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Study of a Double-Layer Trombe Wall Assisted by a Temperature-Controlled DC Fan for Heating Seasons

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Abstract: This paper presents a double-layer Trombe wall assisted by a temperature-controlled direct current (DC) fan. THERB for HAM, a dynamic thermal load calculation software, was used to estimate the heating ability of a double-layer Trombe wall for an office building. We designed a new double-layer Trombe wall that has two ventilated air cavities installed on the south facade of the office building, and a pipe with a temperature-controlled DC fan used to control thermo-circulation. The office building was located in Kitakyushu, Fukuoka, Japan. The temperature of the ventilated air cavity of the double-layer Trombe wall and the indoor temperature were simulated. It was more efficient for the DC fan to start when the ventilated air cavity temperature was 19 °C and the operative temperature of indoor was maintained at 20 °C. The results showed that the double-layer Trombe wall with a temperature-controlled DC fan can reduce yearly heating needs by nearly 0.6 kWh/m^3 and improve the performance of a double-layer Trombe wall up to 5.6% (22.7% in November, 8.56% in December, 1.04% in January, 3.77% in February, and 3.89% in March), compared to the double-layer Trombe wall without an air supply. The ventilated (all day) double-layer Trombe wall performed better than the unventilated double-layer Trombe wall in November, December, February, and March. Thus, the potential of a double-layer Trombe wall can be improved with the assistance of a temperature-controlled DC fan.

Keywords: temperature-controlled DC fan; performance; double-layer Trombe wall; THERB for HAM

1. Introduction

Edward Morse first presented a classic Trombe wall, that is known as a solar heating wall or storage wall [1]. The classic Trombe wall was popularized by Felix Trombe and derives its name from him [2,3]. Its use as a building element was promoted in the 1960s [4,5] and consists of vents, an air channel, a massive wall, and a glass plate. Trombe walls absorb solar radiation and transmit a portion of the energy into the building by conduction and by natural convection [6]. Rabani, M. [7] studied the variations of the Rayleigh number, convective heat transfer coefficient, and the rate of convection, conduction, and radiation heat transfer exchanged with a Trombe wall. This study concluded that radiation is the dominant heat transfer process from a Trombe wall. Heat transfer is more sensible for colds days than for warm days. Hernandez et al. [8] found that a Trombe wall can store the maximum energy of 109 MJ on the coldest day and 70 MJ on the warmest day. Hassanain et al. [9,10] found that when a Trombe wall was used for a greenhouse envelope, the mean temperature of the indoor air and soil increased 1.1 °C and 4 °C during winter nights. A Trombe wall can decrease a house's energy heating need close to 16.36% if a Trombe wall is used for the house envelope [11].

However, Trombe walls have several shortcomings: (1) Low thermal resistance; heat flux transfers from the inside of a building to the outside during nights and cloudy weather [3,12,13]; (2) Inverse thermo-siphon phenomena.; when the interior temperature is higher than the temperature of the mass heating wall, the air is cooled and injected into the interior through the lower vent [3,13,14]; (3) Heat transfer is always uncertain; because of the change of the solar intensity, the obtained heat is not predictable [3]; (4) Low aesthetic value, because the walls are painted black to increase the absorption rate of the wall [3,13].

In order to improve the thermal resistance of the Trombe wall and control supplies, the composite Trombe-Michel wall [15] was developed, which is composed of some different layers. These layers comprise an insulation layer, a ventilated air cavity, a mass heating wall, a closed air cavity, and a glass plate (Figure 1). The composite Trombe-Michel wall work as follows: the glass plate dispatches most of the gained solar beams, and then the mass heating wall absorbs gained solar energy and transfers a portion of the energy into the interior by conduction and part by natural convection. The free solar benefits must be differentiated from direct solar benefits [3]. The composite Trombe-Michel wall has higher thermal resistance because of the insulation layer. The heating can be controlled at any time by controlling the air circulation between the interior and the ventilated air cavity [16]. Shen, J. used the software of TRNSYS to study the efficiency of the classic Trombe wall and the composite Trombe-Michel wall. The results showed that the composite Trombe-Michel wall has better energy performances than the classical Trombe wall in cold and cloudy climates [15,17]. The shortcoming of the composite Trombe-Michel wall is that it needs a device to preclude the reverse thermo-circulation that occurs when the interior temperature is higher than the temperature of the mass heating wall [16]. This problem can be solved by installing an automatic shutter in the vent [18].

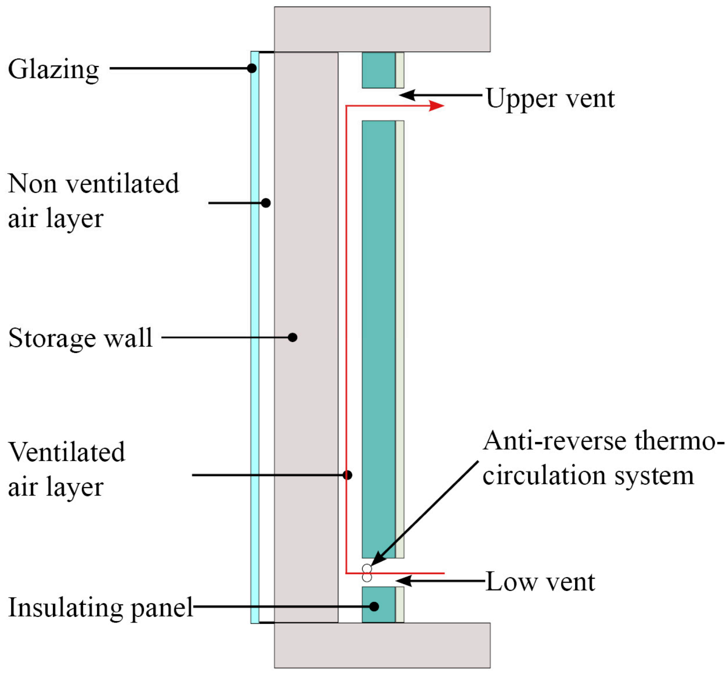

Figure 1. The composite Trombe-Michel wall [15].

Hu, Z. et al. [13] reviewed the most pertinent studies on Trombe walls. They concluded that the 'site' parameters (wind direction and speed, orientation, solar radiation), the 'building' parameters (window effects, construction materials), and the 'Trombe wall' parameters (shading devices, storage wall properties, channel depth, the Trombe wall's area, glazing properties) affect the efficiency of Trombe walls.

Zalewski et al. [14] proposed that the application of low-e double glazing has a greater effect on the efficiency of solar walls in comparison to the use of single glazing. Jaber et al. [19] used life cycle cost criterion to study the Trombe wall ratio (α) impact on residential building heating in the Mediterranean from thermal, environmental, and economic perspectives. They found that the optimum ratio was 37%, which reduced life cycle cost (LCC) by 2.4% and CO_2 by 445 kg annually. Yilmaz et al. [20] presented a study on an existing building with Trombe walls in Istanbul. They investigated inter-space distances (0.05, 0.10, and 0.15 m) between the existing exterior wall and glass and concluded that the inter-space distance does not affect the performance of the Trombe wall system. Hami, K. [21] concluded that the materials used for a mass wall are important for Trombe walls. Leang, E. [22] carried out a simulation study by using the software of Dymola/Modelica. They compared a wall incorporating mortar phase change material (M_PCM) with a concrete storage wall. The results showed that the M_PCM storage wall had a larger capacity of heat recovered than the concrete wall. The classic wall (15 cm concrete storage wall) showed a time delay nearly four times longer than the storage wall (4 cm M_PCM). Djordjević, A.V. [23] concluded that the room temperature with a 0.20-m-thick concrete unvented Trombe wall is higher than that with a 0.45-m-thick concrete unvented Trombe wall within the 24-h cycle of a combined system. If the concrete wall is thicker, the heat takes too long to reach the room, resulting in a lower heat load. Hong, X. [24] proposed a Trombe wall with a Venetian blind, which has the ability of preventing overheating in summer and improving the energy efficiency of heat collection in winter. The simulation study indicated that the optimization of the distance between the Venetian blind and the glass is 0.09 m for an air duct of 0.14 m width with the area of the vent being 0.10 m in height $\times$ 0.60 m in width.

Abbassi, F. [25] used the simulation software of TRNSYS to study the energetic performance of Trombe walls with different building envelopes. The results showed that the high thermal insulated wall can reduce the heating demand greatly. The yearly heating load was reduced by 63% by a 3 m^2 Trombe wall area when the external wall was insulated by 5 cm of expanded polystyrene. Sun, W. [26] investigated the thermal energy efficiency of the photovoltaic Trombe wall (PV-TW) with or without a window on the south side of the building. Having a window on the south side of the building can reduce the PV-TW thermal efficiency by 27%.

Dragićević, S.M. [27] concluded that the efficiency of Trombe walls increases as solar radiation increases. Soussi et al. [28] concluded that the efficiency of Trombe walls is also affected by their orientation. They investigated two orientations (southwest and northwest) for Trombe wall design. The results presented that the total heating and cooling demands of the house was 11,884.5 kWh for the southwest orientation, while they reached 14,355.88 kWh for the northwest orientation. Lambic et al. [29] concluded that the efficiency of Trombe walls decreased with increased wind speed under the same solar radiation.

Briga-Sá, A. [30] carried out an analytical and experimental analysis on the thermal energy performance of Trombe walls for different conditions of occlusion device operation and ventilation openings. The study showed that it is very important to manage the occlusion device operation and the ventilation openings correctly during the day and night. When the shading device and the ventilation system were closed, the top of the air cavity temperature was 19 °C higher than the bottom and the interior temperature was 9 °C higher than the outside air temperature [31]. Bellos, E. [32] presented a new unvented Trombe wall with an added window in the massive wall. The study showed that the new unvented Trombe wall increases the mean daily indoor temperature by approximately 0.5 K. Corasaniti, S. [33] carried out numerical simulations of three types of Trombe wall (sharp edges, rounded edges, and rounded edges with guided flow). The results showed that the guided flow presents the highest energy and exergy efficiency. Jovanovic, J. [34] presented the performance of PV-Trombe walls from the perspective of PV module parameters. The results showed that the impact of the PV module operating temperature can be neglected. The optimal tilt angle of PV modules for generating maximum annual electricity is around latitude angle. Sebald et al. [35] performed a network computer simulation on Trombe walls with a fan. In the results, the fan improved the performance of a Trombe wall by 7% in Madison, 20% in Santa Barbara, and 22% in Albuquerque [35]. Sebald, A. [36] studied the energy performance of a Trombe wall with a fan. The results revealed that the fan can improve Trombe wall performance by 8%. Jie et al. [37] studied the performance of a photovoltaic Trombe wall (PV-TV) without and with a fan. Results showed that the fan can reduce the PV cell temperature by 1.28 °C and reduce the internal temperature by 0.5 °C. Lee, H. [38] investigated the effect of reducing the sensible heat load by using the software of THERB for HAM. The central air-conditioning system integrated a PCM unit and ventilation layer in the air circulation system. The temperature-controlled fan operates the air circulation. The results showed that the total sensible heat was reduced by 28%. However, according to the review presented by the authors, there is no research on how the temperature-controlled direct current (DC) fan affects the double-layer Trombe wall's efficiency. Based on the composite Trombe-Michel wall (Figure 1), we changed the layer of a closed air cavity to a ventilated air cavity, and these changes led to the definition of the double-layer Trombe wall. In addition, it is hard to create a unique rule to accurately estimate the capability of storage and energy recovery of solar energy for the double-layer Trombe wall. It is necessary to use simulation tools such as THERB for HAM developed by Akihito Ozaki. To study the double-layer Trombe wall with a temperature-controlled DC fan, we designed a new simulation module that can control ventilation according to temperature.

This study investigated energy conservation in an office building with a double-layer Trombe wall with a temperature-controlled DC fan for winter heating application. The heating potential of the double-layer Trombe wall with a temperature-controlled DC fan for an office building was estimated using the dynamic thermal load calculation software, THERB for HAM. The double-layer Trombe wall was installed on the south facade of the office building and a pipe was designed with the temperature-controlled DC fan that can control thermo-circulation. The office building is located in Kitakyushu, Fukuoka, Japan. The temperature-controlled DC fan operates the air circulation. The fan operates automatically according to the temperature of the ventilated air cavity. The central concrete core of the wall was painted black to improve the absorption capacity of the wall. In addition, to control air flow from the ventilated air cavity (between the glass and the wall, between the wall and insulation) to the building interior, the ventilation rates of the fan were controlled at 40 m^3/h. The temperature of the room with the double-layer Trombe wall was simulated. The ability of a temperature-controlled DC fan to improve the heating thermal energy performance of a double-layer Trombe wall was studied by comparison to a double-layer Trombe wall without an air supply.

2. Method

2.1. Office Building Description

The building has an office room with underfloor space, as shown in Figure 2. The heating season runs from November 1 to March 31. During the heating season, the operative temperature of the indoor air is maintained at 20 °C by using air conditioning. The ventilation from outdoors into the test room is 33 m^3/h. The wall height of the underfloor space is 1 m. The wall height of the office room is 3.6 m. The roof and floor have a length of 4.85 m and width of 5.615 m. The dimensions of the window are a width of 1.55 m and a height of 2.6 m. Windows are provided with overhangs.

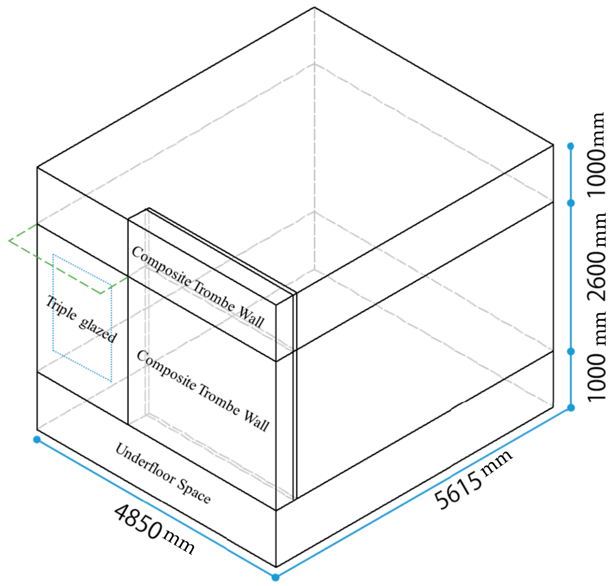

Figure 2. Model of office with the double-layer Trombe wall.

2.2. Description of the Double-Layer Trombe Wall with a Temperature-Controlled DC Fan

We designed a new double-layer Trombe wall, which has two ventilated air cavities (between the wall and the glass, between the wall and insulation) and a pipe with the temperature-controlled DC fan that can control ventilated air. The heat was transferred into the interior by convection through the ventilated air cavity. The performance of the fan was investigated. The geometric features of the double-layer Trombe wall are shown in Figure 3. The double-layer Trombe wall was installed on the south facade of the office building has the following features: (1) Emissivity of the glazing, ε = 0.84; (2) Solar absorption of the massive wall, α = 0.8; (3) Emissivity of the massive wall, ε = 0.9; (4) Wall height, H = 3.6 m; (5) Wall width, L = 2.7 m. Table 1 lists the names of the window layers and massive wall with their thicknesses, thermal conductivity, density, and specific heat.

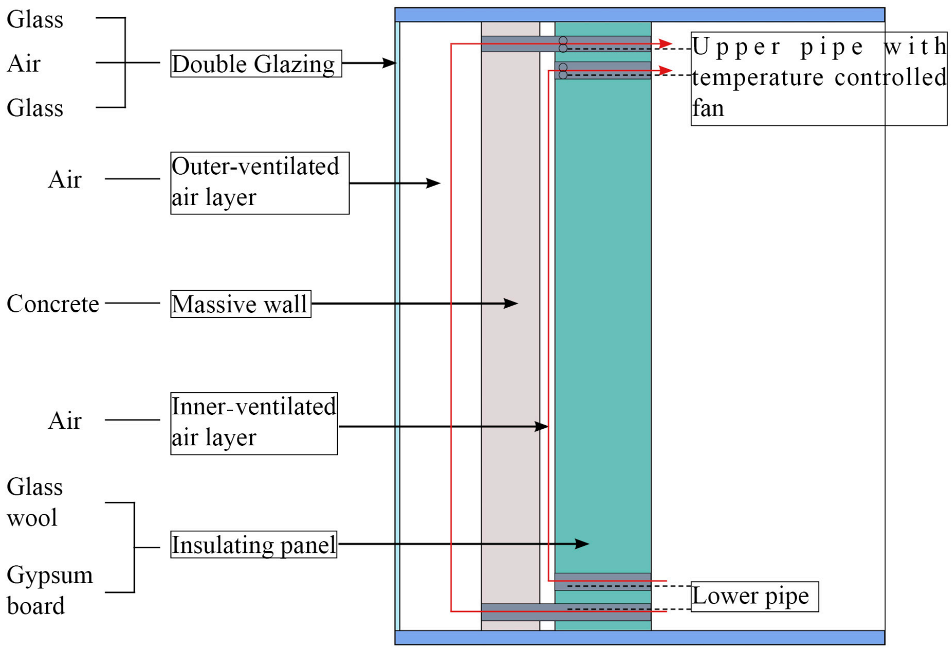

Figure 3. The double-layer Trombe wall assisted with a temperature-controlled DC fan for winter heating.

Table 1. Constructions with their layers used in double-layer Trombe walls.

Layer	Layer	Thickness (m)	λ (W/m K)	p (kg/m^3)	cp (J/kg K)
Double glazing	Glass	0.004	0.78	2540	770
	Air	0.012	0.22	1.2	1000
	Glass	0.004	0.78	2540	770
Outer-ventilated air	Air	0.35			
Massive wall	Concrete	0.35	1.6	2200	840
Inner-ventilated air	Air	0.065			
Insulation	Glass wool	0.4	0.03	16	840
	Gypsum board	0.012	0.22	700	870

2.3. Software, Weather, and Location

In this research, we used the dynamic heat load calculating software THERB for HAM to calculate the temperature at 10-min intervals. The program was initially developed by Akihito Ozaki. THERB for HAM has been developed for calculating the hygrothermal environment: cooling and heating load, humidity, temperature, and sensible temperature for wall assemblies and multiple zone buildings. This software completed HAM (moisture, heat, and air) characteristics such as ventilation (or air leakage), conduction, radiation, and convection, comprising rules of moisture transmission within walls [39]. It is based on the detailed phenomena of describing physical architecture, and can be used to various forms of architectural design, occupant schedules, or structure, etc. The simulation results were validated throughout the BESTEST procedure tests in Japan. The software of THERB for HAM is an assessment tool for annual cooling and heating load computation methods base on the law concerning the promotion of housing quality assurance [38]. Ozaki, A. [40] described the basic theoretical features and applications of THERB for HAM. They verified the accuracy of THERB for HAM by comparing the monitoring and calculation results of a residential building. Lee, H. [38] compared the monitored indoor temperature with the computed results achieved from THERB for HAM. The computed results agreed well with monitored data. The standard years' data over 20 years from 1981 to 2000 of the Automated Meteorological Data Acquisition System (AMeDAS) were used for simulation [41]. The investigated buildings are located in Kitakyushu, Fukuoka, Japan with an altitude of 33.88 and longitude of 130.71.

3. Results

3.1. The Double-Layer Trombe Wall Assisted by a Temperature-Controlled DC Fan Without Air Conditioning

Figure 4 shows the basic climatic parameters including air temperature and average hourly global solar irradiation. The mean temperature in November is 12.4 °C. The mean temperature in December is 8 °C. The mean temperature in January is 6.2 °C. The mean temperature in February is 6.3 °C. The mean temperature in March is 8.7 °C. First of all, we carried out the temperature simulations of the room with the double-layer Trombe wall on one sunny day (January 19) in the absence of air conditioning. The temperature-controlled DC fan operates automatically according to the temperature of the ventilated air cavity, thereby controlling the air circulation. The induction temperature ranged from 17 °C to 21 °C. "No ventilated" indicates the double-layer Trombe wall without air supply. "Ventilated (17 °C)" indicates that the fan is activated when the ventilated air layer temperature is above 17 °C. "Ventilated (all day)" means that the fan is always turned on. The temperature of the room under different air supply strategies is shown in Figure 5. The results showed that having the fan running all day is more efficient. We also carried out the simulations of the temperature of the double-layer Trombe wall for November, December, February, and March in the absence of air conditioning and no air supply. The results follow the same trend as that seen on January 19. In heating seasons, the indoor temperature increased by a maximum of 2.9 °C with the double-layer Trombe wall with a DC fan compared to the double-layer Trombe wall without an air supply. To warm the room in the non-air-conditioned condition, having the fan always running is efficient.

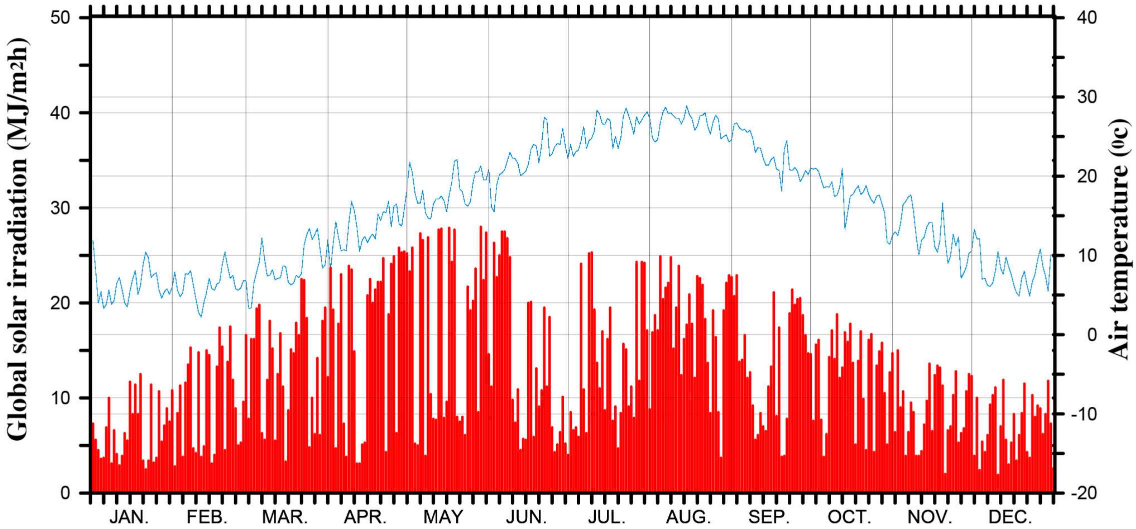

Figure 4. Average hourly global solar irradiation and air temperature.

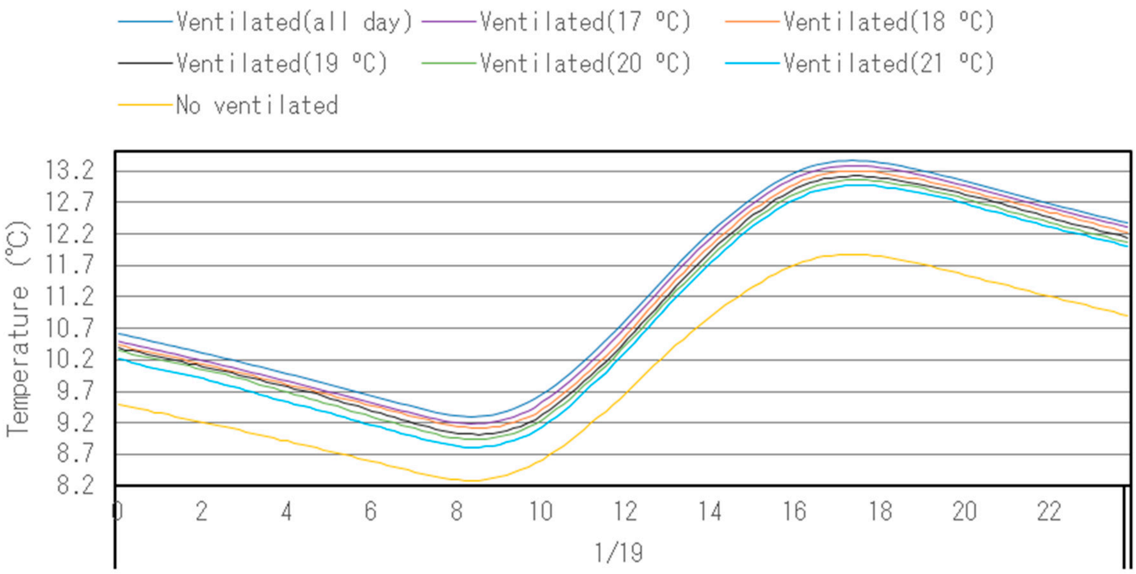

Figure 5. The temperature of the room under different air supply strategies on January 19.

3.2. The Double-Layer Trombe Wall Assisted by a Temperature-Controlled DC Fan on Heating Load Reduction

We also conducted simulations of heating thermal energy for heating seasons with air conditioning (10:00–21:00) and air supply (40 m^3/h). The room temperature was set to 20 °C. Heating thermal energy consumption under different air supply strategies are shown in Figures 6–10. "No ventilated" indicates the double-layer Trombe wall without air supply. "Ventilated (17 °C)" indicates that the fan is activated when the ventilated air layer temperature is above 17 °C. "Ventilated (all day)" means that the fan is always turned on. It is more efficient for the fan to start when the ventilated air cavity temperature is 19 °C, if the operative indoor temperature is maintained at 20 °C. The ventilated (all day) double-layer Trombe wall is better than the unventilated double-layer Trombe wall in November, December, February, and March. The heating thermal energy of ②, ③, ④, ⑤, and ⑥ have similar values. In November, the difference of heating thermal energy between ① and ④ is 0.591 kWh/m^2.

It can reduce the demand for building energy heating close to 22.7%. In December, the difference of heating thermal energy between ① and ④ is 0.479 kWh/m^2. Building energy consumption can be reduced by 8.56%. In January, the difference of heating thermal energy between ① and ④ is 0.088 kWh/m^2. It can reduce the demand for building energy heating close to 1.04%. In February, the difference of heating thermal energy between ① and ④ is 0.265 kWh/m^2. Building energy consumption can be reduced by 3.77%. In March, the difference of heating thermal energy between ① and ④ is 0.221 kWh/m^2. It can reduce the demand for building energy heating close to 3.89%. Therefore, the double-layer Trombe wall assisted by a temperature-controlled DC fan can reduce yearly heating thermal energy needs close to 5.6% compared to the double-layer Trombe wall without an air supply.

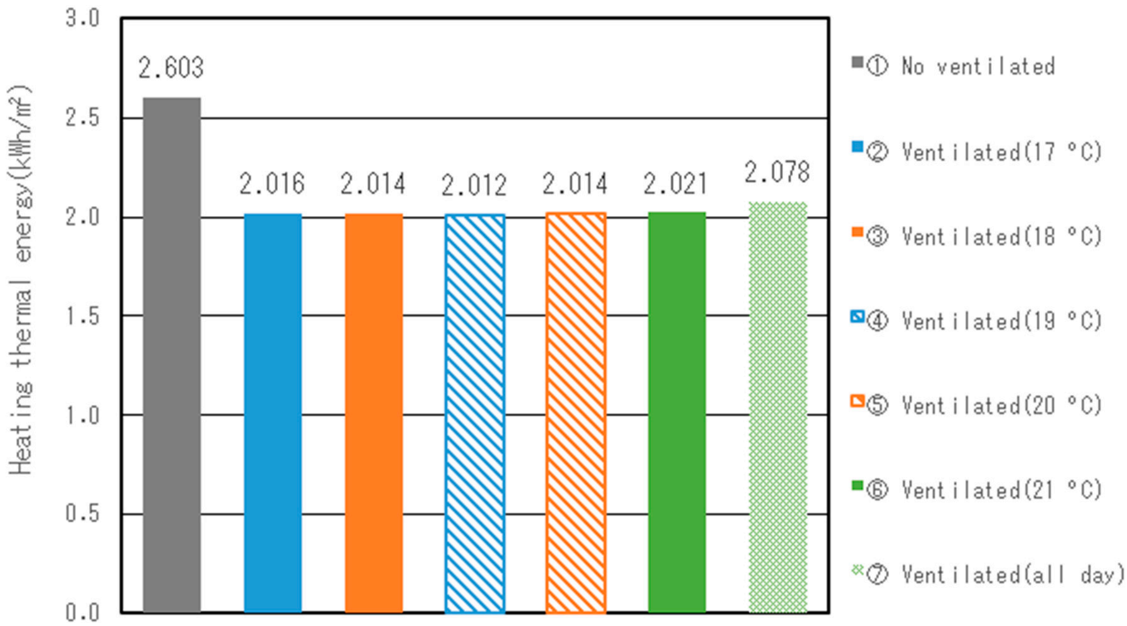

Figure 6. Heating thermal energy consumption under different air supply strategies in November.

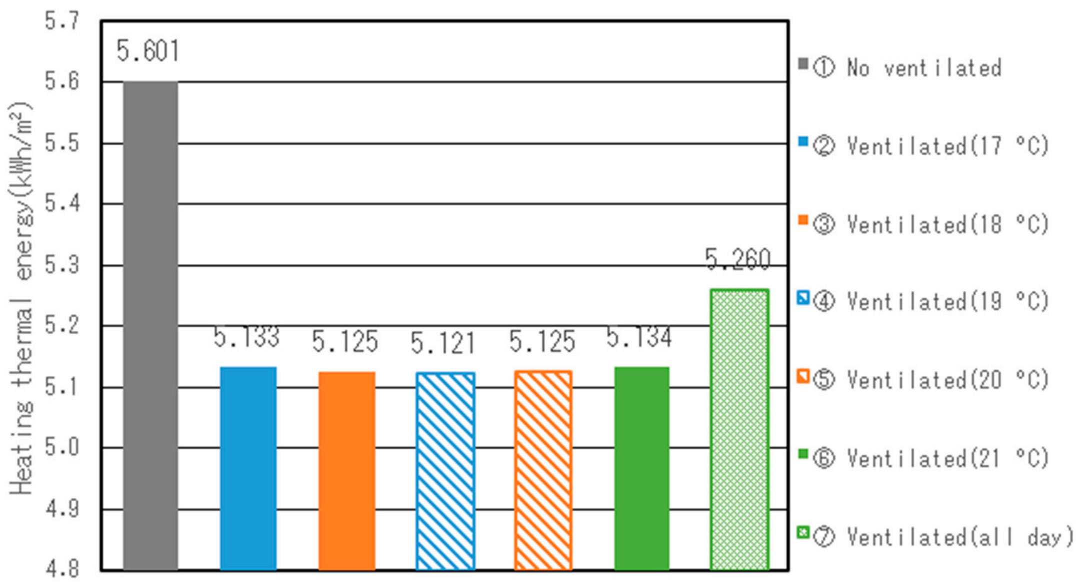

Figure 7. Heating thermal energy consumption under different air supply strategies in December.

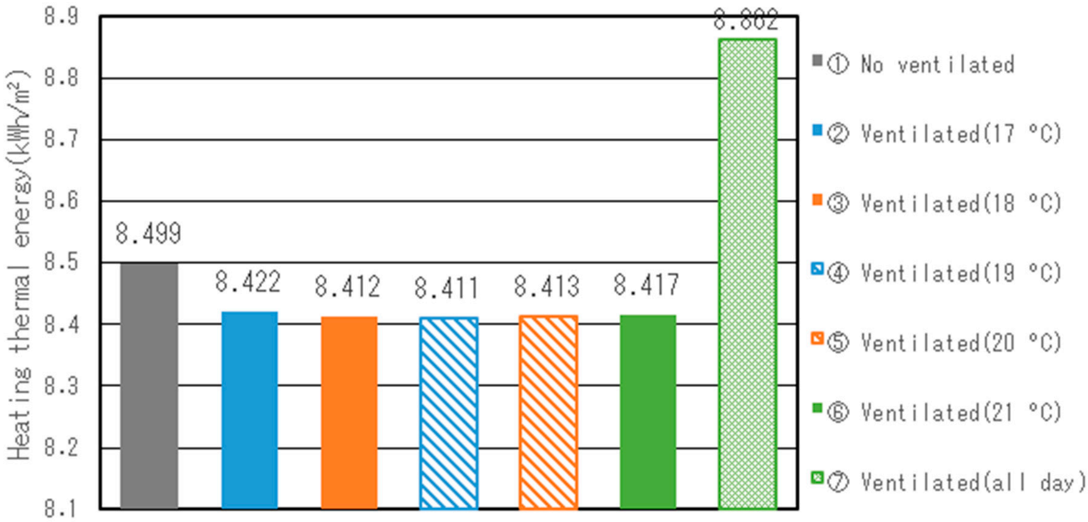

Figure 8. Heating thermal energy consumption under different air supply strategies in January.

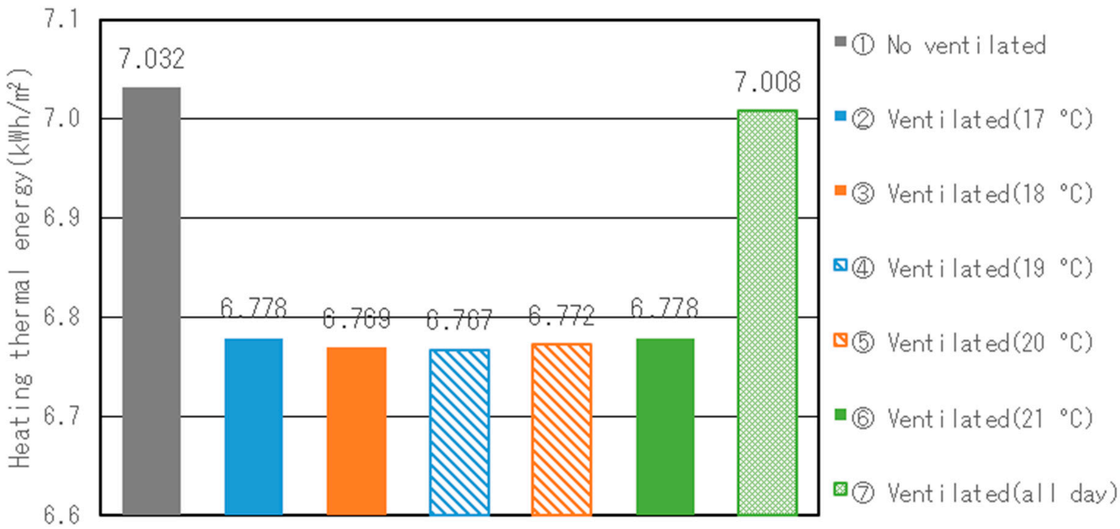

Figure 9. Heating thermal energy consumption under different air supply strategies in February.

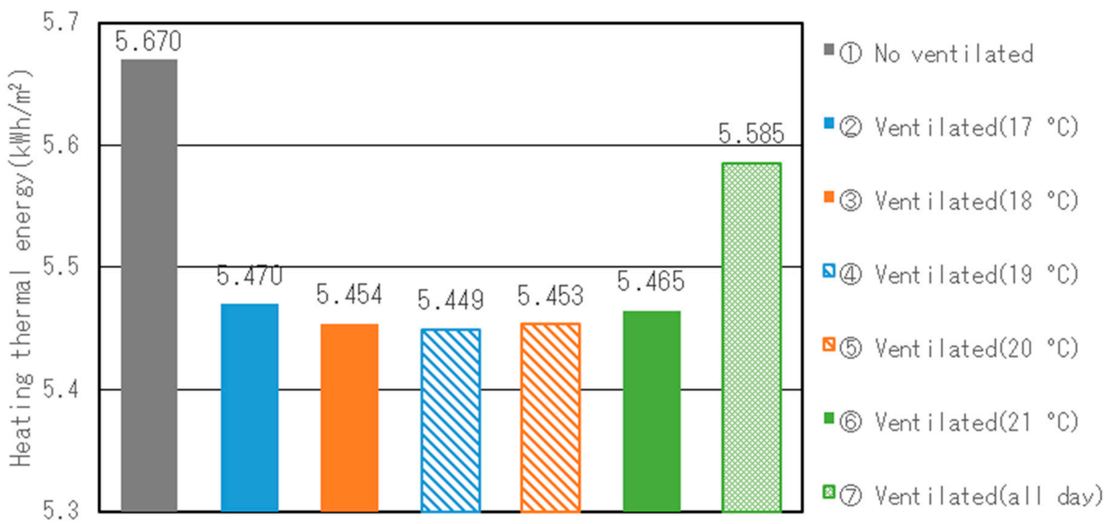

Figure 10. Heating thermal energy consumption under different air supply strategies in March.

4. Discussion

The thermal energy performance of the double-layer Trombe wall assisted by a temperature-controlled DC fan is affected by climatic factors such as global solar irradiation and air temperature. High solar gains and air temperatures are the main climatic conditions that ensure the double-layer Trombe wall performance. The double-layer Trombe wall assisted with a temperature-controlled DC fan can increase the interior temperature quickly and prevent inverse thermo-siphon phenomena, which occur when the interior temperature is higher than the temperature of the mass heating wall. Due to the room insulation, the room temperature decreases slowly in the the night and prolonged cloudy periods. The double-layer Trombe wall absorbs solar radiation and transmits a portion of the heat into the interior by conduction, and transmits portion of heat into the interior by convection. Therefore, the conductive and convective heat transmitted to the room is important to increase the performance of the double-layer Trombe wall. However, the fan increases the convective heat to the room from the ventilated air layer during daytime, which enhances the thermal transfer.

Note that the results are based on simulations that are intended to enhance the reader's insight on improving the efficiency of double-layer Trombe walls. We here attempt to validate the main conclusions of the test structure and physical housing. There are also some problems, such as the energy consumption of the fan and the optimum fan speed, which deserve further research. For future work, research on the optimum thickness of the ventilated air layer and different materials, such as adobe, stone, concrete, brick, phase change material (PCM) etc., alongside the use of a temperature-controlled DC fan for different climatic regions is suggested.

5. Conclusions

The paper aimed to present a novel improvement of Trombe walls: double-layer Trombe walls with temperature-controlled DC fans that have two ventilated air cavities. The heating potential of double-layer Trombe walls assisted with temperature-controlled DC fans for an office building was estimated using the software of THERB for HAM. The calculation method for the heating thermal energy performance of the double-layer Trombe wall with a temperature-controlled DC fan during the heating season is an added value to the scientific knowledge of this system's performance. The double-layer Trombe wall with a temperature-controlled DC fan, which can increase the indoor temperature quickly and prevent inverse thermo-siphon phenomena, was first investigated. The fan increases the convective heat to the room from the two ventilated air cavities during daytime, which enhances the thermal transfer.

In heating seasons, the indoor temperature increased by a maximum of 2.9 °C with the double-layer Trombe wall with a DC fan compared to a double-layer Trombe wall without air supply in the non-air-conditioned condition. To warm the room in the non-air-conditioned condition, it is effective to supply air from two ventilated air cavities together. It is more efficient to have the fan start up when the ventilated air cavity temperature is 19 °C, if the operative temperature of the interior is maintained 20 °C with air conditioning. The results indicated that the double-layer Trombe wall assisted by a temperature-controlled DC fan in Kitakyushu, Fukuoka, Japan, by using solar energy, can reduce yearly heating needs close to 0.6 kWh/m^3 and improve the performance of a double-layer Trombe wall up to 5.6% (22.7% in November, 8.56% in December, 1.04% in January, 3.77% in February, and 3.89% in March), compared to the double-layer Trombe wall without an air supply.

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Conflicts of Interest: The authors declare no conflict of interest.

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