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Trombe Wall Application with Heat Storage Tank

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Abstract

In this study, an investigation was made of the performance of a Trombe wall of classical structure used together with a heat store. Most Trombe walls are able to supply the heating needs of a space to which they are connected without the need for extra heating at times when the sun is shining. However, the heat obtained from the Trombe wall can be in excess of needs at such times, and measures must be taken to provide ventilation to the heated space. It is thought that the heat energy can be used more efficiently and productively by storing the excess heat outside the building and using it inside the building when there is no sunlight. To this purpose, a tank full of water and marble was built as a heat store as an alternative to the general Trombe wall design, and an attempt was made to minimise heat losses by burying it in the ground. It was concluded that in place of a traditional Trombe wall system using a massive wall heat store, a heat store could be constructed in a different position and with different materials. The Trombe wall system which was developed and tested met up to 30% of the energy needed for heating and cooling the building, and reduced the architectural and static disadvantages of Trombe wall systems. As a result of the study, it was seen that where a standard reinforced concrete wall could supply heat to the inside for 7 hours and 12 minutes, the figure for a wall made of paraffin wax was 8 hours and 55 minutes. In the same study, the heat storage thickness of a reinforced concrete wall was calculated as 20 cm, while that of a paraffin wax wall was calculated as 5 cm.

Keywords: Energy Efficiency; Trombe Wall; Greenhouse; Building Construction Material; Heat Storage.

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1. Introduction

Despite the great advantages provided by Trombe walls in reducing heating costs, it is seen that they are little used by the building sector. The reason for this is generally that they do not fit in with the architectural design. However much heat a Trombe wall provides when the sun is shining, it is not able to meet heating needs when there is no sunshine. Attempts have been made to solve this problem by storing the heat obtained during the day using heat-storing walls, water tanks, or black-painted structural elements. The problems of aesthetics and functionality so created in building design have been the main hindrance to the use of Trombe walls.

In the design of the Trombe wall which we present, a water tank filled with pieces of marble is used as a heat store. By burying this water tank in the ground, heat loss is limited, and also the design of the building is made easier. When there is no sun, heat energy stored in the water and marble in the tank when the sun is shining is directed to a panel radiator in the space to be heated by means of a manually started water pump.

In this way, the heating requirements of the room are wholly or partially met when there is no sun by heat energy obtained from the Trombe wall. The rising costs of energy mean that passive systems must be used more in the heating and cooling of buildings. Studies have shown that solar energy systems using passive heating techniques can reduce

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annual costs for heating by 25% [1]. Others have shown that Trombe wall systems can meet up to 30% of annual heating needs [2].

The first Trombe wall was put into operation by Edward Morse in 1881 [3]. From then until now, Trombe walls have continued to be used, with continual developments in aesthetics and functionality. In the usual Trombe wall arrangement, a thick wall, preferably of reinforced concrete and painted black, is built on the south side of the building in order to store the sun's energy. A pane of glass is installed just in front of this wall, covering it, so that the space formed between the wall and the glass surface forms a heat corridor. This design not only helps to meet heating needs, but also, with small design changes, can be used to cool the building [4].

A Trombe wall can be constructed so as to heat, cool, or both heat and cool according to the prevailing conditions by means of small ventilation doors in the wall. Figure 1 shows the arrangement of these vents for winter and summer conditions.

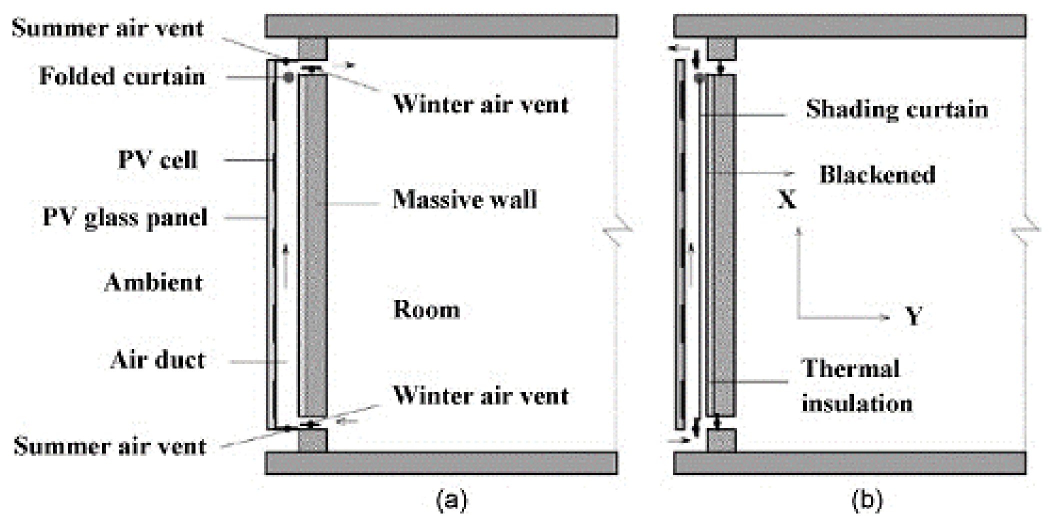

Figure 1. The Use of Air Vents in Trombe Walls in (a) Winter Heating and (b) Summer Cooling Conditions [5]

In winter conditions, or in periods of sunshine when the temperature falls below 10°C, one of the windows at the bottom of the glass or the wall opens. In conditions when the outside temperature is low, the window in the wall is opened. Air warmed in the channel between the wall and the glass enters the room through the window at the top, increasing the inside temperature [4].

In order to cool the inside in summer conditions, the vents at the bottom of the wall and at the top of the glass are opened. The heated air in the air channel rises and draws in air from the room. Removal of the warm air from the inside space helps to cool the room. Covering the outside of the wall which is exposed to the sun with light-proof insulating material will increase the efficiency of the operation of this system [4].

It was stated in a study by Sparrow and Azevedo (1985) that in order for the air flow in the tunnel to be efficient, the distance between the glass and the wall should be at least 4.7 cm [6]. In an experimental study of a house heated by natural ventilation, Bouchair (1994) found that the airflow was at its highest level in a Trombe wall system when the space between the wall and the glass was between 20 and 30 cm. It was found that when the space was 10 cm, the height of the canal had no effect on airflow, but that when the width of the canal was 30-50 cm, the airflow increased with canal height [21].

Warrington and Ameel (1995) conducted an experimental study of the geometry of Trombe walls, examining the isothermality, the façade proportions and the heat variations. It was concluded that as the spaces which enabled heat transfer in the wall increased, there was an increase in the Nusselt number, which is the ratio of convective to conductive heat transfer, but that this caused stratification in the distribution of heat in the room [7].

A Trombe wall is basically a glass surface constructed approximately 20 cm in front of a wall on the southern side of a building. The air between the glass and the wall is heated by the sun, and enters the building through suitably placed vents, thereby heating the interior. When the sun is not shining, the vents are closed, and heat transfer is prevented.

In order for the Trombe wall to contribute to the heating requirements of the building when the sun is not shining, the wall needs to be able to store heat. In this way, the wall, heated by the sun, would be expected to continue to supply heat for a period after the sun had set.

The amount of energy the wall can supply and the length of time it can supply it primarily depend on its construction materials, its mass, and its volume. The use of thick stone walls and walls filled with water, and painting these walls black, are methods which have been used to increase heat storage [8].

Rabani (2015) presents an experimental study of a newly designed Trombe wall, which is a part of the southern wall of a test room, in terms of energy performance and heating comfort during winter operation for the desert climate of the city of Yazd in Iran [9]. Z.T. Hu et al (2017) carried out a study on the traditional T-Wall. This wall usually has drawbacks of low thermal efficiency and high thermal inertia, which lead to poor heating performance and significant energy loss at night-time [10]. Jiankai Dong et al. (2018) found that the air temperature in a test room was higher than 16.0 °C during more than half of the testing time, and that the minimum air velocity was 0.35 m/s at the vent outlet. This was enough to circulate the indoor air to improve the thermal environment. Furthermore, the daily thermal efficiency of the improved T-Wall was higher than 50% during the daytime. Therefore, the results of this study provided valuable insights for improving the heating performance of a T-Wall [11]. Randjelovic (2018) presents an overview of the characteristics of the construction of the Trombe Wall in order to improve thermal stability and reduce energy consumption in buildings [12].

When Trombe walls are used in agricultural structures such as greenhouses or buildings for animals, placing barrels full of water painted black in the heated internal space provides greater heat storage. Given that the initial investment costs of Trombe walls are low and that they lessen the costs of heating buildings, the fact that they are little used today may be because their heat storage structures do not fit with architectural designs.

It is felt that in order for Trombe walls to have a wider field of application, they need to have a new form which does not limit the designer of the building. For this purpose, the heat storage elements need to be located outside the building, and flexibility would be expected in the choice of materials used in the construction of heat storage elements. In addition, the heat stores would be covered with insulating material, increasing their efficiency.

In this project, research was performed on the contribution to the heating of the inside of a building of a Trombe wall constructed with a heat store outside the building and buried in the ground. As well as more efficient and insulated heat store designs, it was expected that greater advantages would be provided in terms of heat efficiency by the PLC supported construction of the system.

2. Materials and Methods

2.1. Materials

The Trombe wall design in the project consisted of a prefabricated building, a Trombe wall, a heat store and a pumping system.

2.1.1. The Prefabricated Building

The Trombe wall was located on a portable prefabricated structure. This building measured 2.20 × 4.00 × 2.20 m, with side walls constructed of polyurethane sandwich panels of 5 cm thickness. The building was set on 18 mm thick precast concrete panels, and a PVC membrane was used. The roof was constructed of galvanized aluminium sheet, and a 5 cm layer of mineral wool was placed between the roof and the PVC panelled ceiling as heat insulation.

The building had 1 × 1 m heat-insulated window units on its south, west and east sides. On the north side there was an entrance door. On the southern side of the building, four 20 × 35 cm vents were located to enable airflow for the Trombe wall which was to be constructed on this building of standard production (Figure 2).

Figure 2. The Model Prefabricated Structure.

The thermal conductivity value (U) stated by the manufacturer of the sandwich panel which was used was 0.4056 W/m^{2}K. Similarly, the conductivity coefficient of the 18 mm thick concrete panels was stated as 0.21 W/m.K, and that of the mineral wool as 0.033 W/m.K. Because the window units were thought not to be produced with argon gas it was considered that they should be treated as double glazed units, and the mean value of their heat conductivity coefficients could be taken as 2.4 W/m^2.K.

The prefabricated building was located in an open area so that no shadows would fall on it.

2.1.2. The Trombe Wall

A sheet of glass of 4 mm thickness was attached to the southern side of the prefabricated building with a welded steel frame (Figure 3).

The Trombe wall measured 4.00 × 2.20 m, with a 20 cm space between the glass and the wall. The total surface area of the glass was 10.56 m^2, of which 8.20 m^2 was facing south.

The internal volume of the system was 1.76 m^3.

Figure 3. The Trombe Wall

2.1.3. The Heat Store

A PE water tank with a volume of 3 m^3 was used as a water store. Marble blocks, which have a higher heat storage capacity than water, were placed in the tank in a way which did not obstruct the movement of the water.

The ability of a material to store heat is related to its specific heat and its heat capacity, while the heat transfer coefficient shows how quickly heat is propagated within a material [13].

Certain heat related properties of the water and marble used to store heat are given in Table 1.

Table 1. Thermic Properties of Marble and Water at 300 K [14, 15]

Material	Density (kg/m^3)	Heat conduction coefficient (W/mK)	Specific heat (J/kgK)	Heat transfer coefficient (10^{-6}m^2/s)	Heat capacity (10^6 J/m^{3}K)
Marble	2800	1.513	1500	0.36	4.20
Water	996	0.615	4178	0.15	4.16

The water tank was buried in the ground both to reduce heat losses as much as possible in an economic way and to hide the tank from view (Figure 4).

Figure 4. The Heat Store

2.1.4. The Pumped Heat Transfer System

Water was used as a fluid to transfer heat between the Trombe wall, a radiator and the water tank. Water transmission was secured by means of a pump, which worked both when the sun was shining and when it was not. The transmission lines were made of 1” PE pipes.

The length of the PE transmission system was 55 m, 43 m of which formed the heating line in the Trombe wall (Figure 5).

The water pumps were operated by a time switch. The pumps maintaining circulation were able to tolerate hot water; they had a power of 500 W and a flow capacity of approximately 1 m^3/h. Valves on the water transmission system could be used to slow the flow of water.

The radiator panel was 1200 × 600 × 105 mm in size, with a pitch distance of 25 mm. At between 65^{o}C and 75^{o}C, the capacity of the panel was calculated to be approximately 2158 W.

Figurer 5. The Pumped Heat Transmission System

2.1.5. Measurement Instruments

Digital thermometers with integrated data loggers were used as measurement instruments. These could record the outside and inside temperatures simultaneously at specified times (Figure 6). The thermometer was set to measure the inside and outside temperatures hourly over a period of 365 days.

Figure 6. The Digital Thermometer

2.2. Methods

With a Trombe wall system, the function of the massive wall is to store heat energy. Therefore, the most important part of a Trombe wall system is the massive wall structure [16].

It is known that as the weight and volume of the massive wall in a Trombe wall system increase, the heat storage capacity also increases, extending the time for which the inside temperature can be maintained. However, a heavier and larger wall poses problems in construction. In order to overcome this, Li and Liu (2014) compared the performance of Trombe walls constructed from materials which could change phase. As a result of the study, it was seen that where a standard reinforced concrete wall could supply heat to the inside for 7 hours and 12 minutes, the figure for a wall made of paraffin wax was 8 hours and 55 minutes. In the same study, the heat storage thickness of a reinforced concrete wall was calculated as 20 cm, while that of a paraffin wax wall was calculated as 5 cm [17].

Even though it may be possible to construct a wall of phase-changing materials, the use of materials with the characteristics of construction materials in the production process increases the practicality of the technique. Studies have concluded that when materials such as bricks, concrete or gas concrete are used as construction materials in the design of a Trombe wall, the best performance is obtained from gas concrete [18].

When Agrawal and Tiwari evaluated wall construction materials from the point of view of economy and performance, they found that a massive wall constructed from gas concrete and a wall thickness of between 30 cm and 40 cm gave the optimum advantage [19].

Because the specific heat of water is greater than that of the building materials, the temperature of the water surface is lower, and for this reason less heat energy is lost by reflection from the water surface. However, it is difficult to construct a Trombe wall in the form of a water tank, and walls are built in practice using solid construction materials [20].

A Trombe wall model was investigated in the study in which water and marble were used together, and which would not be limiting in terms of the building’s static and architectural design. The system was a standard Trombe wall model, but in place of the massive wall, a wall structural element was used with the same characteristics as the other parts. The air in the space between the wall and the glass, warmed when the sun was shining, heated both the inside of the model building by way of the air vents, and also the water in the black pipes located in the channel.

The Trombe wall heated the model building when the sun was shining by mechanisms of heat conduction and convection. These processes happened naturally in the experimental model. However, heat circulation can be more effectively achieved by managing this natural convection by control of the vent system or by fans [8].

The length of the black pipes placed between the wall and the glass was approximately 43 m. The system was filled with water from a filler cap located at the highest point of the pipes. When the sun was shining, the water circulating in this pipe by means of a circulation pump transferred the heat from the black water pipes to the marble in the water tank. In this way, heat collected which was in excess of current needs was stored in the heat store for use after the sun had stopped shining. Because the inside of the model building had no need of heating while the sun was shining, water was not allowed to circulate through the radiator panels.

Sometime after the sun stopped shining, the inside of the model building was in need of heating. Because the vents in the Trombe wall were sources of heat loss, they were closed at times when the sun was not shining, and the water circulation between the Trombe wall and the heat store was stopped. At these times, water circulation between the water store and the radiator panel was started, providing the building's heating requirements in whole or in part.

Times of operation of the pumps supplying pressure to supply hot water from the heat store to the radiator panel when there was no sunlight were set according to the times of sunrise and sunset.

The two pumps providing water circulation had a power of 500 W. It would have been possible to construct a system with a single pump and two-way valves, but in order for measurements to be continued in the case of possible breakdowns, the transmission pipes were designed as in Figures 7 and 8.

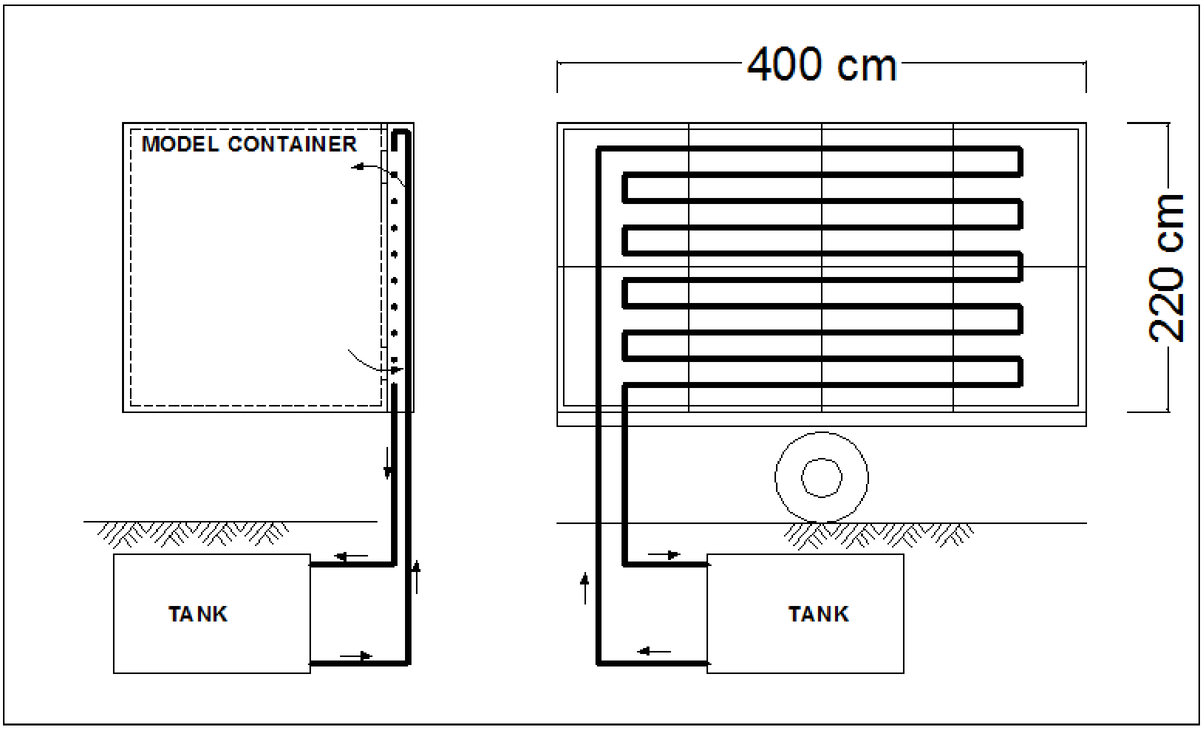

Figure 7. Water Circulation in the Trombe Wall System When the Sun was Shining

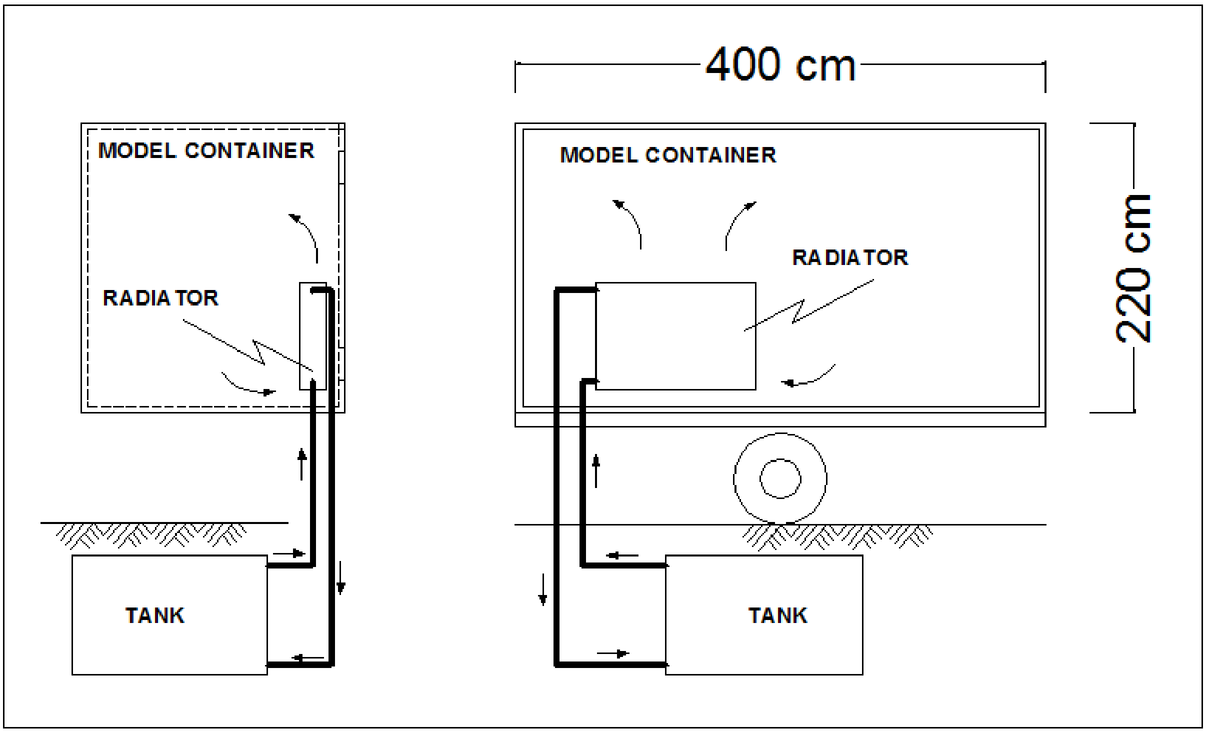

Figure 8. Water Circulation in the Trombe Wall System When the Sun was not Shining

In order to measure the contribution of the heat store to the system, the heat store was operated every alternate day over a one-year measurement period. In this way, inside temperatures were compared on days with similar temperature profiles with the heat store in operation and not in operation.

When determining similar outside temperature series, statistical grouping was not made because there were 24 pieces of data for each day, and hourly temperature changes and daily temperature variation functions were very close to one another. Grouping was made according to how daily average temperature and maximum and minimum temperatures were affected by the heat energy in the outside environment in connection with a large number of parameters such as duration of sunlight time, day length, and light intensity.

3. Results and Discussions

3.1. Annual Temperature Variations in the City of Muğla

An examination of recorded outside temperatures showed that in the months which particularly concerned the topic of the study, October, November, December, January, February and March, outside temperatures varied between -6 °C and 27.9 °C, with an average of 8.0 °C (Figures 9 and 10).

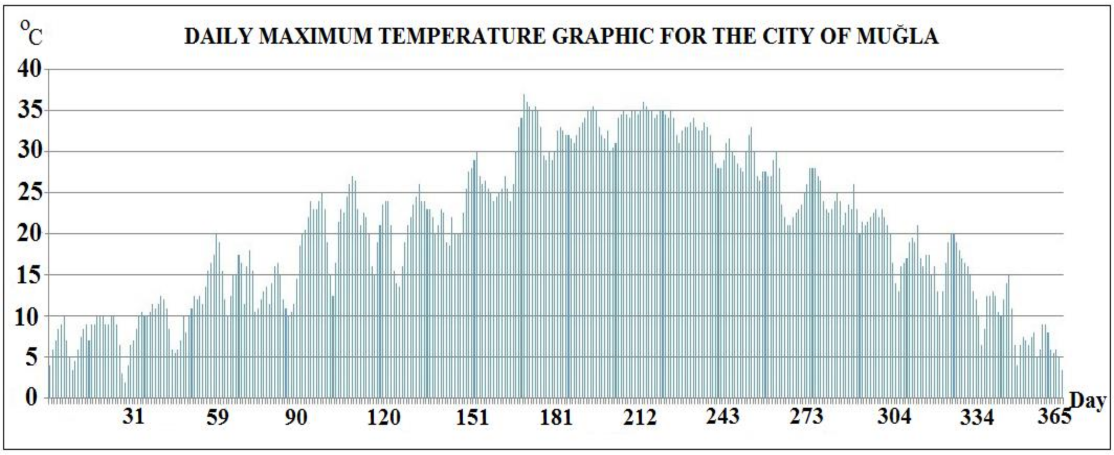

Figure 9. Daily Maximum Temperatures for the City of Muğla in 2016

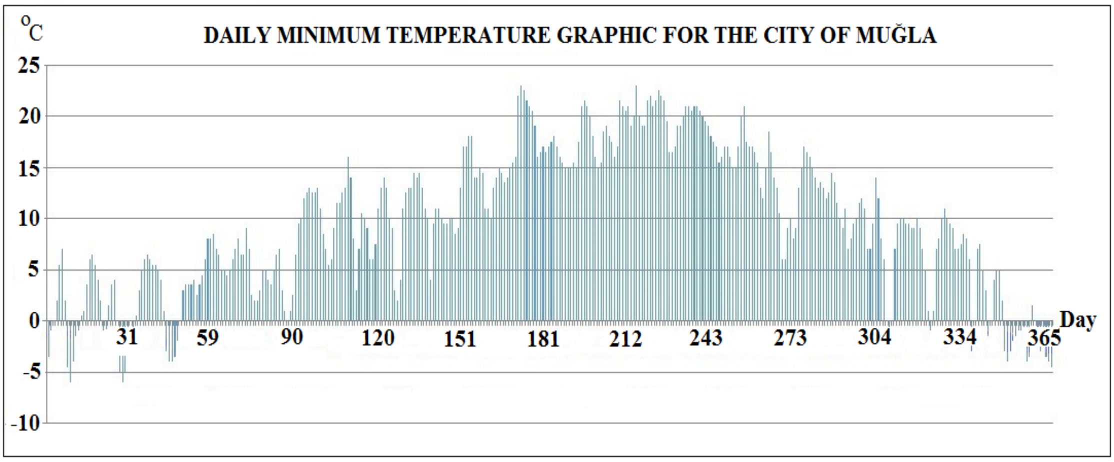

Figure 10. Daily Minimum Temperatures for the City of Muğla in 2016.

Examining temperature series for consecutive days, it was noticeable that hardly any were identical and that the series of consecutive days showed differences in their statistical characteristics. For this reason, series in which the difference between the average, maximum and minimum temperature values was up to 1 °C were taken as identical series.

Just as the inside temperature reached higher values in the winter months with the operation of the heat store in addition to the Trombe wall, the cooling period for times when there was no sun was also lengthened. The graphs below show examples of consecutive days when outside temperatures were similar. Examining the graphs, it can be seen that when the heat store was in operation, an increase in average inside temperatures of 1 °C - 5.5 °C was secured when the sun was shining, and of 1°C - 11.5°C when the sun was not shining (Figures 11-18).

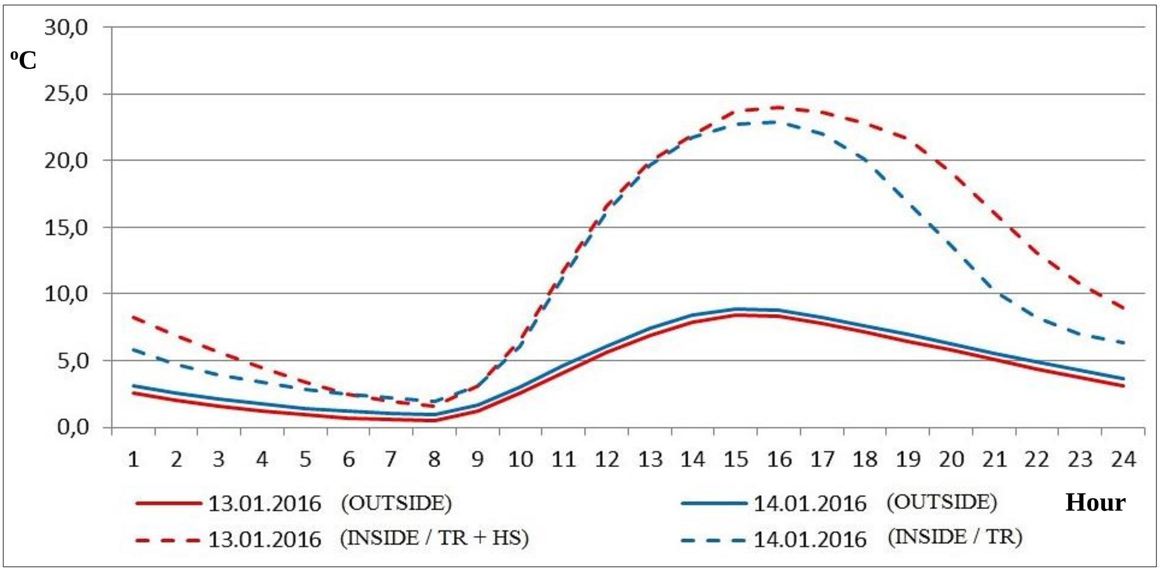

Figure 11. Variation of Temperatures Inside and Outside the Model Building, 13.1.2016 - 14.1.2016

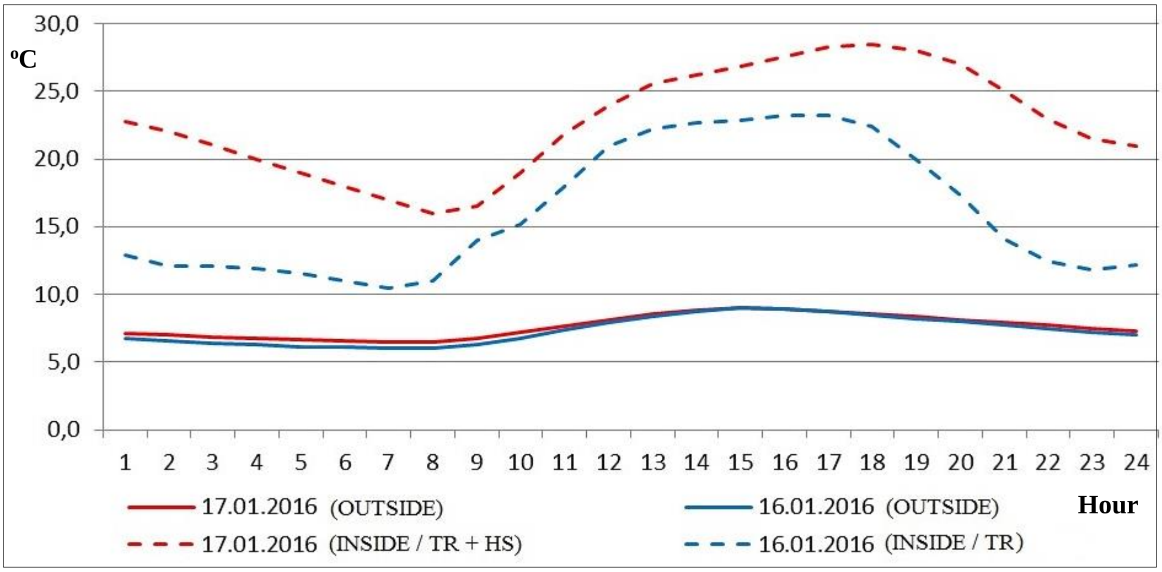

Figure 12. Variation of Temperatures Inside and Outside the Model Building, 16.1.2016 - 17.1.2016

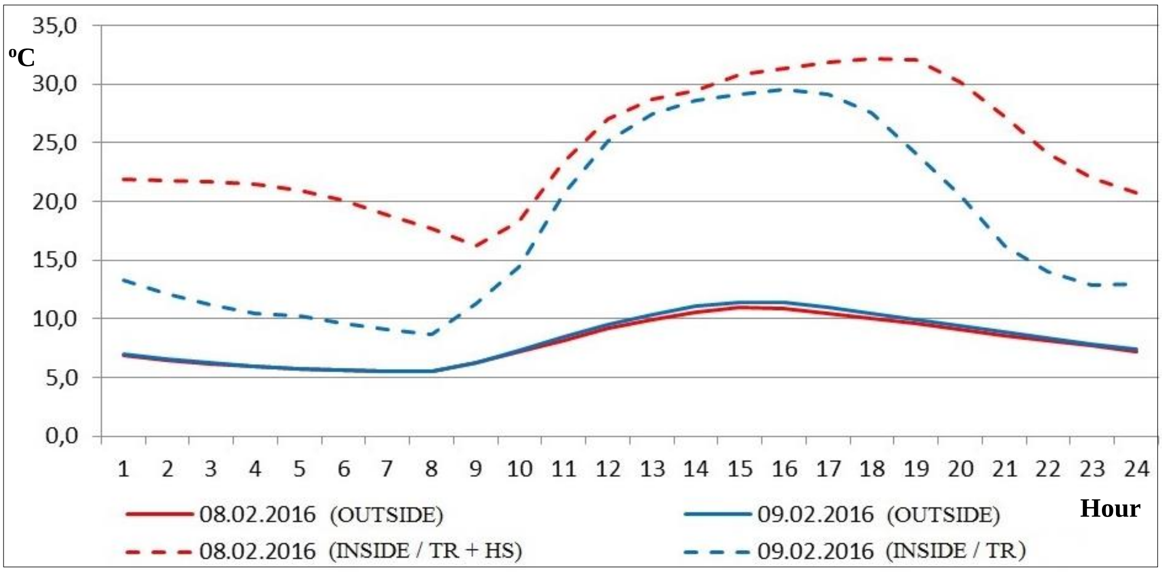

Figure 13. Variation of Temperatures Inside and Outside the Model Building, 8.2.2016 - 9.2.2016

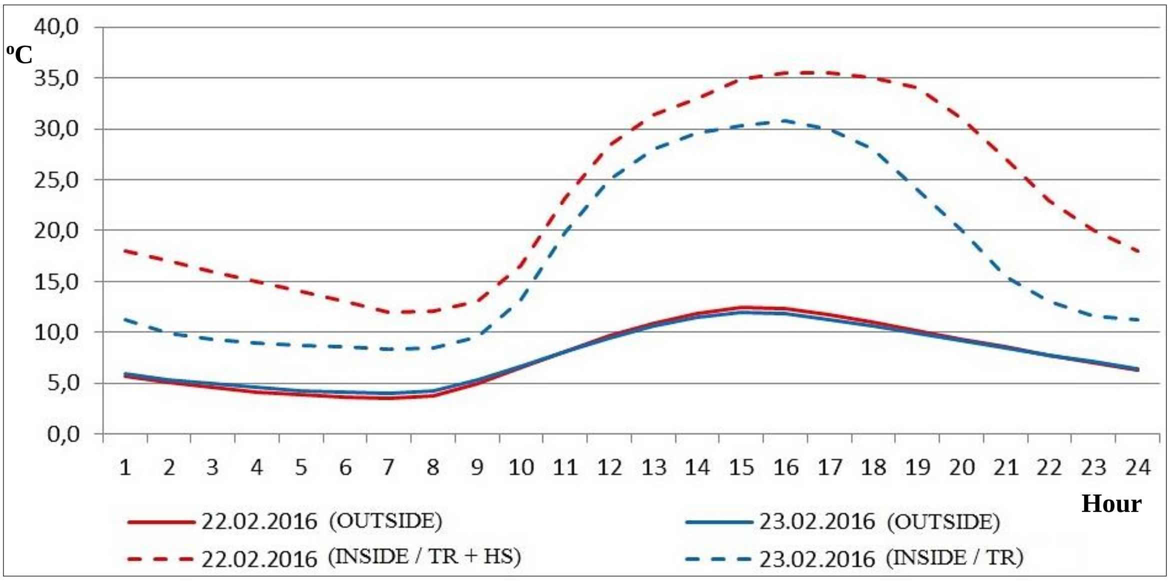

Figure 14. Variation of Temperatures Inside and Outside the Model Building, 22.2.2016 - 23.2.2016

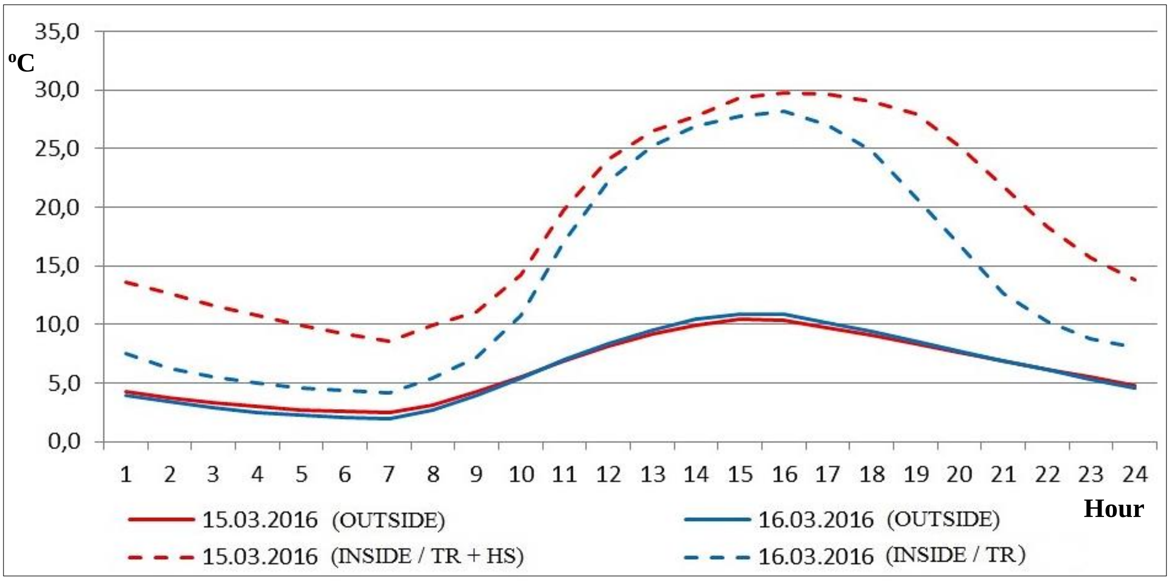

Figure 15. Variation of Temperatures Inside and Outside the Model Building, 15.3.2016 - 16.3.2016

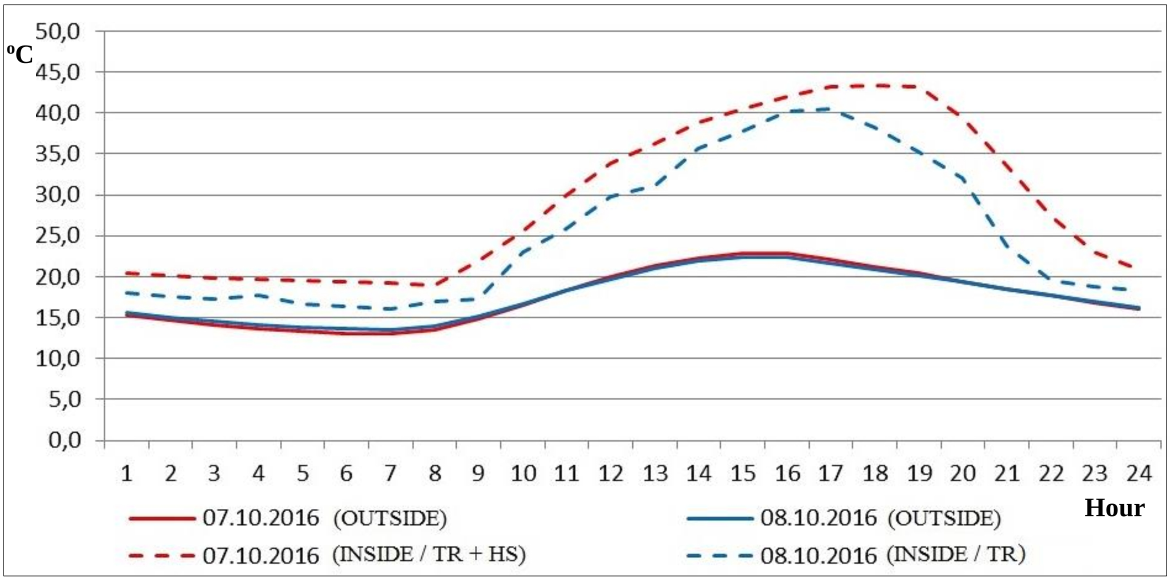

Figure 16. Variation of Temperatures Inside and Outside the Model Building, 7.10.2016 - 8.10.2016

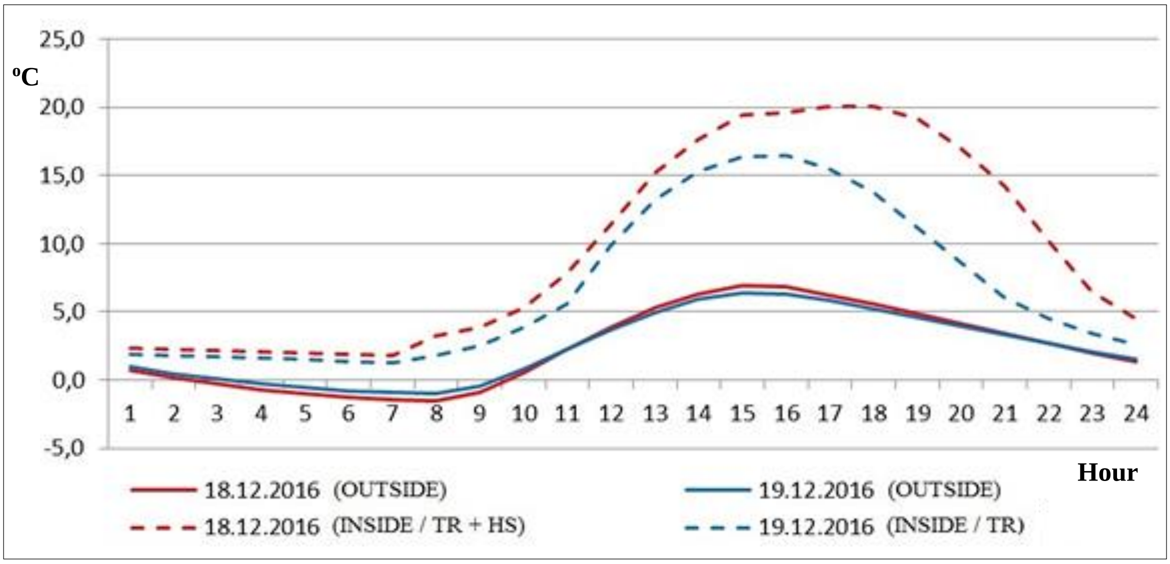

Figure 17. Variation of Temperatures Inside and Outside the Model Building, 18.12.2016 - 19.12.2016

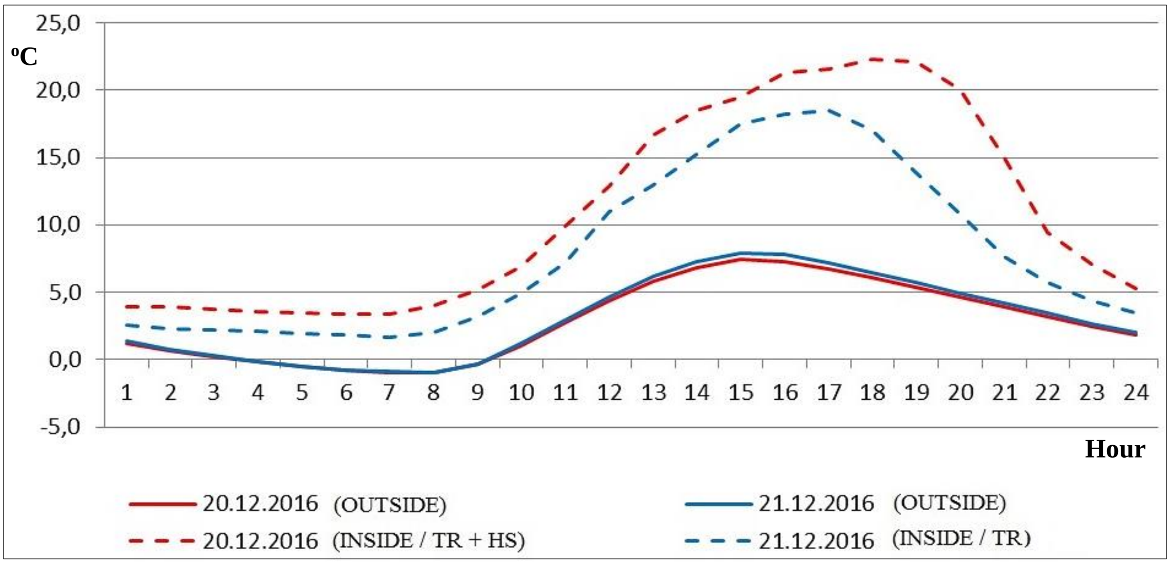

Figure 18. Variation of Temperatures Inside and Outside the Model Building, 20.12.2016 - 21.12.2016.

It was seen that under experimental conditions, the operation of the Trombe wall was largely able to meet the needs for heating the building when the sun was shining, and it reduced heating needs when the sun was not shining because of the heat energy stored in the mass of the building.

When the Trombe wall system was used along with the heat store under experimental conditions, higher inside temperatures were measured throughout the day including when the sun was shining. In particular, the contribution of the heat store to the inside temperature of the building at times when there was no sunshine enabled the Trombe wall to make the inside temperature higher even when the heat store was not operating after the sun started to shine.

Examining temperature variations when the heat store was in operation, it was seen that the stored energy continued to raise the inside temperature after the sun had stopped shining. The graphs show that when the heat store was in operation, the inside temperature continued to increase for three more hours than when it was not operating. However, it was seen that when after a time the amount of stored heat was reduced, the inside temperature fell more quickly than without the heat store. However, at no measurement did the room temperature fall to the level of when the heat store was not used.

When the sun started to shine, the heat store was disconnected, and it was observed that when the sun was shining the increase in inside temperature was similar both with and without the use of the heat store. It was seen that inside temperatures increased according to variations in outside temperatures with a delay of two hours when the heat store was not used, and with a delay of up to five hours when it was used.

In the measurement process in the winter months, the inside temperature of the building was measured to be 1.1 °C - 24 °C above the outside temperature. At similar outside temperatures but when the heat store was not operated, the temperature inside the model structure was measured to be 0.9 °C - 18.9 °C higher than the outside temperature. The measurements performed showed that the use of a Trombe wall together with a heat store similar to that in the project provided an average temperature increase of 24%.

3. Conclusion

Examination of many studies of Trombe walls shows that mathematical models have not given conclusive results because of the large number of parameters affecting the system, such as rainfall, length of sunny periods, cloudiness, and the amount of radiation. For this reason, it was thought to be important to determine the performance of Trombe walls experimentally by comparing the results of simultaneous measurements.

It was concluded that in place of a traditional Trombe wall system using a massive wall heat store, the heat store could be arranged with different construction materials and in a different position. The Trombe wall system which was developed and tested met up to 30% of the energy needed for building heating and cooling, and reduced the architectural and static disadvantages of Trombe wall systems.

The heat store developed as part of this project was constructed under the ground. Therefore, a heat store of much greater volume could be constructed if necessary. It is thought that a larger volume heat store would provide much greater heat recovery.

The system which was designed was completely manually controlled. The operation of the hot water pumps was controlled by timers, but the change in the times of sunrise and sunset meant that these had to be reset approximately every five days. It is thought that a system could be developed in which the opening and closing of the valves and air vents would be controlled by a PLC (Programmable Logic Examination and Control) supported system.

It is thought that a photovoltaic or wind turbine system could be used to provide the energy needed for the motors of a PLC-supported pumped system. In this way, no manpower or electrical energy would be needed to realize the expected 30% heat energy gain of a Trombe wall system. The air vents and hot water pumps and valves of a Trombe wall system could be automated with a PLC system that could be programmed to keep the room temperature at the desired level.

4. Funding

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5. Conflicts of Interest

The authors declare no conflict of interest.

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