significant interest [17]. Furthermore, the incorporation of contemporary heat exchange mechanisms within trombe walls, employing phase transition materials, presents novel avenues for energy conservation in cooling spaces during warmer seasons [18–21]. Phase change materials exhibit unique properties, undergoing phase transitions in response to temperature fluctuations, thereby absorbing or releasing significant amounts of heat during the thermal exchange process. This characteristic makes them suitable for integration into systems that operate effectively both during the day and at night [19,22,23]. Certain scientific studies focus on enhancing the efficiency of passive ventilation systems through the integration of trombe wall technology [24–26], facilitating its application in social and temporary housing [27].

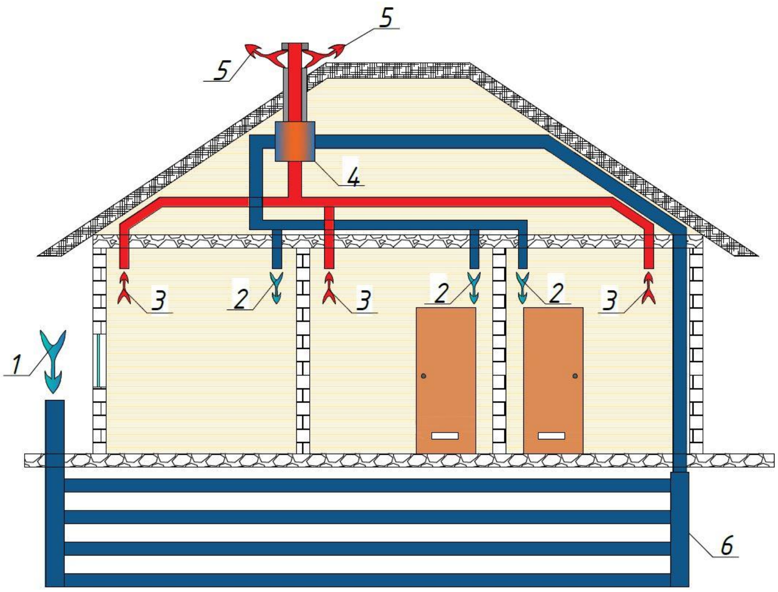

Figure 2. Passive ventilation system with soil heat exchanger and heat recuperators. Illustration by the authors. 1—outside air intake; 2—incoming air into the room; 3—exhaust air from the room; 4—recuperator; 5—exhaust air; 6—soil collector.

During the colder months, trombe walls serve as an effective means of supplying heat to indoor spaces by utilizing the heated ventilation air that passes through the structure, thereby facilitating passive heating within the building (Figure 3). Numerous studies are dedicated to improving the efficiency of such systems by incorporating specialized devices into the air ducts to enhance heat exchange between the heated wall surface and the airflow [28–31]. This strategy proves particularly effective in conjunction with electric heating systems, resulting in substantial reductions in electrical energy consumption [32].

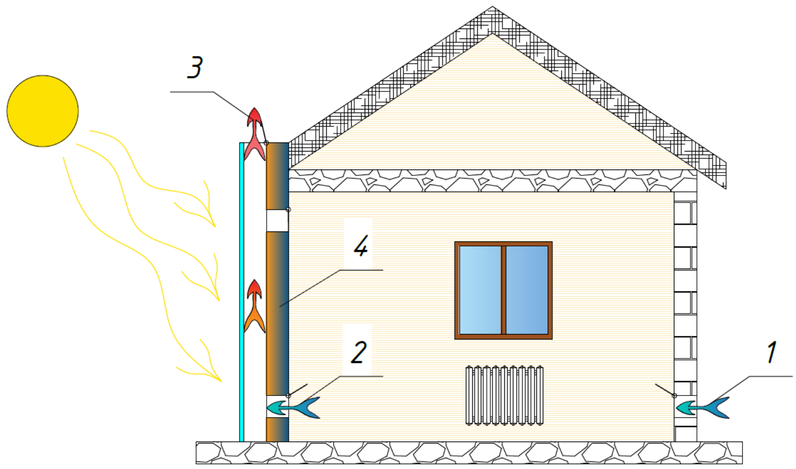

Figure 3. Application of the trombe wall in passive ventilation systems. Illustration by the authors. 1—incoming external air; 2—exhaust air from the room; 3—exhaust air from the channel; 4—accumulative wall.

In the contemporary landscape, marked by advanced technological development in passive ventilation systems, conducting scientific research on their energy efficiency and indoor comfort is increasingly challenging. Consequently, computer modeling has emerged as a key tool, enabling virtual investigations, optimizing ventilation system designs, and improving operational performance. Computer and mathematical modeling allow for the prediction of system efficiency, supporting the development of environmentally sustainable and energy-efficient architectural solutions [11,12,33–37]. Experimental studies are commonly employed to validate theoretical concepts, providing insight into the actual efficiency of passive ventilation systems. Models facilitate extensive variational analyses and optimizations without the necessity for the physical implementation of each design [38–40].

To test theoretical concepts, experimental studies are widely used, which allows the determination of the real efficiency of passive ventilation systems [16,41,42].

The implementation of a comprehensive parametric experiment serves to validate the effectiveness of the chosen technical approach, contributing to the achievement of the desired outcomes in the operation of ventilation systems [43–46]. This methodology has proven particularly advantageous for assessing the impact of wind on passive ventilation systems and determining the optimal placement of intake and exhaust openings in ventilation structures [36,47]. Moreover, it is essential to consider the impact of indoor air currents on the efficiency of these systems [48,49]. Experimental research often employs systematic experimental design, enabling multiple variation analyses and optimization without the need for the physical implementation of each project.

Such research methodologies facilitate the acquisition of more accurate and reliable data, contributing to the development of effective passive ventilation systems. Hence, the authors of this article employed diverse approaches to assess the effectiveness of the trombe wall as a passive ventilation device in an energy-efficient modular residential building.

The study aims to evaluate the effectiveness of utilizing the trombe wall system as a ventilation mechanism within a modular residential building. Through analytical and experimental research, the investigators aim to determine the operational characteristics of the trombe wall when integrated into the building's external envelope. Furthermore, it seeks to assess the trombe wall's potential as a passive ventilation device, aiming to facilitate air exchange within the interior space and reduce reliance on primary climate control equipment. The research objectives include a comprehensive analysis of airflow structures concerning inlet and outlet dimensions and the thickness of the air channel, as well as a thorough evaluation of the system's performance in ventilation mode. Ultimately, the study aims to establish the optimal dimensions of ventilation openings based on the findings of these investigations.

2. Materials and Methods

Based on the authors' preliminary analysis of the available scientific literature, it becomes evident that the use of alternative energy sources as potential energy carriers entails significant costs, even for small-scale heat-generating equipment installations. Consequently, this study proposes a system for the passive utilization of solar energy, specifically through the integration of a trombe wall as a ventilation tool within the hybrid external enclosure of modular housing. The primary objective is to facilitate the necessary air exchange within the module's interior. An illustration of a room section featuring the hybrid external enclosure is provided in Figure 4.

An experimental setup was developed to assess the effectiveness of the proposed technical solution, constructed entirely using the same materials employed in the external enclosure of the modular residential unit (Figure 5).

Thermophysical characteristics of the trombe wall:

1. The proposed design is entirely opaque, lacking any transparency;
2. The thermal resistance of the trombe wall construction is 9.25 $m^2\ KW^{-1}$;
3. The absorptive capacity of the absorber plate is 0.91;
4. Heat loss through the trombe wall is 5 Wm^{-2}.

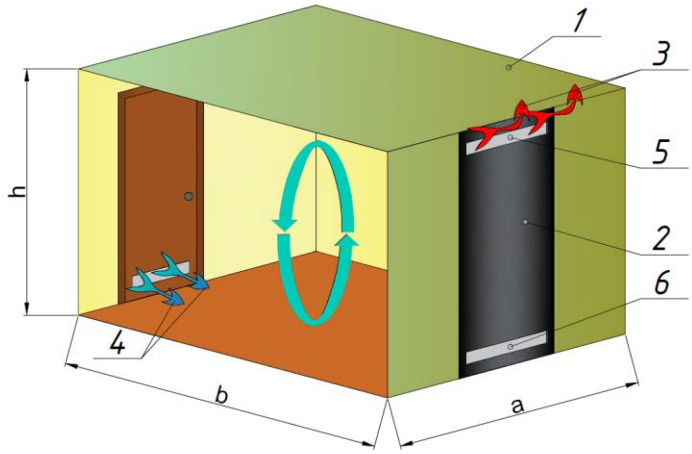

Figure 4. Premises of a modular house with a trombe wall integrated into a hybrid external protection. Illustration by the authors. a—module width 2140 mm, b—module length 2500 mm, h—module height 2600 mm, 1—external protection, 2—trombe wall, 3—exhaust air from the channel, 4—supply air, 5—open control valves; 6—closed regulating valves.

Figure 5. Photo of the experimental installation. Illustration by the authors. 1—external protection, 2—trombe shaft, 3—closed regulating valves, 4—own control valves, 5—infrared getter.

During operation, infrared rays effectively heat the black metal plate positioned on the external surface of the hybrid outer enclosure. This results in the transfer of heat from the heated plate to the air entering the air layer through the lower ventilation opening, initiating the phenomenon of free convection, specifically the "thermosiphon effect". As the air temperature increases, it rises due to a decrease in density and is subsequently expelled outdoors through the upper exhaust ventilation opening. The velocity and volume of air passing through the trombe wall duct are meticulously regulated using control dampers located at the lower intake and upper exhaust openings, in conjunction with the thickness of the duct. Figure 6 illustrates the schematic of the experimental setup operating in ventilation mode.

Table 1 presents the measurement instruments and their specifications used for investigating the characteristics of the trombe wall system. The measured parameters included thermal radiation intensity, air temperature, surface temperature, and air velocity. The intensity of thermal radiation was measured using a pyranometer M-80M, with an absolute error of ±20 Wm^{-2} and a relative error ranging from 0.2% to 0.37%. Air temperature in the measurement zone was determined by the ATT-1004 thermomanometer (LLC "ZAVOD UKRMASHPROM", Kyiv, Ukraine), with an absolute error of ±1.3 °C and a relative error between 0.18% and 1.7%. The surface temperature was measured using the Nimbus-530/1 pyrometer, with an absolute error of ±0.08 °C and a relative error from 0.14% to 0.78%. The air velocity was also measured by the ATT-1004, with an absolute error of ±0.005 m/s and a relative error between 0.6% and

1.25%. From the table, it is evident that the accuracy of the measurements varies depending on the parameter, with the highest relative error observed in air velocity measurements and the lowest in thermal radiation measurements. This variability was considered during data analysis to ensure accurate results.

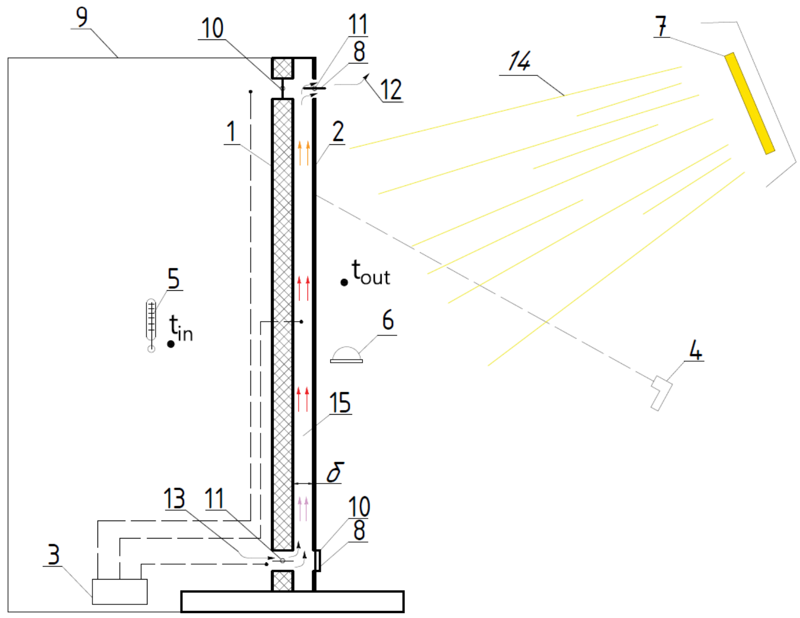

Figure 6. Scheme of the experimental installation for operation in the ventilation mode. Illustration by the authors. t_{in} and t_{out}—the air temperature in the experimental module and outside it, respectively, δ is the width of the air channel. 1—heat-insulating layer; 2—black metal plate; 3—thermal anemometer; 4—pyrometer; 5—thermometer; 6—albedometer; 7—infrared heater; 8—regulating valves; 9—outline of the room; 10—closed flaps; 11—open flaps; 12—exhaust air from the channel; 13—exhaust air from the room; 14—infrared rays, 15—air channel.

For the constant value of the mean error, the allowable measurement error was considered as follows:

$$\Delta np = 3\ s \quad (1)$$

If the error exceeded Δnp, which was calculated Δnp = 0.17, the measurement error was excluded from the calculations and the experiment was repeated. The cumulative error of all measurement systems amounted to 2.1%.

The research was carried out using an experimental setup designed to simulate the living environment of a modular house with a floor area of 5.4 m^2 and a volume of 14 m^3. The experimental studies focused on evaluating the efficiency of the trombe wall as a ventilation device for indoor spaces. The research methodology was structured as follows:

1. The appropriate thickness of the air layer in the trombe wall (15) δ_{min}, through which air movement occurred due to the phenomenon of natural convection, was set. The thickness was adjusted in increments of 30 mm, starting from the minimum value of δ_{min} = 40 mm to the maximum value of δ_{max} = 100 mm;
2. The ventilation openings (11) were left open to allow air to pass through. At the beginning of the experiment, the area of the openings was set to F = 0.012 m^2. Air from the internal volume of the module entered the air gap (15) through the lower ventilation opening and exited through the upper ventilation opening. Subsequently, the area of the ventilation openings was adjusted, ranging from F_{min} = 0.012 m^2 to F_{max} = 0.08 m^2;
3. The infrared heater (7) simulated solar thermal radiation, with a constant power output of 6000 W. The experiments were conducted under steady-state conditions, with the intensity of radiation on the external surface of the trombe wall (2) set to

I = 400 Wm^{-2}. The temperature of the black metal plate surface was measured using a pyrometer (4). Under steady-state conditions, the temperature remained constant at τ = 55 °C;

4. Since the research was conducted under steady-state conditions, in addition to the constant thermal radiation from the infrared heaters, the air temperatures in the experimental module (t_{in} = 20 °C) and outside of it (t_{out} = 16 °C) remained unchanged. The average surface temperature of the irradiated dark metal surface of the trombe wall was also stable at τ = 55 °C. Air temperature measurements were taken using a thermo-anemometer (3) ATT Thermoanemometer-1004, while surface temperatures were recorded with a pyrometer (4) Nimbus-530/1 (Table 1). The experiment was conducted once these physical parameters reached stability.
5. The velocity of the convective air flow within the air layer (15) and through the ventilation openings (11) was measured using a thermo-anemometer (3) ATT Thermoanemometer-1004;
6. Based on the obtained data on air velocities, the areas of the ventilation openings, and the air channel area of the trombe wall, the ventilation air flow rates were calculated. The measured air flow values at the velocity measurement points were consistent. This allowed the determination of the amount of exhausted air, L. Measurements were taken at 10-min intervals over the course of 8 h;
7. Subsequently, the thickness of the air layer (δ) was varied, and for different values of the ventilation opening area (F), the experiment was repeated.

Table 1. Measuring systems.

The Name of the Measured Element	Foto	Absolute Error	Relative Measurement Error	
			Minimum, %	Maximum, %
The intensity of thermal radiation (Piranometer M-80M)		±20 Wm^{-2}	0.2	0.37
Air temperature in the installation zone (ATT thermonemameter-1004)		±1.3 °C	0.18	1.7
Surface temperature (Nimbus530/1 pirometer)		±0.08 °C	0.14	0.78
Air mobility (ATT thermonemameter-1004)		±0.005 m s^{-1}	0.6	1.25

3. Results

An empirical investigation was undertaken to assess the performance of the trombe wall, employing a carefully designed experimental framework that incorporated considerations of factors such as the thickness of the air layer and the dimensions of the inlet and outlet apertures.

3.1. Experiment Planning

Planning the experiment was one of the key stages of the research, enabling a systematic approach to studying the influence of various factors on the research object. The experimental protocol clearly defined the variables, including the air layer's thickness, the ventilation openings' area, and their variations. A certain number of experimental experiments made it possible to reduce the time and costs of conducting large volumes of non-systematic research. Furthermore, the assessment of homogeneity of variance using the Cochran criterion, along with the calculation of critical values, confirmed that the experimental results were both statistically significant and reliable.

The experimental protocol involved the systematic examination of the volume of air extracted by the collector, with specific attention given to the variables of the air layer thickness (δ, mm) and the area of the inlet and outlet openings (F, m^2). The research encompassed variations in the air layer thickness within the range of 40 to 100 mm.

To facilitate the analysis of the measured values, a set of relevant factors is presented in Table 2.

Table 2. Planning factors and levels.

The Name of the Factor	Code Designation	Levels of Factors		Variation Interval
		Lower −1	Upper +1	
thickness of the air layer δ, mm	x_1	40	100	0.3
area of ventilation holes F, m^2	x_2	0.012	0.08	0.014

To assess the individual influence of each parameter, an experimental plan-matrix was formulated in accordance with the guidelines provided by Adler, Kalosh, and Barabaschuk. The initial values for each factor were designated as −1 for the minimum and +1 for the maximum (refer to Table 2). The requisite number of experimental trials was determined using the following formula:

$$N = p^k \quad (2)$$

where the number of levels of factors of the experiment is p = 2 and the number of factors k = 2.

Therefore, the number of experiments was equal $N = 2^2 = 4$. To assess the influence of the specified factors, a full factorial experiment was executed, comprising four distinct experiments. The plan-matrix for the two-factor experiment is presented below (refer to Table 3).

Table 3. Plan-matrix of a complete factorial experiment 2^k by k = 2.

No. of Experiments	Determining Factors		Feedback Function
	x_1 (δ)	x_2 (F)	
1	**2**	**3**	**4**
1	+1	+1	y
2	−1	+1	y
3	+1	−1	y
4	−1	−1	y

The response function is represented by the quantity of air extracted by the collector, denoted as L, measured in cubic meters per hour (m^3h^{-1}). For each experiment, the air quantity was computed as the arithmetic mean of the summation of localized values:

$$L = \frac{1}{K}\sum_{l=1}^{K} L_l, \mathrm{m^3h^{-1}} \tag{3}$$

where K denotes the number of specific local values of the air quantity (L) and l signifies the ordinal number assigned to each respective local air quantity value.

The outcomes of the factorial experiment for the process were encapsulated by a mathematical model of polynomial structure.

$$y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 \tag{4}$$

The planning matrix, research results, and their processing are given in the Table 4.

$$\sum_{i=1}^{N} \underline{y_i} = 159.3;\ \sum_{\mathrm{i}=1}^{N} S_{\mathrm{i}}^2 = 39.16$$

Table 4. Planning matrix and calculation results of an experimental study.

#	Plan				State Variable			$\underline{\mathbf{y_i}}$	s_{i}^2
	x_0	x_1	x_2	x_1x_2	y_1	y_2	y_3		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	+	+	+	+	49.1	42.7	43.2	45.0	12.670
2	+	−	+	−	42.4	37.5	41.2	40.4	6.523
3	+	+	−	−	39.3	34.0	40.3	37.9	11.463
4	+	−	−	+	37.6	32.6	37.7	36.0	8.503

The coefficients of the regression equation were determined by Formula (5), as follows:

$$b_j = \frac{1}{N}\sum_{i=1}^{N} x_{ji}\underline{y_i}, \quad j = 0.1, \ldots, k. \tag{5}$$

where j—factor number; x_{ji}—coded value of the factor in the experiment; $\underline{y_i}$—the average value of the state variable for n parallel experiments of the i-th line.

$b_0 = 39.80$; $b_1 = 1.63$; $b_2 = 2.88$; $b_{12} = 0.68$.

To assess the homogeneity of variance through the Cochran criterion, the calculation involved determining the ratio of the maximum variance to the sum of all variances, as per the following formula:

Gp = 12.67/39.16 = 0.325.

Based on the degrees of freedom, where $f_1 = n - 1 = 3 - 1 = 2$ and $f_2 = N = 4$, as well as the level of significance q = 0.05 critical ratio $G_{(1-P)} = 0.7679$, which exceeded the calculated Gp = 0.380, that is, the calculated variance is homogeneous.

According to the results of the regression analysis, the approximating polynomial took the form

$$y = 39.8 + 1.63x_1 + 2.88x_2 + 0.68x_1x_2 \tag{6}$$

In the equation, y is an optimization parameter that characterizes the amount of air extracted from the trombe wall and x_1 and x_2 are coded values of the factors, which are transformed into their natural values according to the formula.

A detailed examination of the regression coefficients reveals that the factor with the most significant influence on the response function (x_2, representing the area of ventilation holes F, m^2) surpasses the impact of the factor x_1 (indicating the thickness of the layer in trombe walls, denoted as δ, mm).

3.2. The Results of the Study on Air Flow Velocity

The study conducted experimental research on the impact of the air layer thickness in a trombe wall, which ranged from 40 mm to 100 mm, as well as the height and width of the ventilation openings, on air flow velocity within the ventilation channel of a modular house system. This enabled the assessment of air exchange efficiency and the determination of optimal parameters for ensuring proper ventilation. By applying the continuity equation and the air exchange rate formula, the air flow rates and air exchange rates in the module were established based on the system's parameters.

Tables 5–7 present the research results for air layer thicknesses of 40 mm, 70 mm, and 100 mm, respectively.

Table 5. The thickness of the air layer, $\delta = 40$, mm.

Location of Flaps	Flap Height, h, mm	Flap Width, b, mm	Air Velocity in the Flap ν, m s^{-1}
Upper open flap	15	800	0.5
Bottom open flap	15	800	0.5
Upper open flap	35	800	0.6
Bottom open flap	35	800	0.6
Upper open flap	50	800	0.6
Bottom open flap	50	800	0.6
Upper open flap	70	800	0.5
Bottom open flap	70	800	0.5
Upper open flap	85	800	0.4
Bottom open flap	85	800	0.4
Upper open flap	100	800	0.3
Bottom open flap	100	800	0.3

Table 6. The thickness of the air layer, $\delta = 70$, mm.

Location of Flaps	Flap Height, h, mm	Flap Width, b, mm	Air Velocity in the Flap ν, m s^{-1}
Upper open flap	15	800	0.6
Bottom open flap	15	800	0.6
Upper open flap	35	800	0.6
Bottom open flap	35	800	0.6
Upper open flap	50	800	0.6
Bottom open flap	50	800	0.6
Upper open flap	70	800	0.5
Bottom open flap	70	800	0.5
Upper open flap	85	800	0.3
Bottom open flap	85	800	0.3
Upper open flap	100	800	0.2
Bottom open flap	100	800	0.2

Table 7. The thickness of the air layer, $\delta = 100$, mm.

Location of Flaps	Flap Height, h, mm	Flap Width, b, mm	Air Velocity in the Flap ν, m s^{-1}
Upper open flap	15	800	0.6
Bottom open flap	15	800	0.6
Upper open flap	35	800	0.6
Bottom open flap	35	800	0.6
Upper open flap	50	800	0.6
Bottom open flap	50	800	0.6
Upper open flap	70	800	0.6
Bottom open flap	70	800	0.6
Upper open flap	85	800	0.45
Bottom open flap	85	800	0.45
Upper open flap	100	800	0.3
Bottom open flap	100	800	0.3

The continuity equation was used to determine the exhaust air flow at the exit from the trombe wall, as follows:

$$L = v \times F \times 3600, \mathrm{m^3h^{-1}} \tag{7}$$

where v—speed measured during the experiment m/s; F—area of ventilation holes, m^2.

The air exchange rate determines how many times per hour the entire volume of air in the room is completely replaced with fresh air. The formula is as follows:

$$k = L/V \tag{8}$$

Air flow (L): Denotes the quantity of air supplied or extracted from the room within a specified timeframe, measured in cubic meters per hour (m^3h^{-1}).

Volume of the room (V): Represents the total air volume within the room, measured in cubic meters (m^3).

4. Discussion

Based on the results of these investigations, graphical representations were developed to illustrate the relationship between the ventilation air flow rate, the sizes of the ventilation openings, and the thickness of the air layer.

4.1. Determination of Air Exchange Efficiency in the Operation of a Trombe Wall

This stage of the experimental research involved testing the efficiency of the trombe wall design, operating in ventilation mode for modular homes. The optimal air layer thickness and ventilation opening area were determined to achieve maximum air exchange with minimal energy consumption, as the study focuses on a passive ventilation system. Additionally, the correlation between the air layer thickness, ventilation opening area, and air flow rate was examined to understand how changes in one parameter affect the others, and how this can be leveraged to enhance the overall efficiency of the ventilation system.

Figure 7 illustrates the airflow through the trombe wall under ventilation mode.

From Figure 7, it can be seen that the maximum air consumption is fixed at the mark L = 120 m^3h^{-1} with the thickness of the air channel δ = 100 mm and the area of the outlet openings F = 0.056 m^2.

Table 8 presents the ventilation characteristics of the examined trombe wall system, detailing the thickness of the air layer (40, 70, and 100 mm), the area of the ventilation openings (0.012–0.08 m^2), air consumption rates (21–120 m^3h^{-1}), and the air exchange rates

(1.5–8.6 times/h). The findings indicate that the highest air consumption (120 m^3h^{-1}) and the maximum air exchange rate (8.6 times/h) are attained with an air layer thickness of 100 mm and a ventilation hole area of 0.056 m^2. Conversely, reducing either the thickness of the air layer or the area of the ventilation openings diminishes the efficiency of air exchange, underscoring the importance of a carefully balanced selection of these parameters to achieve effective ventilation.

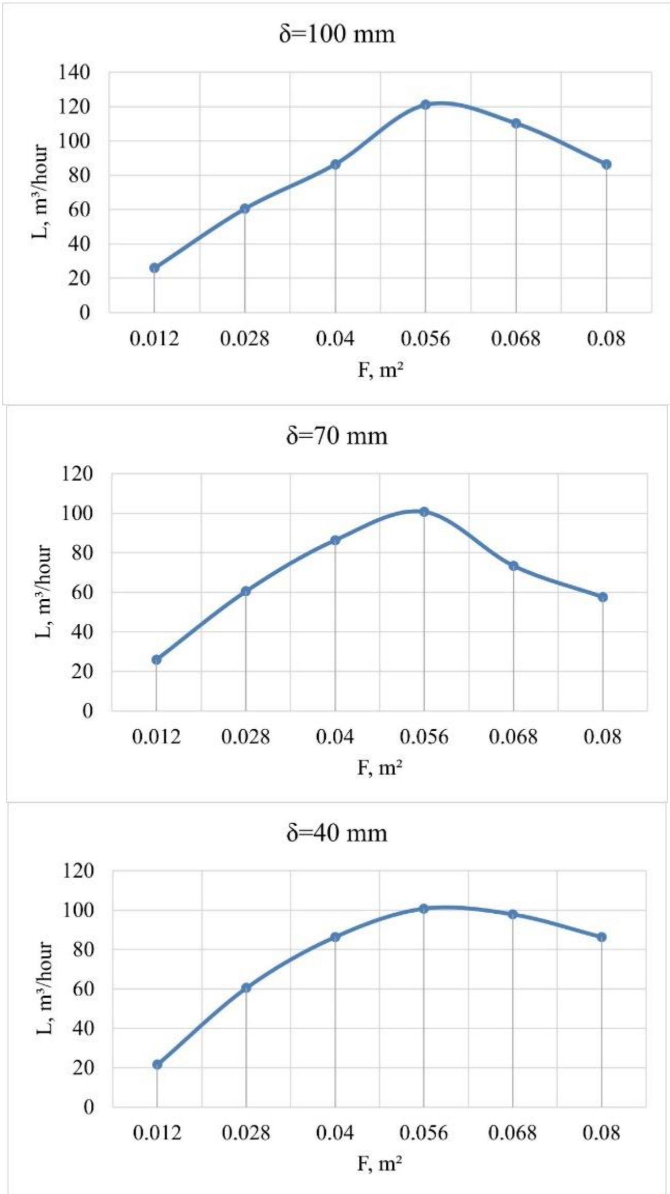

Figure 7. Graphical representations delineating the correlation between air flow (L) and the dimensions of the inlet and outlet ventilation holes-areas (F), along with the thickness of the air channel (δ).

According to the provisions of DBN V.2.5-67-2013, the normative air exchange rate for residential spaces must not be less than 0.6 air changes per hour (h^{-1}). Experimental results indicate that the proposed design of the trombe wall, operating in ventilation mode, effectively facilitates the necessary air exchange within the modular house. Depending on the dimensions of the ventilation openings and the thickness of the air layer, the air exchange rate for a module with a volume of 14 m^3 can vary significantly, ranging from 1.5 air changes per hour (h^{-1}) to 7.1 air changes per hour (h^{-1}).

Table 8. Ventilation characteristics of the examined trombe wall.

The Thickness of the Air Layer, δ	Area of Ventilation Holes, F, m^2	Air Consumption, L, m^3h^{-1}	Multiplicity of Air Exchange, k, h^{-1}
100	0.012	22	1.6
100	0.28	60	4.3
100	0.04	82	5.6
100	0.056	120	8.6
100	0.068	110	7.9
100	0.08	86	6.1
70	0.012	22	1.6
70	0.28	60	4.3
70	0.04	82	5.9
70	0.056	100	7.1
70	0.068	75	5.4
70	0.08	58	4.1
40	0.012	21	1.5
40	0.28	60	4.3
40	0.04	85	6.1
40	0.056	100	7.1
40	0.068	95	6.8
40	0.08	85	6.1

4.2. Computer Modeling of Air Flow Velocity in the Interior of a Modular House

At this stage, an analysis was conducted to assess the effectiveness of the proposed technical solution in facilitating air movement throughout the room, which is critically important for maintaining adequate air exchange without the use of mechanical systems. A detailed evaluation of air flow velocity within the working volume of the room was carried out. This approach allows for an assessment of how effectively the Trombe wall can contribute to reducing energy consumption in modular homes through passive ventilation, thereby diminishing the need for mechanical systems.

Computer simulation of the air exchange process within the space was conducted to validate the appropriateness of the chosen technical solution for passive ventilation in a modular house utilizing the trombe wall system (see Figure 8). The simulation employed the design of the trombe wall utilized in the experimental investigations.

As illustrated in Figure 8, the air flow velocity in key cross-sections of the room, particularly in the areas where occupants are located, remains within acceptable limits. This indicates that the air flow does not exceed a velocity of 0.5 m s^{-1}, which is a crucial criterion for comfort, as higher velocities may cause discomfort, drafts, or even impact the health of residents. This measurement fully complies with the requirements of the Ukrainian State Building Standard DBN B.2.5-67-2013, which regulates microclimate parameters in buildings, including ventilation and air distribution within rooms.

The results of computer modeling, which corroborate these findings, provide further evidence that the proposed technology is effective. Specifically, this pertains to the innovative design of the trombe wall, which functions as a passive ventilation system. This implies that the wall is capable of facilitating natural air movement within the space without the use of mechanical systems, such as fans, thereby making it an energy-efficient solution.

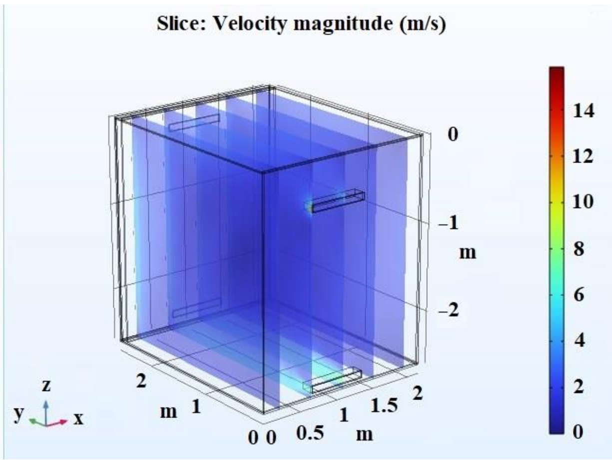

Figure 8. Airflow velocity distribution within the modular house interior.

This design enables the trombe wall to be highly effective for use in modular homes, where ensuring adequate ventilation with minimal energy expenditure is essential. This solution not only maintains a comfortable microclimate within the space but also contributes to enhancing the overall energy efficiency of the building, which is a significant advantage in light of contemporary demands for energy conservation and environmental sustainability.

5. Conclusions

The authors have proposed an original design for a trombe wall intended for modular residential buildings. Its distinctive feature is the use of a 3 mm thick metal sheet, painted black, instead of transparent glazing. This metal sheet serves as a solar thermal energy absorber and, due to its high thermal conductivity, heats the air in the air layer. Consequently, this induces natural convection. Additionally, the metal sheet acts as a structural element of the sandwich panel, serving as the external protection for the modular house. Thus, the authors explore the potential for effectively utilizing this design as a device for facilitating passive ventilation within modular dwellings. Given that passive systems can significantly reduce the overall energy consumption of the building—particularly during warmer months, when energy demands for maintaining indoor climate conditions are considerable—this approach presents a valuable solution.

Experimental studies were conducted to investigate the performance of the trombe wall in ventilation mode. The research was carried out under varying air layer thicknesses and different ventilation opening areas. The proposed configuration of the hybrid external enclosure for the modular house, incorporating the trombe wall, has validated its effectiveness and demonstrated its capability as a supplementary ventilation device within systems designed to maintain the necessary parameters in the modular unit.

After a comprehensive analysis of the obtained graphical dependencies, it was concluded that for the proposed design of the trombe wall, the maximum air flow was $L = 120\ m^3h^{-1}$ and the optimal areas of the ventilation grilles are in the range from 2.5 to 3% of the area of the trombe wall. Under such conditions, the highest air consumption is observed within the air layer, which reflects the phenomenon of natural convection, with an optimal ratio between the geometric dimensions of the air layer thickness and the area of the ventilation grilles.

Another important criterion for evaluating the effectiveness of the ventilation system is the air exchange rate. This criterion is particularly significant, as it ensures the regular renewal of air within the space, removing harmful substances such as carbon dioxide and volatile organic compounds, while maintaining moisture levels and providing comfortable conditions for residents. The effectiveness of the proposed design of the hybrid external enclosure for the modular house, incorporating the trombe wall, has been substantiated. The achievable multiple air exchange rates for a module with a volume of 14 m^3 were delineated, encompassing a range from 1.5 air changes per hour (h^{-1}) to 7.1 air changes per hour (h^{-1}). This spectrum aligns comprehensively with the prescribed requirements for delivering calculated air exchange in both residential and public premises.

Moreover, the computer modeling conducted in this study has led to the conclusion that the velocities within the working volume of the space adhere to regulatory standards, not exceeding 0.5 m s^{-1}. This further confirms the effectiveness of such a system and provides a pathway for future scientific research, particularly in the investigation of passive cross-ventilation systems in modular-type buildings.

5.1. Research Limitations

The study faced certain limitations that should be considered when interpreting the results. The experimental research was conducted under laboratory conditions, which do not fully replicate real-world weather scenarios that significantly impact the performance of the trombe wall. Additionally, the experiments utilized only specific air layer thicknesses corresponding to the modular house's external protection design and ventilation hole sizes, which limits the scalability of the results to other building types. Furthermore, variations in external environmental temperatures throughout the year and fluctuations in solar intensity were not accounted for, as the study focused on a steady-state mode, potentially affecting the system's overall ventilation performance.

5.2. Future Research

Future research will focus on further analyzing the effectiveness of the trombe wall as a passive ventilation system under real operational conditions and in various climate zones for modular homes. Specifically, upcoming studies will examine the impact of climatic factors such as outdoor air temperature and wind load on system performance. Additionally, investigating the potential integration of the trombe wall systems with other energy-efficient passive technologies, such as cross-ventilation, heat storage, or the use of solar collectors, will be a promising method for reducing the building's energy consumption. Moreover, a detailed study of the effects of different geometric parameters of the air layer and ventilation openings will be crucial for achieving optimal air exchange rates and indoor comfort levels.

Author Contributions: Conceptualization, K.M., Y.F. and V.Z.; methodology, Y.F. and V.Z.; software, Y.F.; validation, O.G., Y.F., K.M. and V.Z.; formal analysis, M.A. and Y.F.; investigation, Y.F., K.M. and V.S.; resources, Y.F. and V.Z.; data curation, Y.F., V.S. and M.A.; writing—original draft preparation, V.Z. and K.M.; writing—review and editing, V.Z. and S.-A.M.; visualization, Y.F.; supervision, V.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The author K.M. would like to acknowledge the support of the British Academy/Cara.

Conflicts of Interest: Authors Khrystyna Myroniuk and Stergios-Aristoteles Mitoulis were employed by MetaInfrastructure.org. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Cao, X.; Dai, X.; Liu, J. Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade. *Energy Build.* **2016**, *128*, 198–213. [CrossRef]
2. Hu, Z.; He, W.; Ji, J.; Zhang, S. A Review on the Application of Trombe Wall System in Buildings. *Renew. Sustain. Energy Rev.* **2017**, *70*, 976–987. [CrossRef]
3. Elghamry, R.; Hassan, H. Experimental Investigation of Building Heating and Ventilation by Using Trombe Wall Coupled with Renewable Energy System under Semi-Arid Climate Conditions. *Sol. Energy* **2020**, *201*, 63–74. [CrossRef]

4. Hawks, M.A.; Cho, S. Review and Analysis of Current Solutions and Trends for Zero Energy Building (ZEB) Thermal Systems. *Renew. Sustain. Energy Rev.* **2024**, *189*, 114028. [CrossRef]
5. Taherian, H.; Peters, R.W. Advanced Active and Passive Methods in Residential Energy Efficiency. *Energies* **2023**, *16*, 3905. [CrossRef]
6. Zhelykh, V.; Venhryn, I.; Kozak, K.; Shapoval, S. Solar Collectors Integrated into Transparent Facades. *Prod. Eng. Arch.* **2020**, *26*, 84–87. [CrossRef]
7. Xiao, L.; Qin, L.-L.; Wu, S.-Y. Proposal and Application of Comprehensive Thermal Comfort Evaluation Model in Heating Seasons for Buildings with Solar Trombe Wall. *Appl. Therm. Eng.* **2022**, *213*, 118774. [CrossRef]
8. Brunoro, S. Passive Envelope Measures for Improving Energy Efficiency in the Energy Retrofit of Buildings in Italy. *Buildings* **2024**, *14*, 2128. [CrossRef]
9. Du, L.; Ping, L.; Yongming, C. Study and Analysis of Air Flow Characteristics in Trombe Wall. *Renew. Energy* **2020**, *162*, 234–241. [CrossRef]
10. Elsaid, A.M.; Hashem, F.A.; Mohamed, H.A.; Ahmed, M.S. The Energy Savings Achieved by Various Trombe Solar Wall Enhancement Techniques for Heating and Cooling Applications: A Detailed Review. *Sol. Energy Mater. Sol. Cells* **2023**, *254*, 112228. [CrossRef]
11. Zhang, H.; Tao, Y.; Nguyen, K.; Han, F.; Li, J.; Shi, L. A Wall Solar Chimney to Ventilate Multi-Zone Buildings. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101381. [CrossRef]
12. Shi, L.; Zhang, H. A Mathematical Model for SC-Assisted Stack Ventilation in Multi-Storey Buildings. In *Solar Chimney Applications in Buildings*; Green Energy and Technology; Springer International Publishing: Cham, Switzerland, 2024; pp. 155–182, ISBN 978-3-031-45217-8.
13. Simões, N.; Manaia, M.; Simões, I. Energy Performance of Solar and Trombe Walls in Mediterranean Climates. *Energy* **2021**, *234*, 121197. [CrossRef]
14. Zhang, H.; Yang, D.; Tam, V.W.Y.; Tao, Y.; Zhang, G.; Setunge, S.; Shi, L. A Critical Review of Combined Natural Ventilation Techniques in Sustainable Buildings. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110795. [CrossRef]
15. Ma, Q.; Fukuda, H.; Wei, X.; Hariyadi, A. Optimizing Energy Performance of a Ventilated Composite Trombe Wall in an Office Building. *Renew. Energy* **2019**, *134*, 1285–1294. [CrossRef]
16. Wu, S.-Y.; Wu, L.-F.; Xiao, L. Effects of Aspect Ratio and Inlet Wind Velocity on Thermal Characteristics of Trombe Wall Channel under Different Ventilation Strategies: An Indoor Experiment. *Exp. Therm. Fluid Sci.* **2023**, *141*, 110800. [CrossRef]
17. Gao, Q.; Yang, L.; Shu, Z.; He, J.; Huang, Y.; Gu, D.; Cai, Y. Numerical and Experimental Study on the Performance of Photovoltaic—Trombe Wall in Hot Summer and Warm Winter Regions: Energy Efficiency Matching and Application Potential. *Buildings* **2024**, *14*, 2919. [CrossRef]
18. Mimi Elsaid, A.; Hashem, F.A.; Mohamed, H.A.; Salem Ahmed, M. Improving Summer Cooling in the Egypt Hot/Dry Arid Region Utilizing a Trombe Wall System: A Field Investigation. *Sol. Energy* **2024**, *267*, 112235. [CrossRef]
19. Zheng, X.; Zhou, Y. Dynamic Heat-Transfer Mechanism and Performance Analysis of an Integrated Trombe Wall with Radiant Cooling for Natural Cooling Energy Harvesting and Air-Conditioning. *Energy* **2024**, *288*, 129649. [CrossRef]
20. Dabaieh, M.; Maguid, D.; El Mahdy, D.; Wanas, O. An Urban Living Lab Monitoring and Post Occupancy Evaluation for a Trombe Wall Proof of Concept. *Sol. Energy* **2019**, *193*, 556–567. [CrossRef]
21. Rashid, F.L.; Dulaimi, A.; Hatem, W.A.; Al-Obaidi, M.A.; Ameen, A.; Eleiwi, M.A.; Jawad, S.A.; Bernardo, L.F.A.; Hu, J.W. Recent Advances and Developments in Phase Change Materials in High-Temperature Building Envelopes: A Review of Solutions and Challenges. *Buildings* **2024**, *14*, 1582. [CrossRef]
22. Li, J.; Zhang, Y.; Zhu, Z.; Zhu, J.; Luo, J.; Peng, F.; Sun, X. Thermal Comfort in a Building with Trombe Wall Integrated with Phase Change Materials in Hot Summer and Cold Winter Region without Air Conditioning. *Energy Built Environ.* **2024**, *5*, 58–69. [CrossRef]
23. Sun, Y.; Zhang, N.; Zhang, Z.; Sultan, M.; Yuan, Y. Thermal Performance of a Solar Heat Collection and Storage Wall with Night Insulation in Winter: A Numerical Study. *Energy Build.* **2024**, *303*, 113835. [CrossRef]
24. Ali, M.H.; Mawlood, M.K.; Jalal, R.E. Performance Study of an Isolated Small Scale Trombe Wall with Partially Evacuated Air Gap. *Adv. Mech. Eng.* **2024**, *16*, 16878132231224996. [CrossRef]
25. Yu, B.; Hou, J.; He, W.; Liu, S.; Hu, Z.; Ji, J.; Chen, H.; Xu, G. Study on a High-Performance Photocatalytic-Trombe Wall System for Space Heating and Air Purification. *Appl. Energy* **2018**, *226*, 365–380. [CrossRef]
26. Duan, S.; Jing, C.; Zhao, Z. Energy and Exergy Analysis of Different Trombe Walls. *Energy Build.* **2016**, *126*, 517–523. [CrossRef]
27. Agurto, L.; Allacker, K.; Fissore, A.; Agurto, C.; De Troyer, F. Design and Experimental Study of a Low-Cost Prefab Trombe Wall to Improve Indoor Temperatures in Social Housing in the Biobío Region in Chile. *Sol. Energy* **2020**, *198*, 704–721. [CrossRef]
28. Nguyen, V.T.; Nguyen, Y.Q. *Effects of a Fin on the Wall of the Air Channel on the Performance of a Trombe Wall for Natural Heating*; AIP Publishing: Ho Chi Minh City, Vietnam, 2021; p. 020029.
29. Sady, H.; Rashidi, S.; Rafee, R. Application of Different Trombe Wall Solutions on the Reduction of Energy Load and Sustainable Development in an Eco-Resort Residential Building in Binalood Region with a Cold and Dry Climate. *Environ. Sci. Pollut. Res.* **2023**, *30*, 68417–68434. [CrossRef]
30. Gu, W.; Li, G.; Xiermaimaiti, A.; Ma, T. A Review of Recent Techniques in Performance Augmentation and Evaluation Metrics of Trombe Walls. *Energy Build.* **2023**, *301*, 113693. [CrossRef]

31. Xiao, Y.; Zhang, T.; Liu, Z.; Fukuda, H. Thermal Performance Study of Low-e Glass Trombe Wall Assisted with the Temperature-Controlled Ventilation System in Hot-Summer/Cold-Winter Zone of China. *Case Stud. Therm. Eng.* **2023**, *45*, 102882. [CrossRef]
32. Bojić, M.; Johannes, K.; Kuznik, F. Optimizing Energy and Environmental Performance of Passive Trombe Wall. *Energy Build.* **2014**, *70*, 279–286. [CrossRef]
33. Ben Romdhane, S.; Mahjoub, H.; Mahjoub Said, N.; Jemni, A.; Younsi, Z.; Naji, H. Computational Modelling and Simulation of Trombe Walls as a Passive Ventilation System under an Oceanic Climate. *J. Taibah Univ. Sci.* **2023**, *17*, 2179219. [CrossRef]
34. Hamidi, Y.; Malha, M.; Bah, A. Study of Four Passive Second Skin Façade Configurations as a Natural Ventilation System During Winter and Summer. *Sace* **2021**, *28*, 94–105. [CrossRef]
35. Layeni, A.T.; Waheed, M.A.; Adewumi, B.A.; Nwaokocha, C.N.; Sharifpur, M.; Tongo, S.O.; Okeze, R.C.; Mboreha, C.A. Computational and Sensitivity Analysis of a Dual Purpose Solar Chimney for Buildings. *Mater. Today Proc.* **2021**, *47*, 4126–4136. [CrossRef]
36. Wang, Q.; Zhang, G.; Li, W.; Shi, L. External Wind on the Optimum Designing Parameters of a Wall Solar Chimney in Building. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100842. [CrossRef]
37. Zhang, H.; Tao, Y.; Zhang, G.; Li, J.; Setunge, S.; Shi, L. Impacts of Storey Number of Buildings on Solar Chimney Performance: A Theoretical and Numerical Approach. *Energy* **2022**, *261*, 125200. [CrossRef]
38. Wang, Y.; Chen, X.; Qi, X.; Zhou, J. Numerical Study on the Effect of Optimizing the Trombe Wall Structure with Built-in Fins on Improving Building Energy Efficiency in Severe Cold Region. *Renew. Energy* **2024**, *222*, 119856. [CrossRef]
39. Corasaniti, S.; Manni, L.; Petracci, I.; Potenza, M. Steady- and Transient-State CFD Simulations of a Modified Barra–Costantini Solar System in Comparison with a Traditional Trombe–Michel Wall. *Energies* **2024**, *17*, 295. [CrossRef]
40. Bulmez, A.; Brezeanu, A.; Dragomir, G.; Fratu, M.; Iordan, N.; Bolocan, S.; Rozorea, L.; Popa, E.; Năstase, G. CFD Analysis for a New Trombe Wall Concept. *Buildings* **2024**, *14*, 579. [CrossRef]
41. Liu, H.; Li, P.; Yu, B.; Zhang, M.; Tan, Q.; Wang, Y.; Zhang, Y. Contrastive Analysis on the Ventilation Performance of a Combined Solar Chimney. *Appl. Sci.* **2021**, *12*, 156. [CrossRef]
42. Sornek, K.; Papis-Frączek, K.; Calise, F.; Cappiello, F.L.; Vicidomini, M. A Review of Experimental and Numerical Analyses of Solar Thermal Walls. *Energies* **2023**, *16*, 3102. [CrossRef]
43. Ali, M.H.; Mawlood, M.K.; Jalal, R.E. Minimizing Energy Losses and Enhancing Performance of Trombe Wall Systems through Partial Evacuation of the Air Gap. *Energy Build.* **2024**, *307*, 113959. [CrossRef]
44. Zhang, H.-L.; Li, B.; Shi, D.-K.; Wang, W.-W.; Zhao, F.-Y. Thermal Performance and Ventilation Analysis of a Zigzag Trombe Wall: Full Numerical and Experimental Investigations. *Energy Build.* **2024**, *306*, 113955. [CrossRef]
45. Baïri, A.; Martín-Garín, A.; Adeyeye, K.; She, K.; Millán-García, J.A. Enhancement of Natural Convection for Improvement of Trombe Wall Performance. An Experimental Study. *Energy Build.* **2020**, *211*, 109788. [CrossRef]
46. Wu, S.-Y.; Yan, R.-R.; Xiao, L. A Novel Passive Solar Vertical-Finned-Thermocatalytic-Trombe Wall System for Air Purification and Heating. *J. Clean. Prod.* **2022**, *374*, 134065. [CrossRef]
47. Myroniuk, K.; Furdas, Y.; Zhelykh, V.; Yurkevych, Y. Examining Wind Flow's Impact on Multi-Storey Buildings: A Quest for Quality Improvement. *Prod. Eng. Arch.* **2024**, *30*, 57–66. [CrossRef]
48. Zhelykh, V.; Voznyak, O.; Yurkevych, Y.; Sukholova, I.; Dovbush, O. Enhancing of Energetic and Economic Efficiency of Air Distribution by Swirled-Compact Air Jets. *Prod. Eng. Arch.* **2021**, *27*, 171–175. [CrossRef]
49. Voznyak, O.; Myroniuk, K.; Sukholova, I.; Kapalo, P. The Impact of Air Flows on the Environment. In *Proceedings of CEE 2019*; Blikharskyy, Z., Koszelnik, P., Mesaros, P., Eds.; Lecture Notes in Civil Engineering; Springer International Publishing: Cham, Switzerland, 2020; Volume 47, pp. 534–540, ISBN 978-3-030-27010-0.