An experimental study on the performance of Trombe wall system in summer climate conditions in Hot Summer and Cold Winter zone of China

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Abstract. Trombe wall system is a typical passive building technology that can use stack effect to induce indoor ventilation, adjust indoor thermal environment and reduce building energy consumption. Present researches mainly aimed at its application in winter heating, and seldom involve summer ventilation and cooling. In this research, two comparative test rooms were established, one with the Trombe wall system installed in the south facade, and the other used as a contrast. By comparing the response characteristics of the two rooms to the outdoor climate, the performance of the Trombe wall system was studied in summer climate conditions in hot summer and warm winter zone of China. During the experiment, the indoor and outdoor environmental parameters and the performance parameters of the Trombe wall system were tested. The result illustrated that the Trombe wall system can make full use of the absorbed solar radiation heat to induce indoor ventilation, with a maximum circulating air flow rate of 140m³/h (32.7h⁻¹). And it can effectively reduce the indoor temperature by up to 4.1 °C during the daytime by compared with the reference room. The heat entering the room through the Trombe wall system was more than that of that through the south façade of the reference room. However, the excess heat can be ventilated to the outdoor through the air vents of the Trombe wall system by the effect of high indoor ventilation times. This prevents the air temperature in the room from rising.

1. Introduction
Modern buildings mostly use active mechanical refrigeration to regulate the indoor thermal environment, which leads to high building energy consumption. And humans’ adaptability to climate is restrained. This makes people easy to form dependence on the air-conditioned environment. In order to eliminate these unfavorable factors, more and more research began to focus on passive building energy-saving technology. Tromber wall system is a typical passive building energy-saving technology, usually composed of glass cover, heat-absorbing plate or paint, air gap and ordinary wall. It can make use of absorbed solar energy to induce indoor air flow to achieve indoor air ventilation and heating or cooling [1-5]. At present, most of the research focuses on heating demand in winter. In view of the huge energy saving potential and simplicity of the Tromber wall system, its cooling effect on the indoor environment in the hot summer climate began to arouse the interest of researchers.

For example, F. Stazi et al.[6] in Italy showed that the improved Trombe wall system used in the Mediterranean climate in summer can reduce room cooling energy consumption by 72.9%. Even in severe summer, it can induce ventilation to create a satisfactory indoor thermal environment. E.
Krüger et al.[7] in Brazil conducted research on the Trombe wall system in subtropical regions, and the results showed that the annual heating and cooling energy consumption of the building can be reduced by about 30%. J. Long et al.[8] designed a new type of Trombe wall system based on the summer climate characteristics of the hot summer and cold winter zone in China. A solar collector plate was placed in the air channel of Trombe wall system. The heat absorbed by the solar collector plate was brought into the water tank through the circulation tube, and the thermal radiation reflection layer was set on the outer surface of the heavy wall to prevent the heat from transmitting to the indoor. The main purpose of this paper is to improve the thermal insulation performance of the Trombe wall system. This obviously causes the inability to make full use of the advantages of the Trombe wall system, and its heat-induced ventilation capacity is weakened. The research of H. Wei et al.[9] showed that the Trombe wall system with venetian blind structure can reduce the summer cooling load by up to 70.7% in the hot summer and cold winter zone of China. Y. Zhou and C. Yu[10] designed a ventilated Trombe wall integrated with phase change materials. Through the simulation method, they studied the changes of air channel temperature and energy consumption by comparing the Trombe wall system with and without high reflection coating in summer in the hot summer and cold winter zone of China. However, this paper does not mention the influence of the Trombe wall system on indoor temperature and indoor ventilation. T. Yang et al.[11] combined shallow geothermal energy with Trombe wall system in Shihzei, which is located in severe cold regions of China. The experiment shows that the Trombe wall system can achieve good ventilation and cooling effect. When the outdoor average temperature is 32.3 °C in the daytime, the indoor average temperature is about 28 °C, which meets the design requirements of room temperature in summer. However, there is little experimental study on the performance of collector wall in hot summer and warm winter climate from the current literature, such as studies on the summer performance of the Trombe wall system in specific climatic regions and its regulation on indoor environment. The main purpose of this paper is to study the performance of the Trombe wall system under summer climate conditions in hot summer and warm winter zone of China. In this research, two experimental comparison rooms were established in Dongguan University of Technology, Dongguan, China, one with Trombe wall system and the other as a reference room. Then the indoor and outdoor environment parameters, objective parameters related to the performance of Trombe wall system were tested. And the relationship between these parameters and outdoor meteorological parameters was analyzed to clarify the performance and role of the Trombe wall system in daytime heat insulation, nighttime heat dissipation and indoor ventilation in summer climate. The present work will help to promote the development and application of passive building technology in hot summer and warm winter zone of China.

2. Methodology

2.1 System description

The comparative study was conducted in the two test rooms, one reference room (room 1, as shown in Fig.1 (a)) and the other with the Trombe wall system installed on south facade (room 2, as shown in Fig.1 (b)). The Trombe wall system is composed of the outermost glass cover, air gap, black heat-absorbing coating, insulation plate and innermost calcium carbonate plate, as shown in Fig.1 (c). The internal dimensions of both test rooms are 1.5x1.5x2.0 m³. The walls of the rooms are made from 100mm thick polystyrene color steel plate. The aluminum window frame is installed on the north wall with the dimension of 0.7x0.7m². The 5mm+6A+5mm double glazed glass is used as the glass cover. The width of the air gap is 0.20m. Automatic shading curtain with adjustable angle is mounted above the air gap. The insulation plate adopts a 50mm thick polystyrene color steel plate. The width of the cement plate is 80mm. Two air vents are provided on the upper and lower parts of the inner and outer sides of the Trombe wall system, each with a dimension of 0.3x0.1 m². The low air vent is at 0.05m and the upper air vent is at 1.8m, as shown in Fig.1 (d).
Fig. 1. (a) Room 1, (b) Room 2, (c) Schematic diagram of the Trombe wall system, and (d) Air vent arrangement.

2.2 Experimental setup

The experiments were conducted from 6:00 on June 5th to 6:00 on June 8th, 2021, at the Songshan Lake Campus of Dongguan University of Technology (22° 91’ N, 113° 88’ E), Dongguan, China. The surface temperatures of the Trombe wall system and the south façade of room 1 were measured by PT100 temperature sensors. The heat transferred into the rooms through the south envelope from the outside was measured by the heat flux sensors. The temperature and heat flux test points of room 2 is shown in Fig. 2. Corresponding sensors were also arranged in the same position on the inner and outer surfaces of the south façade in room 2.

Fig. 2. The Trombe wall system parameters measuring point distribution.

The average temperature of nine points on the surface was taken as the corresponding surface temperature. The air velocity of the air vent 1, 2 was measured by the pipeline wind speed sensors. The data of temperature and air velocity is collected and recorded by the Agilent data logger. The temperature and humidity recorders test and record the temperature and relative humidity of the indoor air, air gap and the air vent 1, 2. The average values of three measuring points at the same horizontal position and different height were taken as the temperature and relative humidity of indoor air and air gap respectively. And the averages of the measured values of the two air vents were regarded as the parameter value of exhaust air. The measuring point distribution is shown in Fig. 1(c) and Fig. 2. Outdoor temperature, relative humidity, wind speed, wind direction, sunlight and global solar radiation were measured by automatic weather station monitors and records.
3. Result and analysis
This experiment mainly studies the performance of the Trombe wall system under the summer climatic conditions in hot summer and warm winter zone of China. During the experiment, the indoor side air vent 1, 2, and outdoor side air vent 7, 8 were opened, and other air vents were closed. And the north windows were partially open.

Fig.3 shows the trend of outdoor temperature and solar radiation intensity with time from 6:00 on June 5th to 6:00 on June 8th. It can be seen that the solar radiation reaches its peak at about 12:00, and the maximum solar global radiation intensity was 1053w/m². The outdoor temperature reaches its peak at about 15:00, and the highest outdoor temperature was 40.9°C. The lowest temperature was 25.3°C at night. The temperature difference between day and night reached 15.6°C. This indicates that the change of outdoor temperature is greatly affected by solar radiation and lagging behind the change in solar radiation intensity.

Fig. 4 shows the internal surface temperature (T₁, in) and external surface temperature (T₁, out) of the south facade in room 1, and the surface temperature of calcium cartinate plate (T₂, in) and heat-absorbing coating (T₂, out) in room 2 over time. It can be seen that the trend of the temperatures with time was consistent with that of outdoor temperature (Tₘ). In the daytime, the surface temperature of heat-absorbing coating and its change range were significantly larger than that of external surface of the south facade in room 1. But at the same time point, the surface temperature of calcium cartinate plate was lower than the internal surface temperature of the south facade in room 1, and close to the outdoor air temperature. The internal surface temperature of the south facade in room 1 was about 5°C higher than the outdoor temperature at the peak moment. Fig. 5 shows the change trend of the temperature difference between the inner and outer surfaces of the south facade in room 1 (T₁, out-in) and between the surface of calcium cartinate plate and the heat-absorbing coating in the room 2(T₂, out-in). It can be seen that the temperature differences reached their peak between 13:00 and 15:00, with the maximum value of 15.8 °C for room 2 and 6.4 °C for room1 respectively. Comparing to Fig.3, it can be found that solar radiation has a great effect on the external surface temperature distribution of the south facade, but little effect on the inner surface temperature distribution of the Trombe wall system.

Fig.3. The outdoor temperature and solar global radiation changes with time

Fig.4. Surface temperatures of the Trombe wall system in room 2 and the south façade in room 1 change with time.
Fig.5. Surface temperature differences of the Trombe wall system in room 2 and the south façade in room 1 change with time.

After the heat-absorbing coating absorbs the solar radiation heat and heats up, the air in the air gap can also be heated. The stack effect was formed in the air gap under the action of temperature difference between the air in the air gap and the indoor air. It induced the indoor air to flow from the air vent 1, 2 through the air gap, and finally to the outdoor from air vent 7, 8, while the outdoor air entered from the north window. In this paper, the hourly average air velocity of air vent 1, 2 was multiplied by the corresponding vent area and 3600, and then the hourly exhaust air rate can be obtained. Due to the specific airflow organization form in room 2, the indoor circulating air flow rate (CAF) can be considered equal to the hourly exhaust air rate of air vent 1, 2. The air change rate (ACR) of the room 2 can be obtained by dividing the circulating air flow rate into the room volume. Fig. 6 shows the CAF and ACR with time. Compared with Fig.3 and Fig.4, it can be seen that the change trend of the CAF and ACR of the room 2 was consistent with that of the outdoor temperature and solar radiation intensity. But the CAF and ACR stayed at the peak level longer. The peak level period occurs from 10:00 to 15:00, and the maximum values were 105m³/h (24.5h⁻¹) in June 5th, 122m³/h (28.6h⁻¹) in June 6th, and 140m³/h (32.7h⁻¹) in June 7th respectively. But the peak level lasted longer to 19:00 on June 7th, and an abnormal high value (199m³/h, 46.6h⁻¹) appeared between 18:00 and 19:00. This can be attributed to the influence of outdoor wind speed and wind direction. The data from the automatic weather station indicated that the wind direction during this period was mainly southeast and southwest wind, and the maximum wind speed reached 2.2 m/s. This may be the main reason for the abnormal change of the CAF and ACR. From Fig.6, it also can be seen that the maximum CAF can reach 66m³/h, 79m³/h and 88m³/h at night on June 5th, 6th and 7th, respectively. It indicate that the Trombe wall system can still play the role of inducing indoor ventilation, although there was no solar radiation at night. The above analysis shows that the Trombe wall system can effectively induce indoor ventilation, and isolate the heat directly from outdoor into the indoor air. In addition, due to the effect of the ventilation at night, although the Trombe wall system increase the thermal resistance of the south facade, it will not be conducive to the dissipation of indoor heat to the outdoor.

Fig. 6. Circulating air flow rate and air change rate change with time.

Fig.7 shows the changes of the indoor air temperatures, the temperature of the air vent 1, 2 and the air gap over time. It can be seen that the indoor air temperature of room 1 and room 2 was very close to the outdoor air temperature from 18:00 to about 8:00 the next morning. In the daytime, the indoor air temperatures showed the same changing trend with the outdoor air temperature, and the indoor air temperature of room 1 is significantly higher than that of room 2 at the same time. The maximum indoor air temperature of room 1 was 38.2 °C, 42.5 °C and 43.6 °C on June 5th, June 6th and June 7th, respectively. The maximum outdoor temperature at the corresponding time was 35.8 °C, 40.2 °C and
40.8 °C, respectively. And the maximum indoor air temperature of room 2 was 35.8°C, 38.4 °C and 39.7°C, respectively. This indicate that the Trombe wall system can effectively insulate and reduce the indoor peak temperature by up to 4.1°C during the daytime compared to the reference room. From the Fig.7, it can also be seen that the average air temperature of the air vent 1, 2 had a very small difference with the indoor air temperature, which is due to the high air change rate in the room. However, the temperature difference between the air vents and the air gap was very obvious. During the daytime, the average temperature of the air gap is about 10.5°C higher than that of the air vents. This contributes to the stack effect in the air gap, which also explains the mechanism behind the high indoor air change rate.

Fig. 7. The indoor air temperature of room 1 and room 2, the temperature of the air vent 1, 2 and the air gap change with time.

Fig.8 shows the variation of heat flux over time on the inner surface of south façade in room 1 and on the inner surface of the Trombe wall system in room2. It can be seen that the heat flux of inner surface of the Trombe wall system was much higher than that of the inner surface of south façade in room 1 from 12:00 to 18:00, even in the night time from 18:00 to 6:00. It was because that the temperature difference between inner surface and outer surface of the Trombe wall system was much larger than that of the south facade in room 1 as shown in Fig. 5. Generally the more heat transferred from outdoor to indoor, the higher the room temperature will rise. However, it can be found from Fig. 7 that the indoor air temperature of room 2 has not risen higher than that of room 1. This can be attributed to the high ACR, which taking away the excess heat transferred from the inner surface of the Trombe wall system into the room 2. And it reduces the temperature difference between outdoor and indoor air.

Fig. 8. Heat flux through the inner surface of south façade in room 1 and the inner surface of the Trombe wall system in room2.

4. Conclusion
In this paper, comparative experiment was conducted between the room with a Trombe wall system and the reference room under the summer climate condition in hot summer and warm winter zone of China. The indoor and outdoor environmental parameters and the performance parameters of the
Trombe wall system were tested and analyzed. Some conclusions can be drawn as follows.

1. The solar radiation has a great influence on the external surface temperature of the south facade, but little effect on inner surface of the Trombe wall system.
2. The Trombe wall system can effectively utilize the stack effect to induce indoor ventilation. When the outdoor temperature is near the peak value, the thermal induced ventilation capacity of the Trombe wall system reaches the maximum, with the maximum values of 105m³/h (24.5h⁻¹) on June 5th, 122m³/h (28.6h⁻¹) on June 6th, and 140m³/h (32.7h⁻¹) on June 7th respectively.
3. At night time, due to the induced ventilation effect of the Trombe wall system, it can effectively dissipate the indoor heat to the outside and use the outdoor low-temperature air to cool the indoor environment.
4. Compared with the reference room, the Trombe wall system can effectively reduce the indoor peak temperature by up to 4.1 °C during the daytime.
5. The heat entering the room through the Trombe wall system was higher than that entering the reference room from the south façade. However the high indoor circulating air flow rate can contribute to the excess heat to be ventilated to the outdoor through the air vents, without causing an increase in the indoor air temperature.

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