Trombe Wall Nodal Temperature Evaluations with Energy Plus Finite Difference Algorithm and Comparison with Monitored Values

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Abstract

There are extensive studies on the validation and verification of the CondFD algorithm of Energy Plus. Some of these studies are referred in this work. This study focuses on testing the agreement between the evaluated nodal temperatures by Energy Plus CondFD algorithm simulations with the monitored ones for a particular application of a Trombe wall.

Monitoring of Trombe wall nodal temperatures from 13th January 2016 to 26th February 2016 was carried out and compared with those obtained from Energy Plus simulations. It has been found that Energy Plus CondFD algorithm results are agreeing with monitored values with some discrepancy.

Introduction

Trombe wall is a thermally heavy structure, which is placed in an appropriate position in buildings in order to supply passive heating during winter and to prevent overheating during summer. Locations having high solar intensity are very suitable for Trombe wall applications (Duffie and Beckman 2013, Kalogirou 2009).

A simple passive Trombe wall structure is made up from a heavy masonry or concrete dark painted wall with a glass cover on its outer surface. A narrow air gap exists between the glass cover and the wall, which is heated due to the greenhouse effect. The temperature of the wall increases as solar radiation transmitted through the glass cover is absorbed. This process is slow and generates time dependent temperature gradients in the wall. The stored energy is released to the room side of the Trombe wall structure by convection and radiation, (Duffie and Beckman 2013). If well designed, this type of Trombe wall can provide effective passive heating.

Trombe wall applications were studied many times before from different aspects such as mathematical modelling, energy saving potential and real life testing. Shen *et al* (2007) developed finite difference models for two different types of Trombe wall i.e. classical and composite. The authors compared their model outputs with the outputs of TRNSYS Type 36 module. Bajc *et al* (2015) carried out CFD simulations for a Trombe wall installed building under moderate continental climate conditions. Trombe wall's temperature and the adjacent space's temperature profiles were generated in order to evaluate the energy saving potential of the Trombe wall application. Chel *et al* (2008) investigated the performance of a honey storage building by monitoring building air temperatures and comparing them with those obtained by TRNSYS simulations. The authors carried out TRNSYS simulations of the honey storage building with Trombe wall and proposed that retrofitting the existing building with Trombe wall will save heating energy.

There are building simulation programs that can model Trombe walls and simulate buildings that involve them. One example of these programs is Energy Plus. Energy Plus does not have a specifically designed module for modelling Trombe walls; rather it uses the existing elements and algorithms of itself for modelling them. It has an algorithm for evaluating the convection coefficient in the air gap lying between the Trombe Wall and the glass layer. This algorithm is validated by Ellis (2003).

In Energy Plus, there are several models, such as Conduction Transfer Functions, Conduction Finite Difference (CondFD) model etc., for evaluating the heat transfer in building elements. Tabares-Velasco *et al*. (2012) already validated the CondFD model.

This work aims to investigate the agreement of Trombe wall interior temperatures (node temperatures) obtained by CondFD model of Energy Plus with those monitored for a real case in a test building. This will give an insight about the capability of fabric interior temperature estimation by CondFD model of Energy Plus for the particular case of Trombe wall.

Methodology

The test building shown in Figure 1 is a 12.2 m^2 floor area building which is built for research purposes and is located at the Eastern Mediterranean University campus in Famagusta (Lat. 35.1°, Lon. 33.9°), North Cyprus. The plan of the building is given in Figure 2. The Trombe wall thickness is 16 cm and its area is 11.9 m^2. It is installed on the south façade of the building and is painted with black color dye. In this study, it is intended to monitor the interior temperatures of the Trombe wall during a period in the heating season and compare the monitored values with the values obtained from simulations. Thus, this study has three segments: monitoring, modelling & simulation and comparisons.

Figure 1: Trombe wall test building.

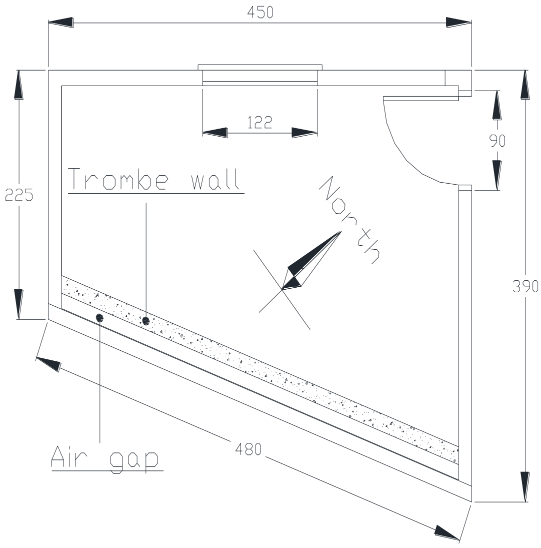

Figure 2: Plan of the test building (dimensions are in cm, air gap thickness is 14 cm).

Monitoring

Trombe wall indoor surface and outdoor surface temperatures as well as Trombe wall inner node temperatures; all referred as nodal or node temperatures were monitored by employing thermocouples with a data acquisition system from 13th January 2016 to 26th February 2016 (a period of heating season in Cyprus). The outdoor air temperatures and the global solar radiation were also recorded.

The thermocouples of K type (Chromel-Alumel) were utilized. The wire diameter of thermocouples are 0.81 mm and the measurable temperature range with those thermocouples is 0-1250 ºC with error limit of ±2.2 ºC. A pyranometer was used for monitoring the global solar radiation that was mounted on the frame of the Trombe wall glass cover. The Eppley Precision Spectral Pyranometer Model PSP with single point, hourly average and daily average uncertainties of 10 W/m^2, 2% and 1% was employed. A data acquisition system with a computer was used to collect the data. The employed data acquisition system is Omega OMG-DAQ-3000 series featuring a 16-Bit/1-MHz A/D converter. This unit is connected to a computer by a USB cable and has channels that thermocouples or any voltage input can be connected.

Six thermocouples were used to measure associated temperatures. Five were employed for measuring the nodal temperatures of the Trombe wall and one was used with a radiation shield for monitoring the outdoor air temperature. The nodal temperatures (5 nodes in total) were measured at the midpoint of the Trombe wall by placing thermocouples 4 cm apart from each other in the wall. Node 1 stands for the outer surface and node 5 stands for the inner surface of the Trombe wall. Node 2, node 3 and node 4 have 4 cm, 8 cm and 12 cm distance from the outer surface of the Trombe wall. The schematic of the experimental setup for monitoring is shown in Figure 3.

Parameters were recorded for every 20 minutes throughout the monitoring period. The system was restarted on 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 maintenance for the main power lines and two due to a maintenance 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.

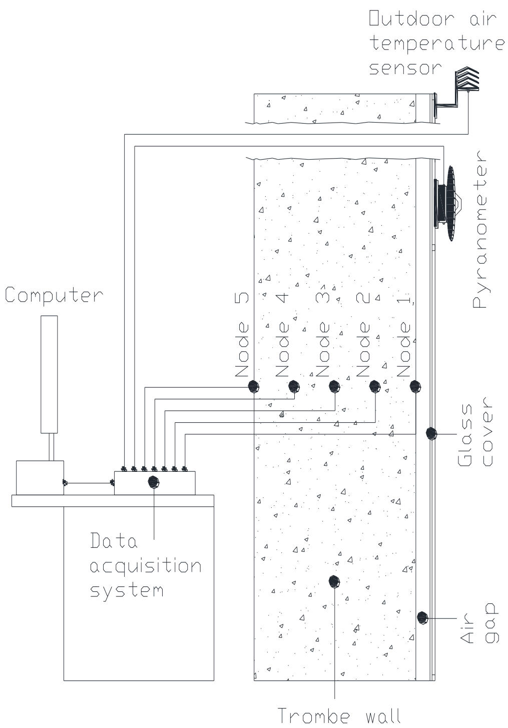

Figure 3: Schematic of the experimental setup.

Building Modelling

In order to run dynamic simulations with Energy Plus for evaluating the nodal temperatures for the Trombe wall, it is necessary to generate the building model with Energy Plus.

The building is modelled as two zones. The first zone is referred as “zone 1” and it is the zone for occupancy whereas second zone is the zone (air gap), 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 walls. The model of the building is shown in Figure 4.

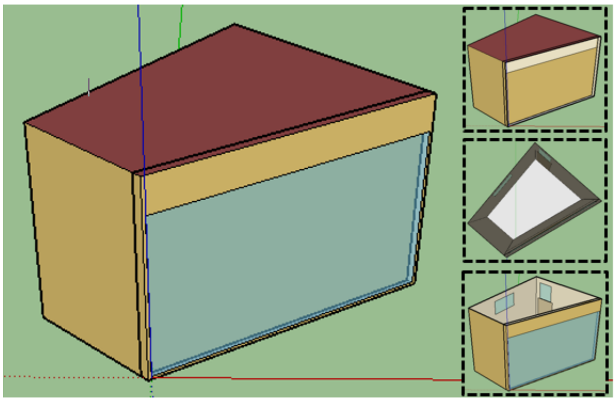

Figure 4: Building model for simulations.

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 (CondFD) methods, etc. CTF method is used frequently for sensible heat only solutions, whereas CondFD method is used for advanced applications such as evaluating the nodal temperatures within the building fabric, (U.S. Department of Energy (2016-1), U.S. Department of Energy (2016-2)). In this work CondFD algorithm was selected since the Trombe Wall nodal temperatures are to be evaluated. 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.

There is not any active heating and cooling equipment in the test building, therefore, no heating or cooling equipment was 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 internal gain from the computer (including screen) is 450 W. The lamp was turned on occasionally for only maximum of 10 minutes in a day. Therefore, in the simulation, the computer was always kept on and the lamp was always kept off.

The Trombe wall is made up from reinforced concrete having a 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 5. Table 1 shows thermophysical properties of the building fabric. Properties of the building fabric are sourced from ASHRAE (2013) and 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 respectively.

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 respectively.

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

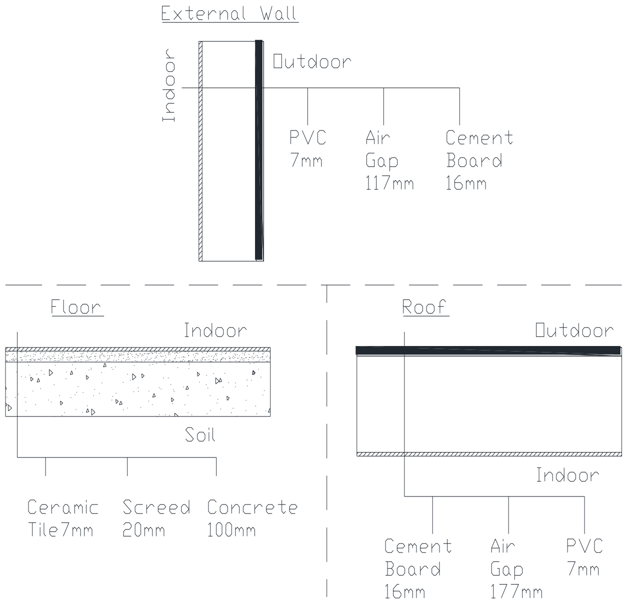

Figure 5: Constructions of the test building..

Table 1: Thermophysical properties of the test bulding fabrics.

Material	Property			
	k	ρ	C_p	a
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^{2}K/W
k: thermal conductivity (W/m.K), ρ: density (kg/m^3), C_p: specific heat (J/kg.K), a: solar absorptance

Mathematical Model and Simulations

Energy Plus has two different schemes for CondFD algorithm. These are Crank-Nicholson and fully implicit schemes. In this study, fully implicit scheme is selected, as it is more stable over time though, it can be slower, (U.S. Department of Energy (2016-1)). As the building model is not complex, this will not generate a significant problem.

The fully implicit scheme is first order in time and is solved by Adams-Moulton method. The finite difference form of the heat conduction equation for the fully implicit scheme is,

$$C_p\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t}=k_W\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x}+k_E\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}, \tag{1}$$

Where,

Cp= specific heat of material (J/kg.K), ρ= density of material (kg/m^3), Δx= node thickness or node spacing (m), *T*= node temperature (K), *j*= time discretization index, *i*= spatial discretization index, Δt= time step (s), k_W= thermal conductivity for interface between node i and node i+1 (W/m.K), k_E= thermal conductivity for interface between node i and node i-1 (W/m.K).

Since the Trombe wall in this study made up from single fabric (reinforced concrete) $k_W=k_E=k$.

Equation (1) is generated for each node of the construction. In fully implicit scheme there are four different types of nodes namely: interior surface nodes, interior nodes, material interface nodes and external surface nodes. A discretized layer consists of two half nodes at each end and full size nodes at the interior. The mesh structure of two-layer construction is shown in Figure 6. It should be noted that Trombe wall is single layer structure thus, has no interface node.

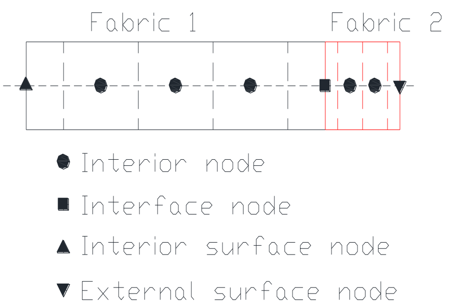

Figure 6: Mesh structure of two-layer construction. (Reproduced from U.S. Department of Energy (2016-2)).

The discretization of the constructions depends on the thermal diffusivity (α) and the time step (Δt), hence Energy Plus generates different node thickness for different materials and different time steps. The node thicknesses are evaluated by,

$$\Delta x=\sqrt{C\alpha\Delta t}, \tag{2}$$

Where, *C*= space discretization constant, α= thermal diffusivity, m^2/s.

Space discretization constant C is the inverse of Fourier number. The Fourier number is,

$$Fo=\frac{\alpha\Delta t}{\Delta x^2}. \tag{3}$$

CondFD algorithm of the Energy Plus enables the user to control the space discretization constant for the simulations. As the value for the space discretization constant increases the algorithm generates coarser node spacings (less nodes) and in contrast as its value decreases algorithm results in finer node spacings (more nodes). The number of nodes for a layer is evaluated by dividing the layer thickness to the Δx and rounding up. Then the Δx is updated by dividing the layer thickness to the number of nodes. In Energy Plus CondFD algorithm, Gauss-Seidel iteration scheme is used to calculate the node temperatures. The number of Gauss-Seidel iterations is limited to 30, however, when the sum of the all node temperatures between the last and the previous iteration differs by less than 0.000001 ^{o}C the iterations stop, (U.S. Department of Energy (2016-2)).

Since five nodes within the Trombe wall were monitored, it was necessary to set the C values in order to match the mesh of the model with the real case. The C values were varied and 28 Energy Plus simulation files were generated all having the same model parameters but different C values. Dynamic thermal simulations were carried out for the generated models. The obtained number of nodes and the node spacing for Trombe wall for each model are given in Table 2.

It should be noted that weather data of Larnaca (Lat. 34.9^o, Lon. 33.6^o) is used for simulations as Famagusta's weather data does not exist in the Energy Plus. Weather of Famagusta and Larnaca is very similar as both locations lie on the coast, have almost the same latitude (Famagusta: 35.1^o, Larnaca: 34.9^o), do not have significant differences in their geographical features and are only 50 km away from each other.

Table 2: Number of nodes and node spacing for different C valued models.

C	**# of nodes**	**Δx (m)**	**C**	**# of nodes**	**Δx (m)**
0.01	209	7.69×10^{-4}	5	10	0.0178
0.02	148	1.09×10^{-3}	6	9	0.0200
0.03	121	1.33×10^{-3}	7	8	0.0229
0.04	105	1.54×10^{-3}	8	8	0.0229
0.05	94	1.72×10^{-3}	9	7	0.0267
0.1	66	2.46×10^{-3}	10	7	0.0267
0.2	47	3.48×10^{-3}	11	7	0.0267
0.3	39	4.21×10^{-3}	12	7	0.0267
0.4	33	5.00×10^{-3}	13	6	0.0320
0.5	30	5.52×10^{-3}	14	6	0.0320
1	21	8.00×10^{-3}	15	6	0.0320
2	15	0.0114	16	6	0.0320
3	13	0.0133	17	6	0.0320
4	11	0.0160	18	5♣	0.04♣

♣: Experimantal case

It is seen in Table 2 that when the C is 18 same node number is obtained with the same node spacing as the experimental case. The locations of the nodes are identical for the simulations and monitoring for this case. The C values of 6, 3, 1, 0.4, 0.7, 0.04, 0.03, 0.01 are also resulting in meshes that have nodes coinciding with the locations of the nodes for the experimental case although generating more nodes. The rest of the C values are not delivering the meshes that have nodes coinciding with the node locations of the experimental case therefore, they are not further investigated.

Data Analysis, Results and Discussion

Although the simulation time step was one minute, Energy Plus models set to report hourly values. During monitoring, data were stored for every twenty minutes, whereas their hourly averages are used in data analysis.

The hourly values of solar radiation and outdoor air temperature acquired from simulations and monitoring were plotted and compared. It was found that the period of 08.02.2016-11.02.2016 was the most similar period for the monitored and simulated outdoor air temperature and solar radiation. This period can be seen in Figure 7. It is clear that 8th and 9th of February are the most similar days for the monitored and the simulated values within this period. The nodal temperatures acquired from monitoring and the simulations are shown in the Figure 8 and Figure 9 respectively together with solar radiation and outdoor air temperature. It is clear in those figures that both simulated and monitored temperatures are following the same trend and are showing the similar response to solar radiation. Note the reduction in the nodal temperature as the solar radiation drops during 10th of February. It is also clear that the response of the node 5 (outermost node) is the fastest to the changes occurring in the solar radiation. In contrary, the innermost nodes are experiencing some time lag to respond the changes.

Although the discrepancy between the solar radiation and outdoor air temperature values are less in 8th of February (most similar day), the following day i.e. 9th of February has been selected for further investigation since the slow response of the Trombe wall and the associated time delay would cause better matching results for the following day.

Nodal Temperatures for 9th February

The node temperatures of the Trombe wall acquired by simulations of the models having different C values (18, 6, 3, 1, 0.4, 0.7, 0.04, 0.03, 0.01) are plotted together with the monitored node temperatures. It has been observed that for the C values of 18, 6, 3, 1, 0.4 and 0.7, the monitored and simulated temperatures are following the similar trend, whereas for the rest (C= 0.04, 0.03, 0.01) the simulated nodal temperatures diverge significantly from the monitored values. Therefore, it is decided to present the results for the C=18 which generates the same mesh as applied in the experimentation. The nodal temperatures acquired from the simulations and monitoring for 9th February 2016 are given for node 1 to 5 in Figures 10 to 14. It is seen in those figures that the monitored and the simulated values are following similar trend and agreeing with each other for most of the hours. The averages of the hourly differences of the simulated and monitored node temperatures are evaluated and it is found that the greatest average discrepancy (average over the day) occurs for node 1 (outermost node) with 2.2 ºC. Node 1 and Node 3 experience the maximum absolute discrepancies as 4.8 ºC and 4.7 ºC at 08:00 and 15:00 respectively.

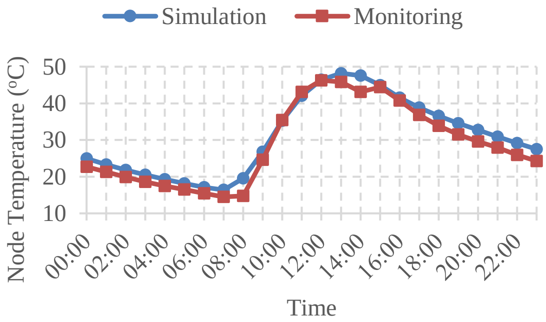

Figure 10: Node 1 temperatures for 9th February.

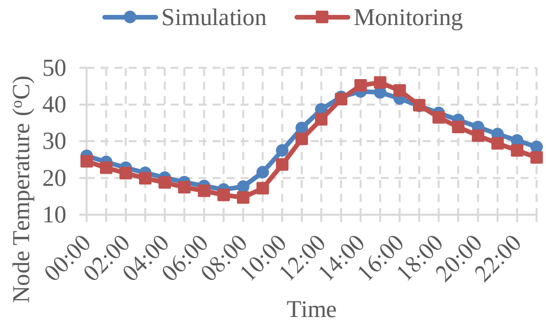

Figure 11: Node 2 temperatures for 9th February.

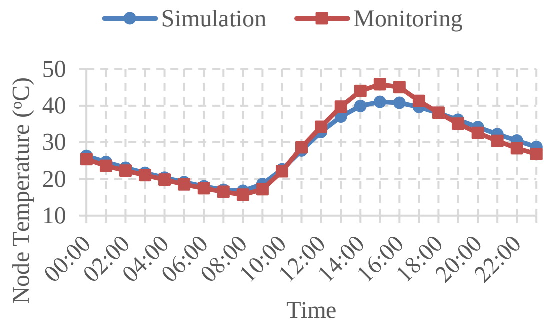

Figure 12: Node 3 temperatures for 9th February.

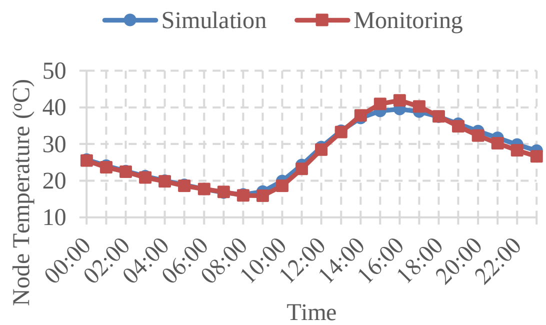

Figure 13: Node 4 temperatures for 9th February.

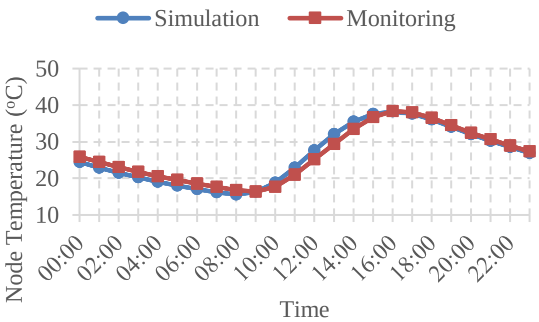

Figure 14: Node 5 temperatures for 9th February.

Cumulative Frequency Occurrence of Nodal Temperatures

The hourly values of the occurring nodal temperatures throughout the monitoring and simulation period (13th January 2016-26th February 2016) has been investigated in order to comprehend the long term matching between the acquired data from simulations and monitoring. The cumulative distribution frequency (CDF) curves are generated for this purpose. Again only the results from the simulation of the model having C=18 is considered. The CDF curves for node 1 to 5 are given in Figures 15 to 19.

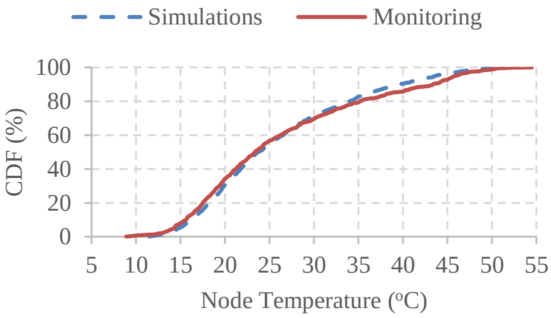

Figure 15: CDF curves for node 1 temperatures.

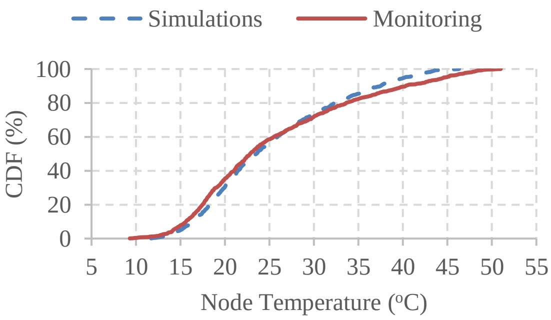

Figure 16: CDF curves for node 2 temperatures.

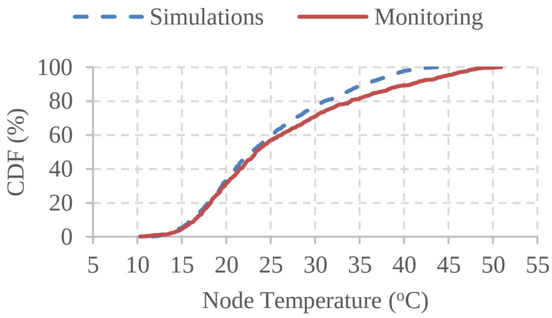

Figure 17: CDF curves for node 3 temperatures.

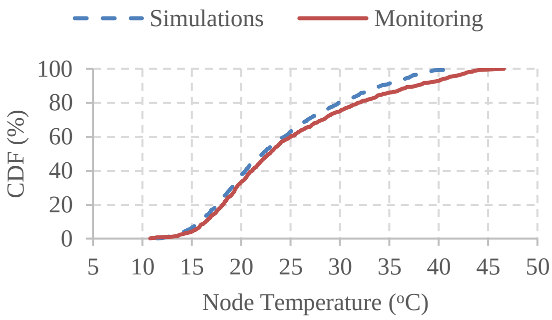

Figure 18: CDF curves for node 4 temperatures.

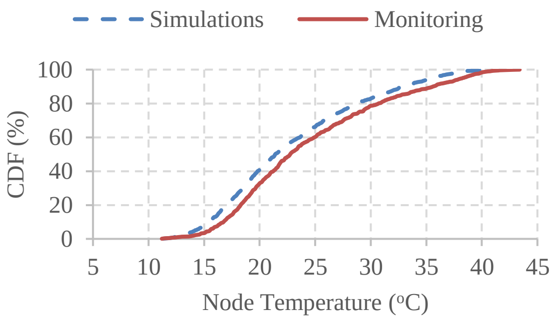

Figure 19: CDF curves for node 5 temperatures.

Once the CDF curves are investigated it is seen that the monitored and simulated temperatures for the Trombe wall nodes are similar. There is some discrepancy and it is obvious that the simulation nodal temperatures are slightly higher than the monitored ones in general. The maximum difference between the simulation and monitoring in the percentage of occurring temperatures below a certain value is around 7-8 points and occurs for node 3 (the middle node). For the rest of the nodes the maximum difference is around 5 points.

It is seen in Figures 15 to 19 that the similarity of CDFs are decreasing towards the interior of the wall. The most likely reason for this is the effect of the discrepancy between the actual material properties (thermal conductivity, specific heat etc.) and those used in the simulations. The properties of the materials are less influential on the surface nodes, whereas they are dominant in the interior nodes and it is more likely that any difference between the actual material properties and those used in simulations will have greater effect in terms of experienced temperatures in the interior nodes.

Conclusion

This study investigates the accuracy of the CondFD algorithm of Energy Plus for evaluating the nodal temperatures within a construction. The investigation has been carried out by comparing the real monitored nodal temperatures with the temperatures obtained from Energy Plus simulations. The investigation has been done for a particular construction, which is a Trmobe wall. In total five nodes has been studied.

Different space discretization constants (C) has been used in Energy Plus models in order to observe the effect of varying C on the node temperatures. It has been found that the C value resulting in same node number with same node spacing (same mesh) as the experimental case is giving accurate results to a certain degree. It is also found that C values below 0.1 give results significantly different from monitored values.

Detailed investigations were carried out for a particular day i.e. 9th February 2016 which is a day in the most similar period (similar outdoor air temperature and solar radiation). It has been shown that Energy Plus CondFD algorithm predicts the temperatures with some discrepancy. This can be seen when Figure 10 to 14 is investigated. It is found that the maximum average of differences of the hourly values' between the simulated and monitored values occurs for 9th of February in the outermost node as 2.2 ^{o}C.

The CDF curves for the nodal temperatures were also generated for the period of 13th January 2016-26th February 2016. The CDF curves showed that the cumulative of the occurring node temperatures obtained by Energy Plus CondFD algorithm is agreeing with some discrepancy with the monitored values. The agreement is less for the interior nodes. This is thought to be mainly due to the differences between the actual material properties and those taken from ASHRAE (2013) and CIBSE (2006) guides and used in simulations. As the effect of material properties for interior nodes is more dominant, any discrepancy between the actual material properties and those used in simulations can cause this difference. Further investigation is required to reveal this precisely.

Consequently, it can be concluded that Energy Plus can be used to evaluate the nodal temperatures of Trombe walls (for wall + air gap + glass cover configuration) however, users should be aware that there might be some discrepancy with the actual case especially for interior nodes.

Investigation of the heat fluxes for the monitored nodes and those obtained from Energy Plus simulations would be another valuable future work that can contribute this study.

It should be also noted that the experimental data used in this study covers about one third of the heating season (from 13th January 2016 to 26th February 2016). Whole year monitoring can be done as another future work.

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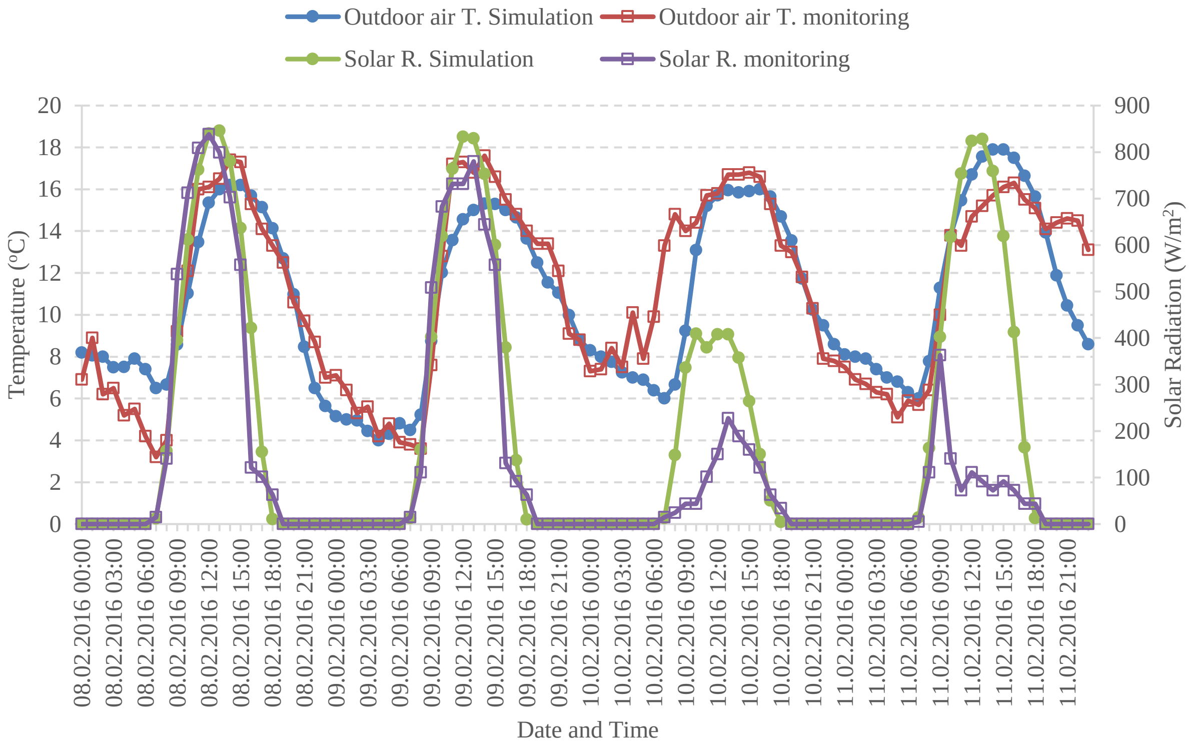

Figure 7: Hourly values of solar radiation and outdoor air temperature acquired from simulations and monitoring for the period of 08.02.2016-11.02.2016.

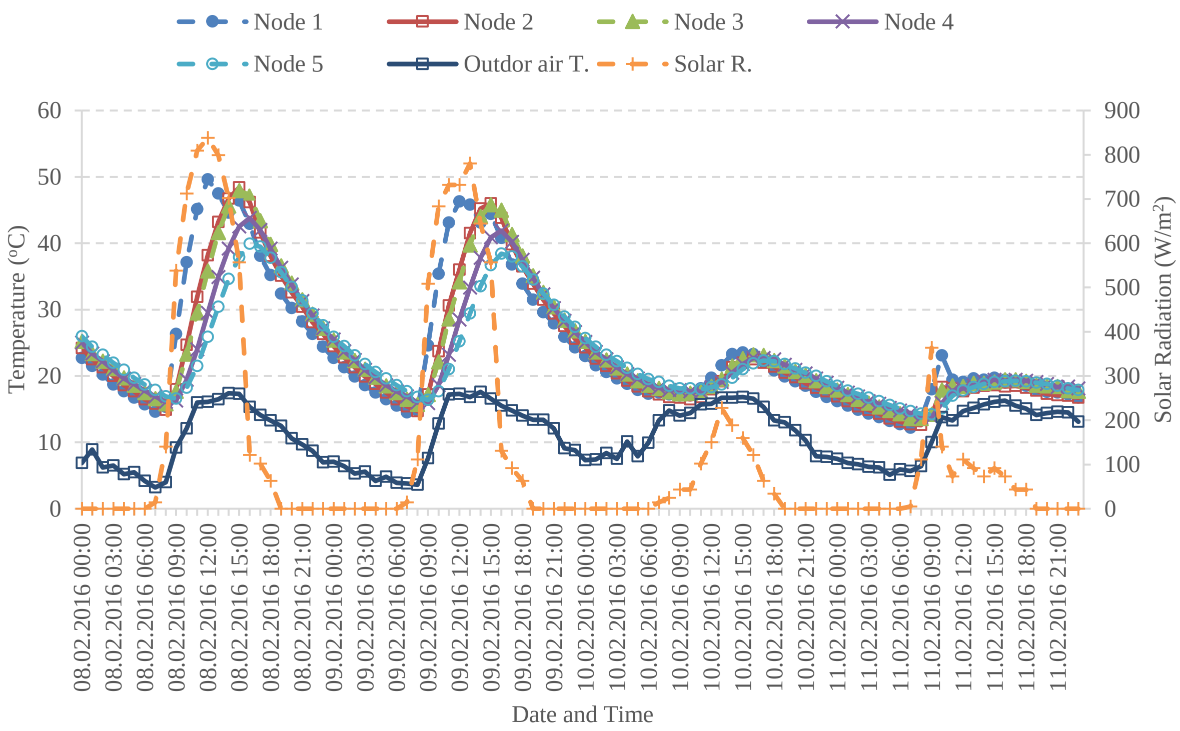

Figure 8: The nodal temperatures as well as outdoor air temperatures and solar radiation acquired from monitoring for the period of 08.02.2016-11.02.2016.

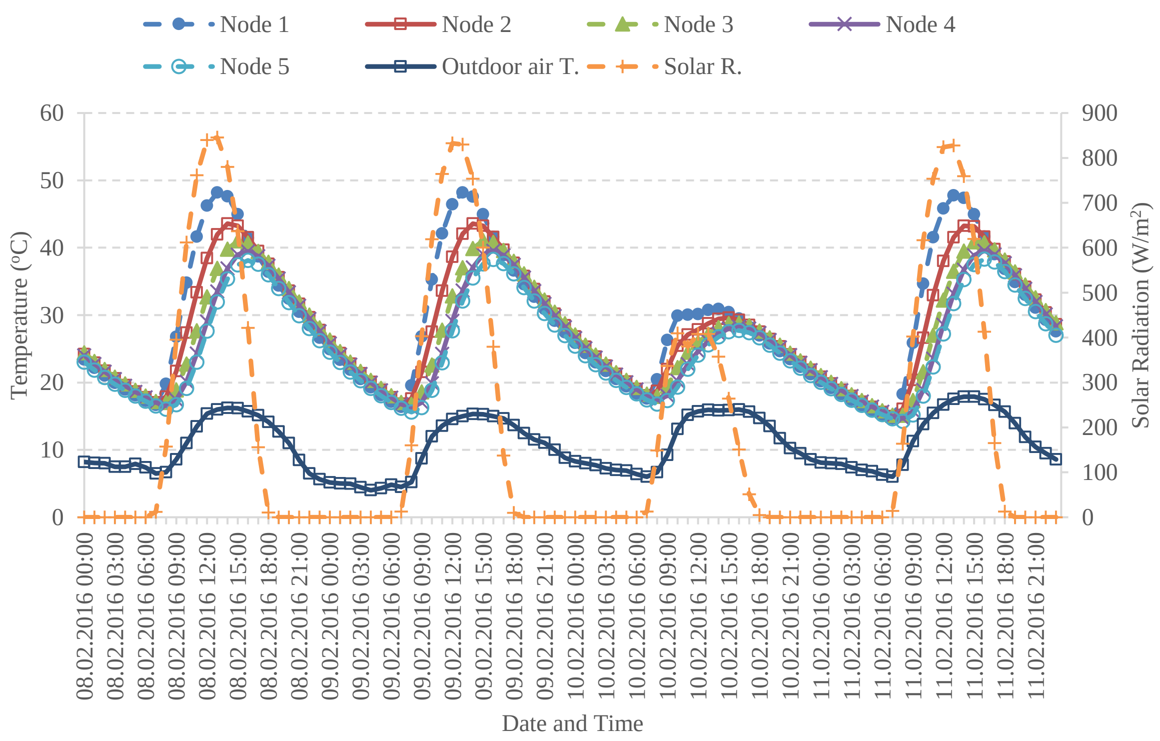

Figure 9: The nodal temperatures as well as outdoor air temperatures and solar radiation acquired from simulations for the period of 08.02.2016-11.02.2016.