COMPARISON OF DYNAMIC THERMAL SIMULATION RESULTS WITH EXPERIMENTAL RESULTS: TROMBE WALL CASE STUDY FOR A CYPRUS TEST BUILDING

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ABSTRACT

Cyprus' location offers abundant of solar insolation during heating season, which could be exploited by a Trombe Wall yielding comfortable built environment and reduced heating load.

This work investigates thermal performance of a Trombe Wall installed test building. The work compares the outputs from Energy Plus simulations with the experimental results that were obtained during a period of heating season in Cyprus.

The test building has floor area of 12.2 m^2 and involves south facing Trombe Wall with a surface area of 11.9 m^2. Monitoring of solar radiation, outdoor and indoor air temperatures, Trombe Wall indoor and outdoor surface temperatures was carried out from 13th January 2016 to 26th February 2016. Dynamic thermal simulation was carried out for the same period.

Simulation results showed good agreement with the monitoring results. Simulated and monitored Trombe Wall inside and outside surface temperatures were very similar whereas, indoor air temperatures were slightly higher for simulations.

INTRODUCTION

Using thermal mass is a widely used method for controlling extreme temperatures in buildings. This method works by storing heat in a heavy structure during daytime causing slow increase of temperature thus preventing occurrence of extreme values. The stored heat subsequently is released during night-time resulting in higher temperatures in the built environment. This method is widely used to heat buildings particularly in the areas having relatively high diurnal temperature difference.

A particular application of thermal mass is Trombe Wall. This is a plain wall, which is made from materials having high density and specific heat capacity. Outside face of the wall is painted black or coated with a high absorptivity material in order to increase absorbed solar radiation. The wall is normally made from concrete and installed on the south façade of the buildings for the northern hemisphere locations. A glass is also installed in front of the Trombe Wall and a narrow air gap exists between the wall and the glass cover. The glass layer increases the temperature of the air gap by greenhouse effect.

There have been many attempts by researchers to create simulation models of Trombe Wall performance. Zalewski et al. (2002) compared four different types of these walls based on three years-long experimental results. They proposed a model, which can be used for studying the energy efficiencies of the Trombe Walls in different conditions. Shen et al. (2007) conducted a numerical study on thermal behaviour of classical or composite Trombe walls. They found that the composite wall performed better than the classical wall in cold or cloudy weather. Rabani et al. (2013) developed a numerical simulation for a Trombe wall under Yazd weather conditions. The results showed that the Trombe wall made of paraffin wax can keep the room warm longer compared to concrete, brick or hydrated salt walls. Bajc et al. (2015) conducted a CFD analyses for a passive solar house with Trombe wall for Belgrade weather. It was concluded that the Trombe Wall has a major contribution to heating in winter. Hong et al. (2015) developed a complete 3-D model to investigate the performance of a Trombe wall equipped with a venetian blind. The results revealed that the efficiency of the Trombe Wall can increase slightly in winter.

The objective of this paper is to investigate the real life performance of a Trombe Wall building in terms of experienced temperatures. It is also aimed to compare and validate the results from Energy Plus simulation with the experimental results for the particular application in this work in order to give building designers a benchmark for a real life application of Trombe Wall to the Cyprus buildings.

In Energy Plus, there is not a special module for modelling the Trombe Wall. However, there is an option for selecting the convection algorithm for the narrow air gap lying between the outer face of the Trombe Wall and the glass cover. This algorithm is designed for evaluating the heat transfer coefficient (*h*) in the narrow air gap and is based on the ISO standard (ISO, 2003). The rest of the objects in the Energy Plus is used as usual during modelling the Trombe Wall installed building. The convection algorithm was already validated both theoretically and experimentally (Ellis, 2003).

METHODOLOGY

The building that is simulated and monitored is a test building, which is built for research on passive and active low energy methods. It is located in the campus of Eastern Mediterranean University in Famagusta (Lat. 35.1^{o}, Lon. 33.9^{o}), Cyprus.

Thermal simulation of the building was carried out by dynamic thermal simulation program Energy Plus by using the weather data of Larnaca (Lat. 34.9^{o}, Lon. 33.6^{o}) as Famagusta's weather data does not exist in the Energy Plus. Weather of Famagusta and Larnaca is very similar as two locations are only 50 km away from each other and both lie on the coast. These locations do not have significant differences in their geographical features too.

Energy Plus is selected as the thermal simulation program since it is a powerful, widely used, free and open source thermal simulation program. In addition, Energy Plus gives great flexibility for modelling the Trombe Wall as it does not have a special module for this purpose (except for evaluating *h* in the air gap between the Trombe Wall and glass cover). It uses the existing features or objects of Energy Plus for modelling Trombe Wall. This gives opportunity to apply different wall configurations with different features. (U.S. Department of Energy, 2015).

Computer simulation was carried for a period of heating season and results were compared with the monitored data that was collected during the same period. The period was from 13th of January until 26th of February. Only the heating season is considered in this work as the Trombe Wall is usually used for passive heating applications though there might be use for overheating control during cooling season.

The monitored parameters were solar radiation, Trombe Wall inside and outside surface temperature, outdoor and indoor air temperature.

Simulated Building

Simulated building consists of two zones. First zone is referred as zone 1and it is the zone for occupancy whereas second zone is the zone, which lies between the Trombe Wall and the glass cover. Second zone is referred as Trombe Wall zone. Two zones are separated from each other by interzone partition, which is the Trombe Wall itself in this work. The building has to be modelled in this way as Energy Plus does not have a separate module or object for Trombe Wall.

Simulated building floor area is 12.2 m^2 and the Trombe Wall area is 11.9 m^2. Picture of the test building is shown in Figure 1. Plan of the test building and the model for simulation is shown in Figure 2 and Figure 3 Respectively.

There are several heat transfer algorithms in Energy Plus for simulating the heat flow through building fabric such as Conduction Transfer Function (CTF), Conduction Finite Difference (CFD) methods, etc. CTF method is used frequently for sensible heat only solutions whereas, CFD method is used when the nodal temperatures within the building fabric is to be evaluated. In this work CTF algorithm was selected since the Trombe Wall building is dominated by sensible heat capacity and it is not intended to find the Trombe Wall nodal temperatures. Selected time step for the simulation is kept as low as possible i.e. one minute in order to increase the accuracy of the results.

Figure 1 The test building

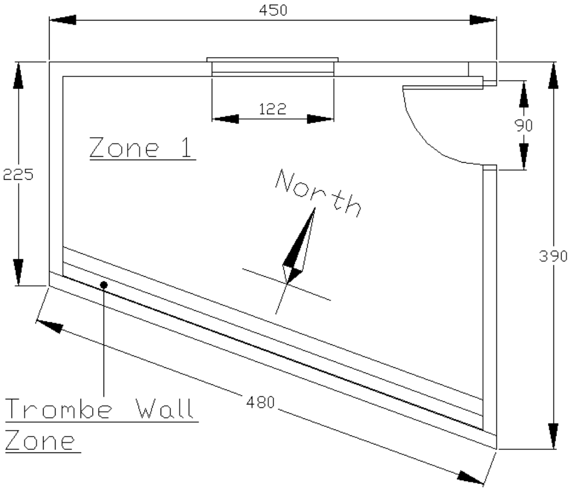

Figure 2 Plan of the test building (dimensions are in cm, thickness of the Trombe wall zone is 14 cm)

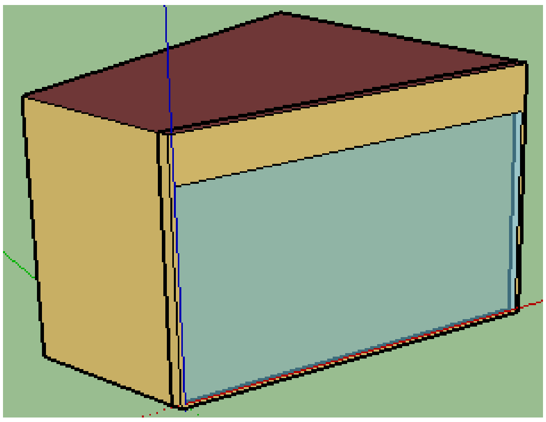

Figure 3 Three dimensional model of the building (building height is 3.3m)

There is not any active heating and cooling equipment in the test building, therefore, no heating or cooling equipment assigned to the simulated building.

A desktop computer and a fluorescent lamp exist in the building as internal heat sources. The computer is used for monitoring the data and it is always on. The wattage of the computer (including screen) is 450 W. The lamp is off almost at all times in the test building. It is only turned on when the logger is restarted every day or every other day for monitoring for only 5 or 10 minutes. Therefore, in the simulation computer was always kept on and the lamp always kept off.

The Trombe Wall is made up from reinforced concrete having thickness of 16 cm. Its outer surface is black painted. Outer walls and roof are made from cement boards and PVC with an air gap in between them. This is relatively low cost and practical to install for a test building. The floor is constructed from reinforced concrete, screed and ceramic. Floor lies on top of a hardcore. The building constructions are given in Figure 4. Table 1 shows thermophysical properties of the building fabric. Properties of the building fabric are sourced from ASHRAE (ASHRAE, 2013) and CIBSE (CIBSE, 2006) guides.

The glass cover of the the Trombe Wall is aluminium framed single glazed window. Thickness of the glass is 6 mm and the glass is clear. Conductivity and conductance values of the glass and the frame are 0.9 W/m.K and 6.9 W/m^2.K respectiveley.

There are two single glazed windows in the building employing PVC frame and 6 mm clear glass. Conductivity and conductance values of the glass and the PVC frames are 0.9 W/m.K and 2.2 W/m^2.K respectiveley.

The door of the building is made up from 4.5 cm thick PVC having conductivity value of 0.16 W/m.K.

Table 1
Properties of the building fabric

MATERIAL	PROPERTY			
	k	ρ	c_p	α
Reinforced concrete	1.9	2300	840	0.7
Black paint	0.85	2400	1000	0.96
PVC	0.19	1200	1470	0.26
Cement Board	0.25	1400	840	0.73
Ceramic tile	0.8	1700	850	0.6
Screed	1.4	2100	650	0.73
Thermal resistance of the air gaps is 0.14 m^2K/W k: thermal conductivity (W/m.K), ρ: density (kg/m^3), c_p: specific heat (J/kg.K), α: solar absorptance				

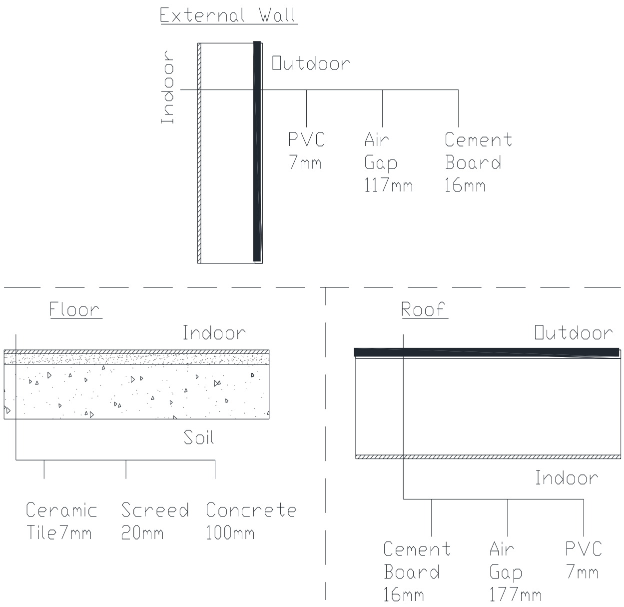

Figure 4 Building constructions

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Experimental Setup

The monitoring of the test building was performed by employing thermocouples for measuring the indoor air temperature and surface temperatures of the Trombe Wall (both inside and outside). The outdoor temperature and the global solar radiation was also recorded. A pyronometer was used for monitoring the global solar radiation that was mounted on the frame of the Trombe Wall glass cover. A data acquisition system with a computer was used to collect the data. The data acquisition system is Omega OMG-DAQ-3000 series, 1-MHz, 16-Bit USB Data acquisition module which thermocouples or any voltage input can be connected to its channels. The system setup and a general view of the system are shown in Figure 5 and Figure 6 respectively.

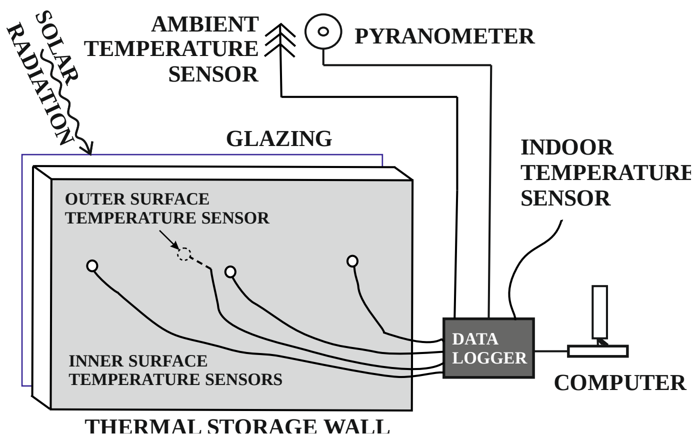

Figure 5 Experimental setup

Figure 6 General view of the experimental setup

Six thermocouples were used to measure associated temperatures. Three were employed for measuring the inside surface temperatures of the Trombe Wall (one placed at the midpoint and two at the sides). One thermocouple was placed at the midpoint of the outer surface of the Trombe Wall. One used to measure outdoor air temperature with a radiation shield and the last one was placed in the test building 90 cm above the floor for measuring the indoor air temperature. A close up view of thermocouple for measuring the outdoor air temperature with radiation shield and the pyranometer as well as the data acquisition system is shown in Figure 7

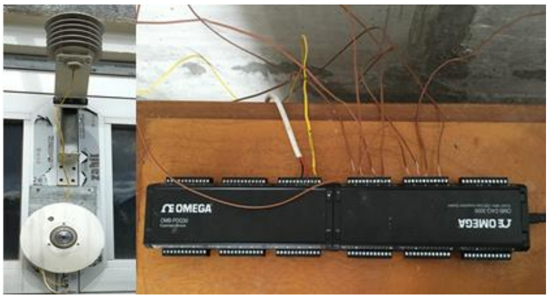

Figure 7 Close up view of the outdoor air thermocouple, pyranometer and data acquisition system

Monitoring period was the same as the simulation period (13th of January-26th of February). Recording of the parameters was performed for every 20 minutes. The system was started in the morning on everyday or every other day. Once the recording ended the system was restarted for recording again. This is done in order to avoid loss of significant amount of data if there is an electrical power cut. During the monitoring period there were electrical power cuts; two due to a maintanence for the main power lines and two due to a maintanence of electrical services and power generator of the campus building. Therefore, the data for 16th January 12:00-18th January 09:00, 31st January 09:00-1st February 07:00, 16th February 09:00-17th February 08:00 and 18th February 10:00-19th February 08:00 were lost.

RESULTS AND DISCUSSION

As it was stated in preceding sections test room air temperature, Trombe Wall inside and outside surface temperatures, outdoor air temperature and solar radiation were considered for investigation. Hourly values for these parameters were used for comparisons. The time step for the Energy Plus simulation was one minute but the results are reported hourly. Results from monitoring were also reduced to hourly values by averaging values for every three time step. The results are presented for a typical day and as cumulative distribution function curves (CDF) of the whole values.

Typical Day Results

A typical day for comparison was found by comparing the daily average values of solar radiation and outdoor air temperature of monitoring and simulation results. The difference of daily solar radiation and outdoor air temperature between monitoring and simulation results was minimum for 22nd January. 2.7 W/m^2 difference between the monitoring and simulation results was found for daily solar radiation whereas, 1 ^{o}C difference occurred for outdoor air temperature between monitoring and simulation results. Results for indoor air temperature, Trombe Wall inside and outside surface temperatures, solar radiation and outdoor air temperature are given in Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12 respectively.

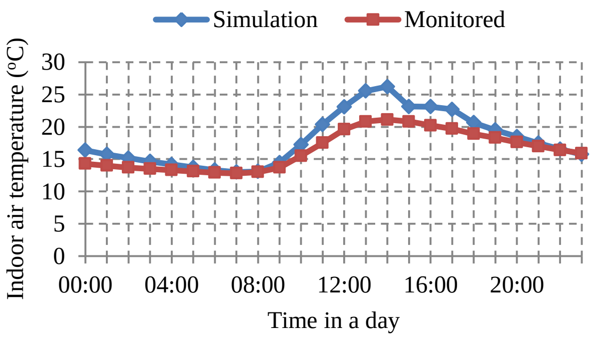

Figure 8 Indoor air temperatures

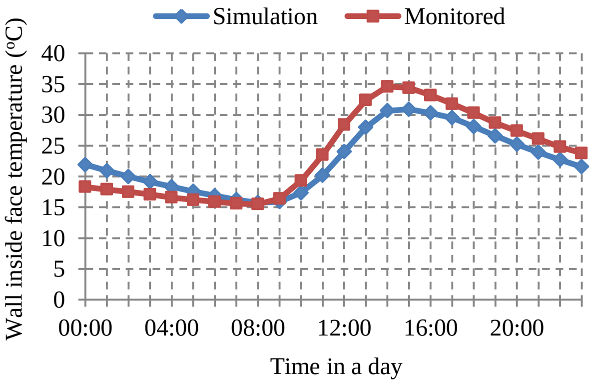

Figure 9 Trombe Wall inside surface temperatures

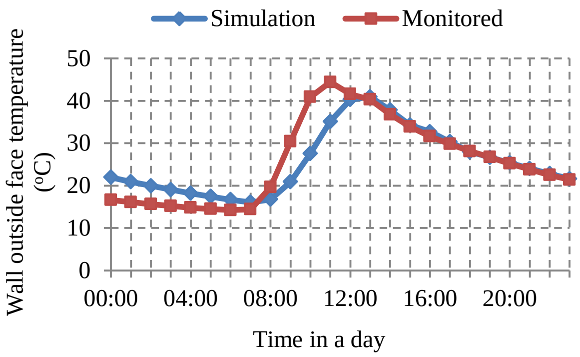

Figure 10 Trombe Wall outside surface temperatures

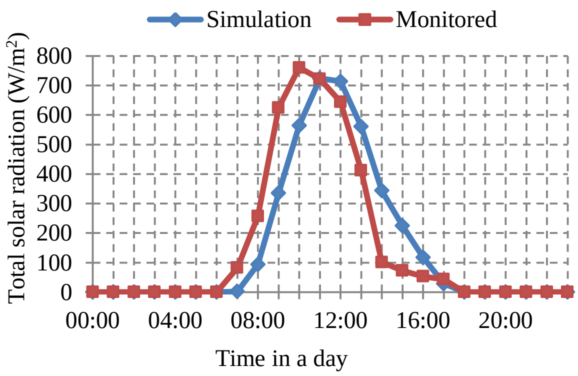

Figure 11 Solar radiation

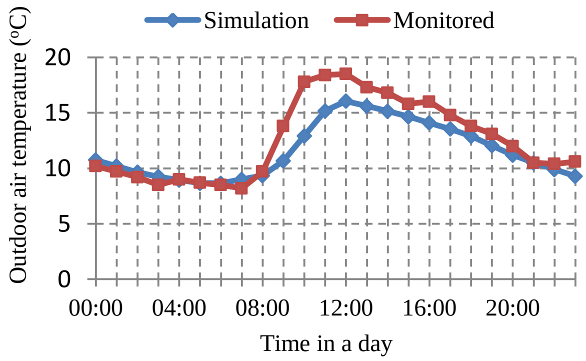

Figure 12 Outdoor air temperatures

As it is seen in above figures, simulation results agree with monitored values with some discrepancy. This is expected as it is almost impossible that the weather data for simulation will match exactly with the instant real weather. In addition, there has to be some discrepancy between the material properties (taken from literature) used in simulation and existing materials' properties in real application.

Indoor air temperatures are having very similar values during morning and night hours. Through the afternoon hours, a peak difference of 5.1 ^{o}C occurs at 14:00. The daily average of the indoor air temperature difference between the monitored values and simulated results are 1.7 ^{o}C. It is also seen in Figure 8 that simulations are resulting higher temperatures and higher fluctuations. It should be noted that the indoor air temperature reported in the simulation results are zone mean air temperature, which is the average temperature of the air temperatures at the system time step.

Recorded Trombe Wall inside and outside surface temperatures are agreed with the simulated temperatures with some discrepancy. The daily average of the Trombe Wall temperature difference between the monitored values and simulated results are 2.3 and 2.9 ^{o}C for inside and outside surfaces respectively. It is also seen in the Figure 9 and Figure 10 that inside surface temperatures show better agreement than outside surface temperatures. The peak discrepancy for outer surface temperature reached up to 13.3 ^{o}C which is significant, whereas the peak discrepancy for the inside surface temperature reached up to 4.9 ^{o}C. It is thought that this is because of the rapid response of the outer surface to the solar radiation falling on the wall. As it is seen in Figure 10 and Figure 11 the peak discrepancies for inside surface temperature between the monitored and simulated results corresponds to the same period as peak discrepancies of solar radiation. It should also be stated here that three temperatures (mid wall and sides) were recorded for the inside surface temperature and their average is reported in this work whereas a single (mid wall) temperature recording has been done for the outer surface. Obviously, this has effect on this discrepancy too.

It is seen in Figure 11 and Figure 12 that solar radiation and outdoor air temperature values for simulation and monitoring agrees with each other with daily average discrepancies of 59.2 W/m^2 and 1.2 ^{o}C and also with standard deviation (of hourly differences) of 88.5 W/m^2 and 1.7 ^{o}C.

Cumulative Results

The monitored and simulated data are also investigated in terms of frequency distributions. This enables to comprehend the relatively long-term comparisons of the simulation results and monitored values as well as performance. CDF curves for indoor air temperature, Trombe Wall inside and outside surface temperatures, solar radiation and outdoor air temperature are given in Figure 13, Figure 14, Figure 15, Figure 16 and Figure 17 respectively.

It is seen in Figure 13 that frequency of the occurring indoor air temperatures are almost identical up to 15 ^{o}C. However, there is an increasing gap up to 21 ^{o}C. It is also clear in Figure 13 that simulations are giving higher indoor air temperatures. This is agreeing with the typical day (Figure 8) as experienced temperatures in reality were lower than the simulation results.

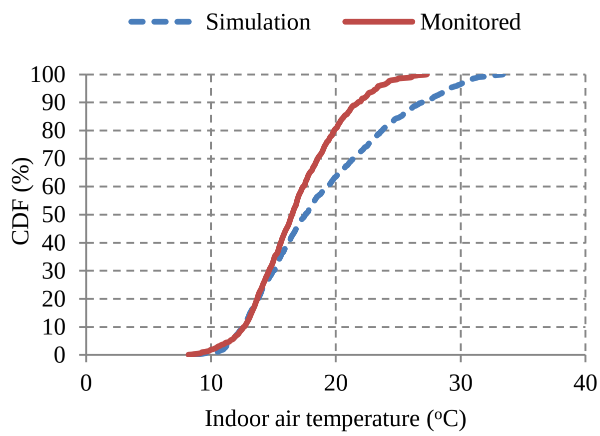

Figure 13 CDF curves for indoor air temperatures

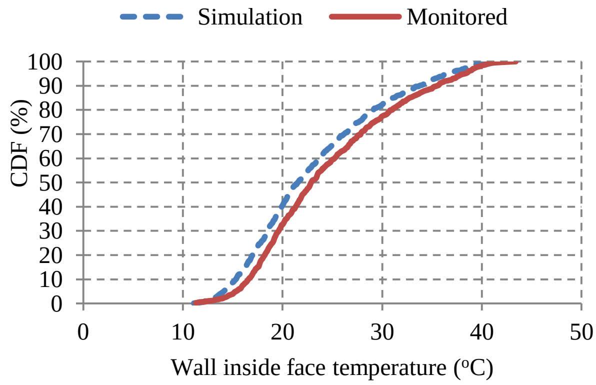

Figure 14 CDF curves for Trombe Wall inside surface temperatures

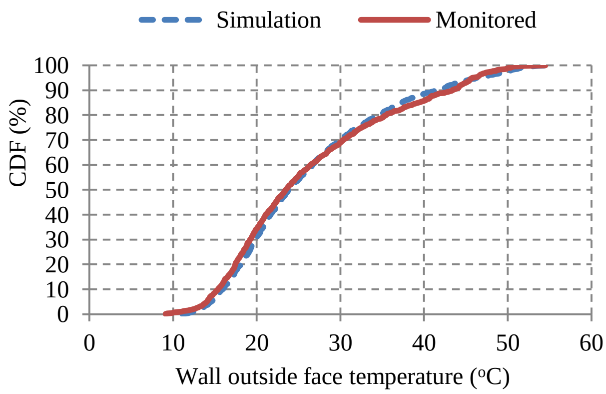

Figure 15 CDF curves for Trombe Wall outside surface temperatures

When the Figure 14 and 15 are investigated, it is seen that monitored inside and outside surface temperatures of the Trombe Wall well matches with the simulation results. The closeness of the monitoring and simulation results is more for outside surface temperatures. It is seen in Figure 16 and Figure 17 that CDF's of solar radiation and outdoor

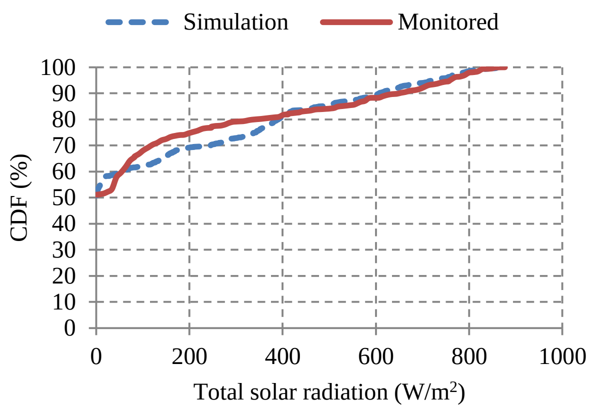

Figure 16 CDF curves for solar radiation values

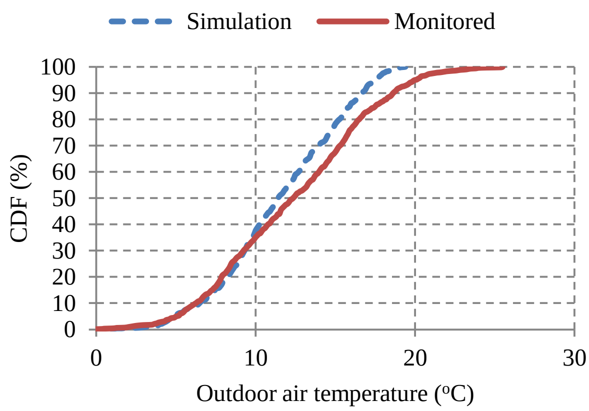

Figure 17 CDF curves for outdoor air temperatures

air temperatures are also agreeing well with each other. Perhaps this is the main reason that CDF's for outside surface temperatures of monitored and simulation results are closer than the CDF's for inside surface temperatures.

Coldest Day Results

According to the monitored results, Trombe Wall performed well during the considered heating period. The coldest day for this period was 25th of January. Average outdoor air temperature on that day was 6.1 ^{o}C and the lowest temperature occurred at 22:00 as 2.1 ^{o}C. The average indoor air temperature during the coldest day was 12.8 ^{o}C and the indoor air temperature when the lowest outdoor temperature occurred was 12.1 ^{o}C at that day.

The coldest day occurred on 4th of February for the Simulation. The average outdoor temperature during that day was 6.1 ^{o}C and the lowest outdoor temperature occurred at 07:00 as 1 ^{o}C. The average indoor air temperature during that day calculated as 16.5 ^{o}C and the indoor air temperature corresponding to the lowest outdoor temperature was 8.7 ^{o}C. Coldest day temperatures are shown in Table 2.

Table 2
Coldest day temperatures

		$T_{o,avg}$ (°C)	$T_{i,avg}$ (°C)	$T_{o,min}$ (°C)	T_i (°C)
25th Jan.	Monitoring				
		6.1	12.8	2.1	12.1
	Simulation				
		11.2	18.7	8.9	12.2
4th Feb.	Monitoring				
		13.0	18.0	5.0	13.6
	Simulation				
		6.1	16.5	1.0	8.7

$T_{o,avg}$: Daily average of outdoor air temperature, $T_{i,avg}$: Daily average of indoor air temperature, $T_{o,min}$: Minimum outdoor temperature occurring on coldest day, T_i : Indoor air temperature corresponding to the minimum outdoor air temperature. (25th Jan: coldest day for monitoring, 4th Feb: coldest day for simulation)

CONCLUSION

This work investigates the dynamic thermal simulation results and experimental results for a Trombe Wall installed test building. It is aimed to compare the simulated temperatures with the monitored temperatures. Indoor air temperature, Trombe Wall inside and outside surface temperatures, outdoor air temperature and solar radiation were considered for investigation.

A typical day investigation showed that simulation results and monitored values follow the same trend with some discrepancy. For indoor air temperatures, simulation results were slightly higher than the monitored values with a peak of 5.1 °C. Trombe Wall inside and outside surface temperatures for simulation and monitoring had discrepancy as well for the typical day. Simulated and monitored outdoor air temperatures and solar radiation for that day showed some dissimilarity, which is thought as the main reason for the difference in indoor air and Trombe Wall surface temperatures.

When the CDF curves are investigated we see that there is an agreement with the typical day results; higher temperatures in simulation for indoor air temperatures.

It is also seen in CDF curves that values are similar for simulated and monitored results for the Trombe Wall inside and outside surface temperatures as well as outdoor temperatures and solar radiation.

Generally, Trombe Wall performed well in terms of increasing the indoor air temperatures. During the monitoring, coldest day occurred with daily average temperature of 6.1°C. Daily average indoor air temperature for that day was 12.8 °C. During the coldest hour at that day, indoor-outdoor temperature difference was 10 °C. The coldest day values for simulation were similar to monitored ones with daily average outdoor temperature of 6.1°C. Daily average indoor air temperature for that day was 16.5 °C for simulation. For simulation, during the coldest hour at that day, indoor-outdoor temperature difference was 7.7 °C. It is seen that simulation is giving higher average indoor air temperature.

It is concluded that Energy Plus is giving accurate results for simulating Trombe Wall particularly for this case study. The results are very accurate for Trombe Wall inside and outside surface temperatures (can be seen in CDF curves). However, Energy Plus is giving higher values for indoor air temperatures. Therefore, Designers should consider that simulations might result in higher temperatures for the indoor air and perform their designs accordingly.

As discussed earlier there are differences between the monitored and simulated outdoor air temperatures and solar radiation. These differences are potentially different enough for causing the discrepancies between the simulations and the monitored values for indoor air and Trombe Wall surface temperatures. In the ideal case, monitored outdoor data should be converted to Energy Plus weather data file and should be used for simulations. However, this is not within the scope of this work and it could be considered for future work.

There is also uncertainty with a certain extent regarding the actual thermophysical properties of the Trombe Wall and the literature values used in Energy Plus simulations. A further investigation should be done for determining the actual thermophysical properties of the Trombe Wall for use in the Energy Plus simulations.

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