Original Research Article

The Significance of Time Step Size in Simulating the Thermal Performance of Buildings

ABSTRACT

The determination of the internal air temperature of a building is pivotal to its design in the determination of heating and cooling loads and the assessment of the thermal comfort for the occupants. Autodesk CFD analysis is one of many application programs which can assist in calculating building internal air temperatures and using a smaller time step size can provide more accurate results when simulating a shorter period. However, the long term simulations of building thermal performance over weeks or months involves long computing times. The simulation results using smaller time steps also predict a smaller daily internal temperature fluctuation range compared to that observed in a real building.

To solve these issues a larger time step can be used. This speeds up the computing time and also results in a higher predicted (and more realistic) internal temperature fluctuation range. This is demonstrated in this paper, where the larger time scale technique is used with an average capacity PC machine to perform the simulations. This fast CFD simulation method is used to simulate the thermal performance of a series of existing housing test modules constructed using a range of walling systems. The performance of the proposed computing technique is assessed by comparing the internal air temperature of each building at the floor level.

To find the time step which gives the most accurate simulation of the measured internal air temperature, CFD simulations were carried out for various time steps (15, 30, 60, 80, 100, 120, 150, 180 minutes); it was found that 80 and 100 minute time steps gave the most accurate representation of the real fluctuation. The fastest simulation with the most accurate results was for a 80/100 time step where more than 87% of the results fell within a 3℃ range compared to the real data. This also required only 1% of the computing time compared to a 1 minute time step.

Keywords: Thermal performance, building enclosure, CFD analysis, long term simulations

1. INTRODUCTION

The design of energy efficient buildings requires thermal simulation programs to calculate the building internal air temperature, which is an important parameter in determining the required energy for heating and cooling to achieve thermal comfort for the occupants.

Since thermal simulations need to reflect the actual performance of the buildings, the precision of any thermal assessment will have direct consequences on the estimation of the building energy consumption/costs and the amount of GHG emissions. There are many software applications to determine the internal air temperature and energy consumption; however most of these applications are not generally available for everyday users because they require advanced PC and excessive time to proceed simulations [1]. One of the more powerful potential tools in the simulation of building performance is Computational Fluid Dynamics (CFD) which has been used for more than 40 years in a wide range of areas related to heat transfer [2]. However, it has limitations in modelling the thermal performance of buildings due to the long computing times involved.

CFD analysis can be used to analyse complete buildings to find the internal air temperature at any point within the building space. Some thermal modelling programs couple Building Energy Simulation (BES) and Computational Fluid Dynamics where the CFD analysis uses a small time-step and BES handles the long-term simulation [3, 4, 5, 6, and 7]. The main issue with CFD alone for long term simulations is the excessive computing time [8, 9, 10, and 11].

Smaller time steps size can provide more accurate results than a larger one for shorter simulation period but when simulating for longer period (weeks or months) smaller time steps it appears to have the following issues;

1. Long computing time.
2. The use of smaller time steps results in the prediction of a smaller daily temperature fluctuation range compared to the actual temperature fluctuation range.

The main focus of this paper is the presentation of a method which solves these issues in a faster and more accurate way, thus providing the means of using CFD for representative long thermal period simulations.

1.1 Full-Scale Test Modules

To solve the previous issues, CFD alone (without coupling with any software) is used to simulate the long term building performance. The building internal air temperature is evaluated using large time steps and one for economic and faster simulation. This speeds up the simulation time as well as predicting a higher temperature fluctuation range similar to the measured values.

The performance of four full scale housing test modules is simulated using Autodesk CFD Simulation. The simulation is conducted using temperature data obtained from the test modules, each incorporating a different walling system and therefore having a different thermal performance.

For the past decade an extensive research program on the thermal performance of Australian housing has been underway in the Priority Research Centre for Energy at the University of Newcastle, Australia [12]. The research program has included the construction of four full scale housing modules and monitoring the thermal performance of the modules under a range of seasonal conditions.

The modules were selected to signify typical forms of building in Australia. All the modules were constructed on the University of Newcastle, Callaghan Campus (Longitude 151.71 and latitude 32.92 (south)). All modules had a square floor plan of 6m x 6m as shown in Figure 1 and spaced 7m apart to reduce wind obstruction and avoid shading.

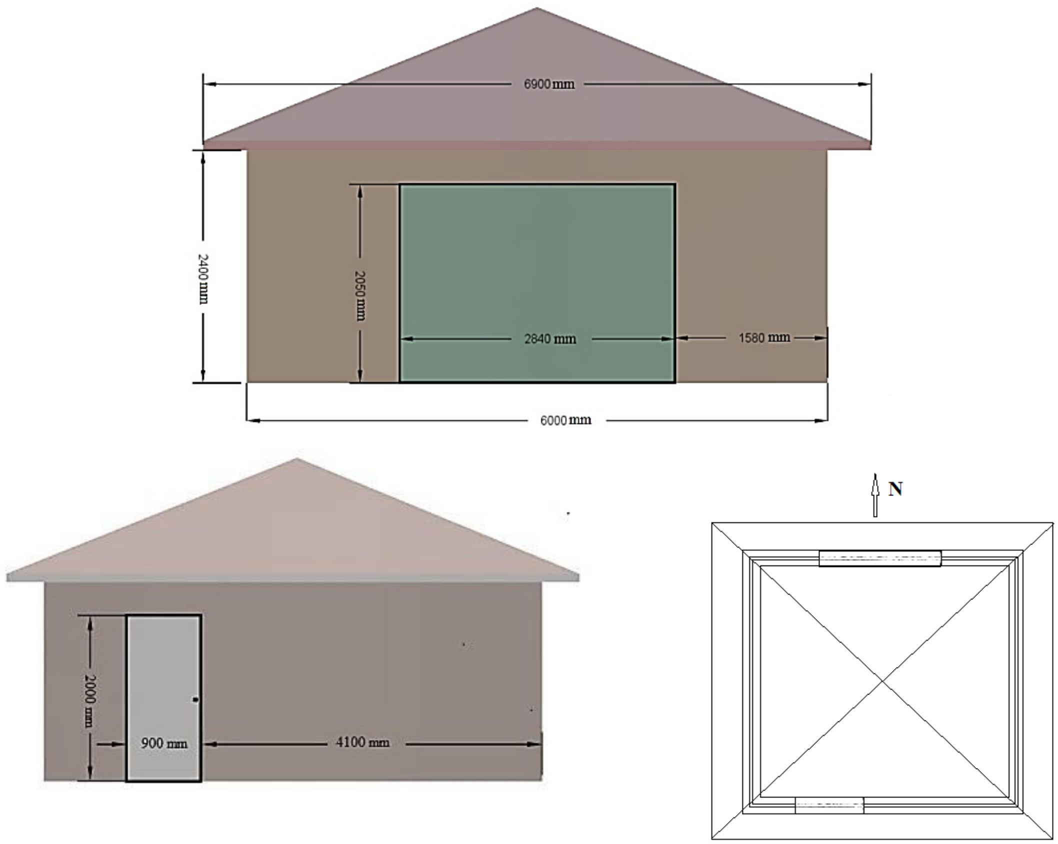

Figure 1. Full scale test modules plan [12].

The modules had some common features:

- A heavily insulated door in the southern wall to eliminate any heat losses and make easy access to the module.
- In the northern wall of each module a 6.38 mm laminated clear glass window in a light colour aluminium frame was included to allow solar ingress.
- A 10mm plasterboard ceiling with R3.5 glass wool batts insulation between rafters. Concrete or clay tiled roof with sarking insulation.

The designation of each module is based on its walling system:

- Cavity Brick Module (CB)
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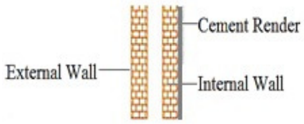

Figure 2. Walling system for Cavity Brick Module.

Walling for CB module consists of 2x110 mm brickwork skins with 50mm cavity; 10mm internal render covered the internal walls as shown in Figure 2.

- Insulated Cavity Brick Module (InsCB)

Walls for InsCB; 2x110 mm brickwork skins with 50mm cavity (R1 polystyrene insulation fixed to cavity side of interior brick skin) and the internal wall covered by 10mm internal render as shown in Figure 3.

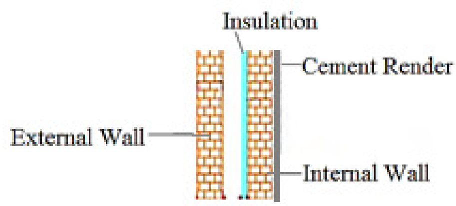

Figure 3. Walling system for Insulated Cavity Brick Module

- Insulated Brick Veneer Module (InsBV)

InsBV walls consist of; 110 mm external brickwork skin; internal timber frame with low glare reflective foil and R1.5 glass wool batts covered by 10mm plasterboard as shown in Figure 4.

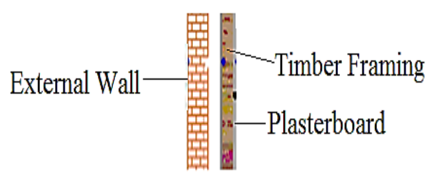

Figure 4. Walling system for Insulated Brick Veneer Module.

- Insulated Reverse Brick Veneer Module (InsRBV)

External walls; 2-3mm acrylic render on 7mm fibro-cement sheets on timber stud frame insulated by R1.5 glass wool batts insulation. The internal walls; 110mm brick skin covered by 10mm internal render as shown in Figure 5.

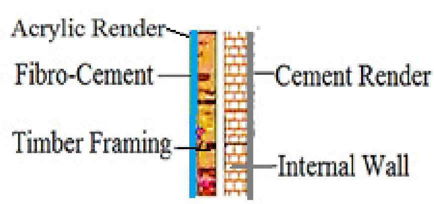

Figure 5. Walling system for Insulated Reverse Brick Veneer Module.

Sensors were installed in all modules to measure internal temperature and external weather conditions. The data were taken and recorded at 5 minute intervals for the whole testing period [14]. All modules were in a "free-floating" mode where the internal air temperature was determined solely by the external environment with no artificial heating or cooling. The internal air temperature was recorded at a 1200mm height inside the building. During the observation period all the modules were air tight with no ventilation provided.

1.2 Issues Related to Long Term CFD Simulations

1.2.1 Time Step Size

Most weather stations record the temperature at minute or 5 minutes intervals. If short intervals such as these are used in CFD simulations over the long term (weeks, months), long computing times are required. This is not practical if fast, accurate results are required. The main factors controlling the simulation time are the simulation period and the time step size; here the main focus will be on time step size.

In the Autodesk CFD Simulation package (2014) seems to be user-friendly and the time step size and transient analyses can be amended and terminated after a certain number of time steps [13].

1.2.2 Temperature Fluctuation Range

In this paper the temperature fluctuation range is defined as the difference between the maximum peak temperature to the minimum temperature during a 24 hour daily cycle as shown in Figure 6.

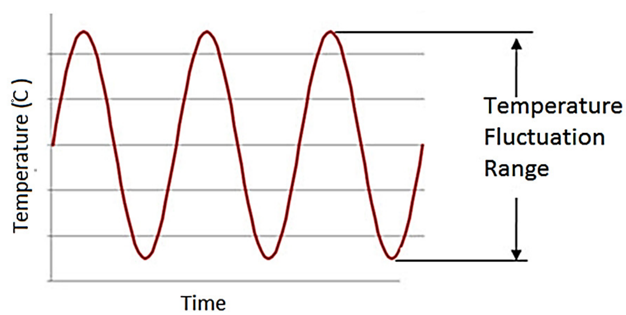

Figure 6. Temperature fluctuation range (peak to peak amplitude) for 24 hour daily cycle.

CFD analysis in conjunction with small time steps does not reproduce the temperature fluctuation range well. For example, as shown in Figure 7, CFD simulations for a small time step of 15 minutes predict a smaller daily temperature fluctuation range compare with the measured data temperature fluctuation range. For a 15 minute time step the fluctuation range was 2.53ºC for the CFD analysis, while a 4.58 ºC temperature fluctuation was observed for the real building. This trend was observed for all of the smaller time steps.

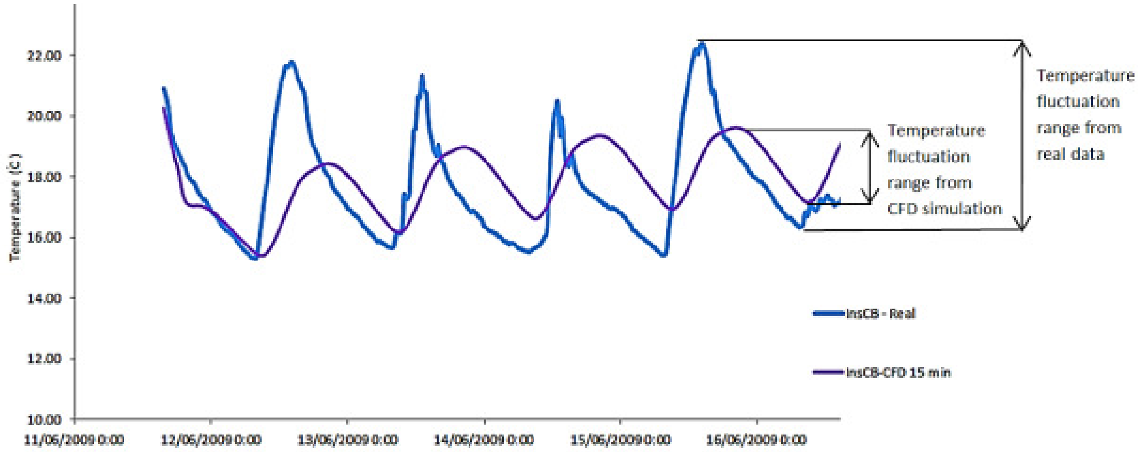

Figure 7. Temperature fluctuation range difference between real data and CFD simulation for InsCB.

2. COMPUTATIONAL FLUID DYNAMICS (CFD) METHODOLOGY

CFD is a division of fluid mechanics that uses numerical approaches and algorithms to analyse and solve problems that involve fluid flows and heat transfer [14].

The geometrical characteristics of each module and material properties were modelled using CFD environment. A large external environment of a 100m x 100m x 100m external volume in the shape of a cube to surround the building was constructed in CFD. Then the material properties for each module were assigned with the same thermal properties as the real modules. An automatic mesh was generated for analysis of the module then a grid independence test was conducted to ensure that the CFD simulation was correct.

A transient solution mode, heat transfer, flow and radiation were enabled and calculated in the CFD simulation software by entering the exact location and date of the real modules. The solar heating function was also enabled with the latitudinal and longitudinal position of the test modules reflecting their locations. An appropriate date, time and orientation were also entered to reflect the real conditions.

Transient temperature boundary conditions were applied to the surface of the cubical external volume. To run simulations for different time steps, a representative external air temperature needed to be calculated for each time step. This was obtained by averaging the external air temperature surrounding a module observed at 5 minute intervals over the required time step (see Table 1).

Table 1. Calculating new outside air temperature for different time steps used in CFD simulation.

Time steps	Calculating new time	Time interval

	steps (minutes)	(minutes)
15 minutes	$[\sum_{i=1}^{3}(\mathrm{Ti})]/3$	7.5
30 minutes	$[\sum_{i=1}^{6}(\mathrm{Ti})]/6$	15
60 minutes	$[\sum_{i=1}^{12}(\mathrm{Ti})]/12$	30
80 minutes	$[\sum_{i=1}^{16}(\mathrm{Ti})]/16$	40
100 minutes	$[\sum_{i=1}^{20}(\mathrm{Ti})]/20$	50
120 minutes	$[\sum_{i=1}^{24}(\mathrm{Ti})]/24$	60
150 minutes	$[\sum_{i=1}^{30}(\mathrm{Ti})]/30$	75
180 minutes	$[\sum_{i=1}^{36}(\mathrm{Ti})]/36$	90

As shown in Figures 8 and 9, the simulations of the average external air temperature for different time intervals resulted in minimal difference between the 15, 30, 40 45, 60, 120, 180 minute time intervals (less than 2% error between maximum and minimum values for any time interval).

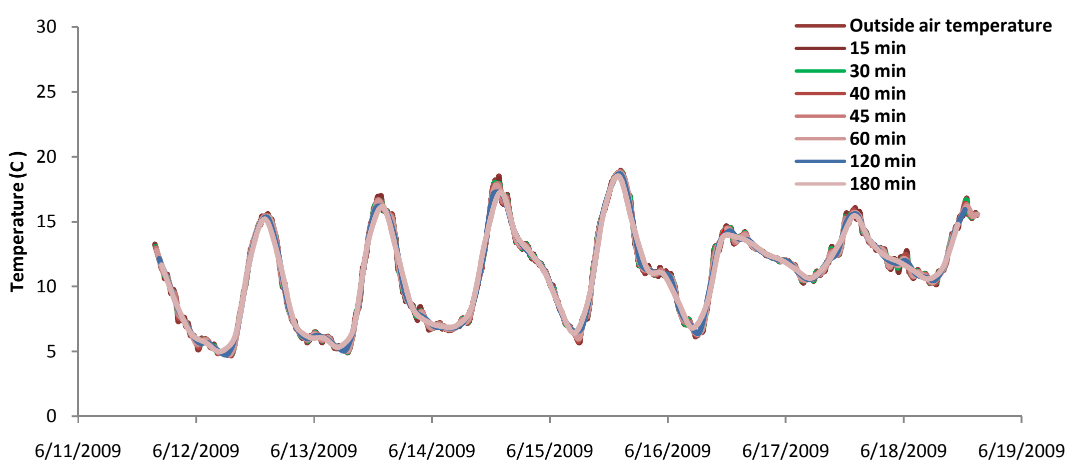

Figure 8. Outside air temperature in winter for different time intervals.

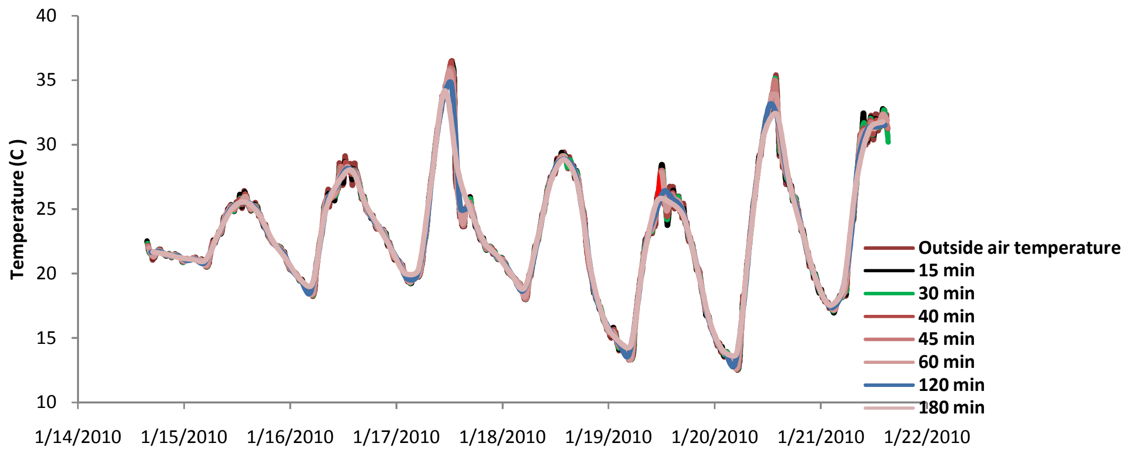

Figure 9. Outside air temperature in summer for different time intervals.

The variation of the internal air temperature of the four existing house test modules was compared to the simulated CFD results at the same position inside the building (at 1200mm height) to ensure the accuracy of CFD's simulations. CFD transient analyses were run for each module for different time steps 15, 30, 60, 80, 100, 120, 150, 180 minutes and one inner iteration (the only thing changed in each simulation was the time step size). This process was repeated for each module and the results were validated by experimental data of temperature distribution inside the modules as shown in Figure 10.

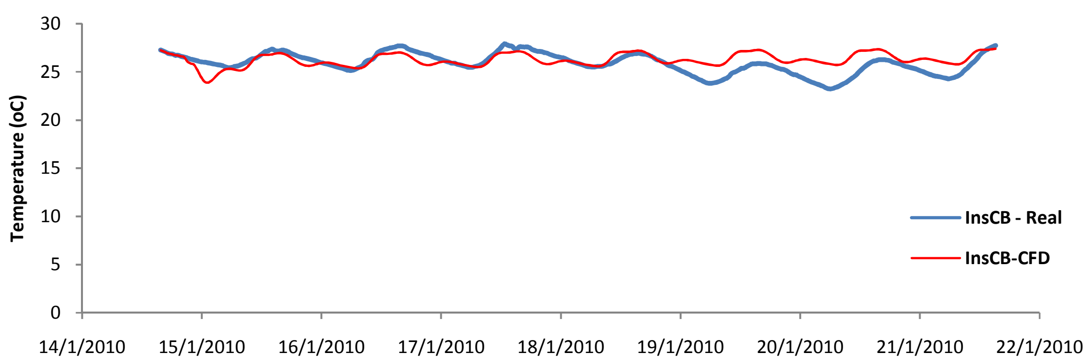

Figure 10. Comparison between real data and CFD simulation for InsCB.

3. RESULTS AND DISCUSSION

Simulations were run for each module for different time steps with everything else being held constant, and the simulation results compared with the real results. As can be seen from Table 2, the use of a small time step size (1 or 15 minutes) on a desktop PC to analyse the performance of the housing module over a week, a month or a whole season requires very long computing times.

Table 2. Computing time for different time steps.

Time step (minutes)	Computing time for one week	Computing time for 30 days	Computing time for a season (120 days)
1	1 Day 1 hour 5 minutes	4 Days 4 hours	17 Days 17 hours
15	1 hour 50 minutes	7 hours 26 minutes	23 hour 30 minutes
30	55 minutes	3 hours 39 minutes	14 hours 22 minutes
60	30 minutes	1 hour 52 minutes	7 hours 13 minutes
80	23 minutes	1 hour 25 minutes	5 hours 26 minutes
100	20 minutes	1 hour 9 minutes	4 hours 22 minutes
120	17 minutes	58 minutes	3 hours 39 minutes
150	15 minutes	47 minutes	2 hours 56 minutes
180	13 minutes	40 minutes	2 hours 27 minutes

Note: The simulation was carried out on Dell latitude e5440 with Intel ® Core ™ i5-4200 U CPU @ 2.3 GHz with installed memory (RAM) 8GB. Windows experience index 5.9 which assesses key system components on scale of 1-7.9.

Comparisons could then be made of the computing time and the internal temperature fluctuation range for different time steps (15, 30, 60, 80, 100, 120, 150, 180 minutes) to determine the combination which was closest to the real results. The CFD simulations were run for all modules. However, only the detailed results for the InsCB will be presented here (results for the other module types were similar).

Detailed analyses of the InsCB module simulations for a summer week

Simulations of internal temperature were carried out for the InsCB module for one week in summer from 14/01/2010 to 22/01/2010 for different time steps as shown in Figure 11.

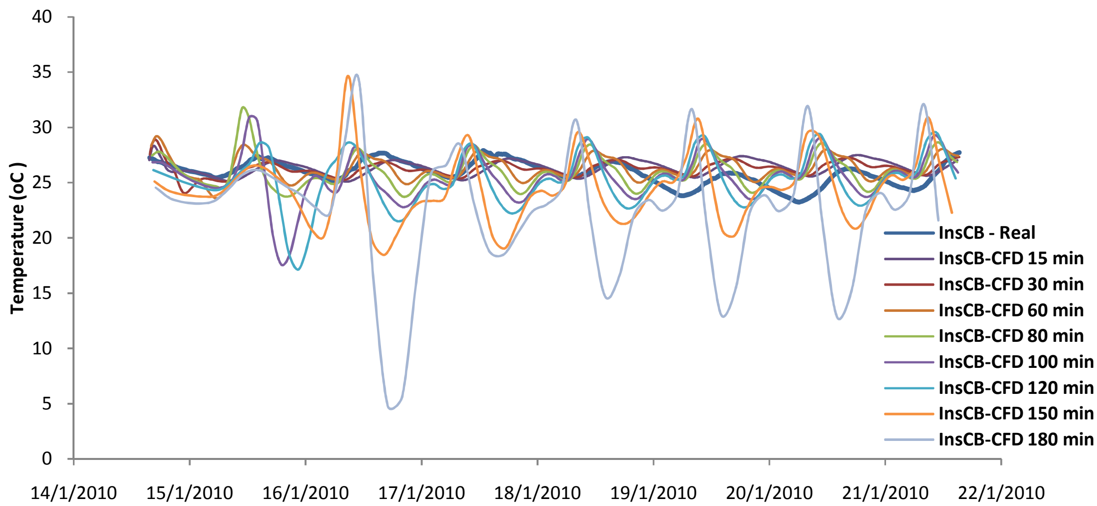

Figure 11. Comparison between real data and CFD simulation for all different time steps 15, 30, 60, 80, 100, 120, 150, 180 minutes for InsCB in a summer week.

The average internal temperature fluctuation range for real data was 2.33 ºC, while the average temperature fluctuation range from the CFD analyses for 15, 30, 60, 80, 100, 120, 150, 180 minutes time steps were 1.94ºC, 1.60ºC, 2.89 ºC, 4.40 ºC, 5.32 ºC, 6.45 ºC, 9.42 ºC, 19.07 ºC respectively, with the average temperature fluctuation range increasing with larger time step size.

Detailed analyses of the InsCB module simulations for a winter week

The internal temperature simulations for the InsCB module for one week in winter (southern hemisphere) between 11/06/2009 to 19/06/2009 for different time steps are shown in Figure 12.

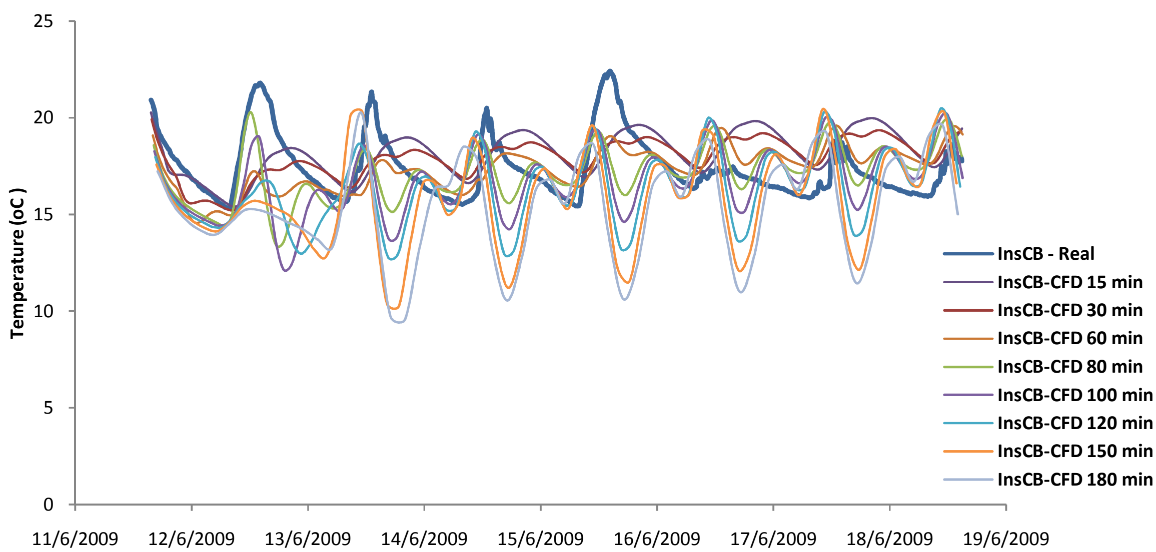

Figure 12. Comparison between real data and CFD simulation with all different time steps 15, 20 30, 35, 40 45, 60, 80, 100, 120, 150, 180 minutes for InsCB in a winter week.

The average temperature fluctuation range for real data was 4.58ºC while the average temperature fluctuation range from the CFD analyses for 15, 30, 60, 80, 100, 120, 150, 180 minutes time steps were 2.53ºC, 1.62ºC, 2.25ºC, 3.27ºC, 4.75ºC, 6.32ºC, 7.83ºC, 7.72ºC respectively. Once again, the average temperature fluctuation range increased with larger time step size.

It can also be that seen from above that the summer temperature fluctuating range for the real data was less than that for the winter which allowed more sun enter the module due to the lower solar angle. This heated the building interior during day time, and also allowed the building to cool more quickly at night due to the lower external winter temperatures.

3.1 Comprehensive simulation results for all modules

Simulations were run for each module using different time steps (15, 30, 60, 80, 100, 120, 150, 180 minutes) then the simulation results for internal temperature compared with the real results - the average observed internal temperature fluctuation ranges for one summer and winter week are shown in Table 3.

Table 3. Average temperature fluctuation range for one week for all modules from real data.

Season/Module	CB	InsCB	InsBV	InsRBV
Summer	2.47 ºC	2.33 ºC	4.70 ºC	3.16 ºC
Winter	4.56 ºC	4.58 ºC	6.71 ºC	5.69 ºC

It is apparent from the above and Figures 13 and 14 below, that there is direct relationship between the time step size and temperature fluctuation range with the temperature fluctuation range increasing with larger time step size for both the summer and winter weeks.

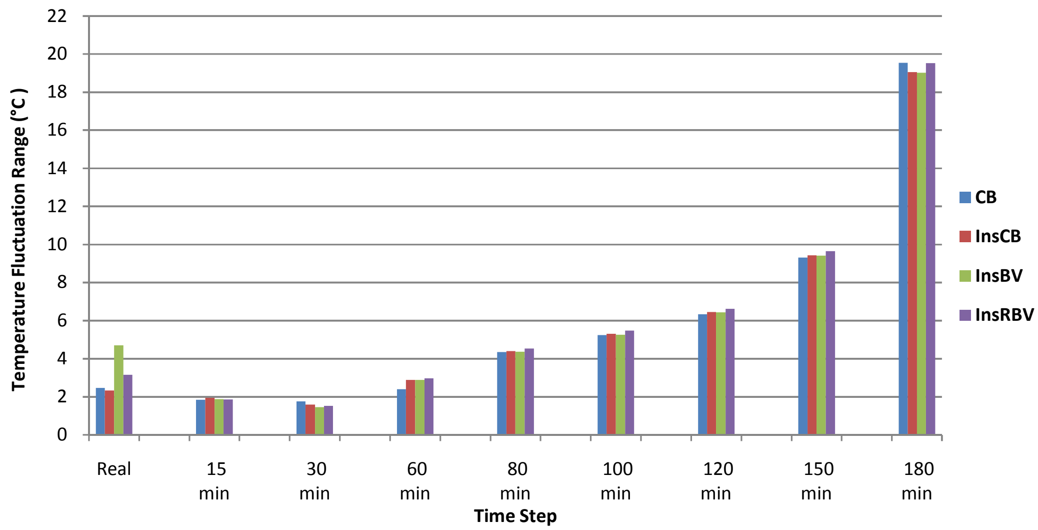

Figure 13. Summer internal temperature fluctuation range for different time steps.

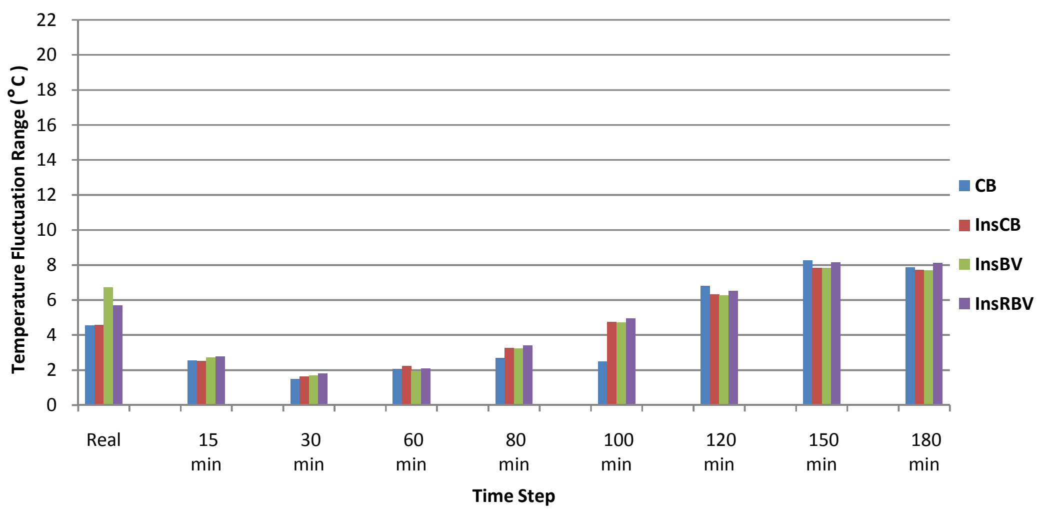

Figure 14. Winter internal temperature fluctuation range for different time steps.

Applying larger time steps (60, 80, 100, 120, 150, 180 minutes) will increase the fluctuation range to match the real fluctuation range. Comparison of the results that fell within the 0- 3℃ range compared to the real data was used to find the time steps which gave the most accurate results compared to the measured internal air temperature for each module (in summer and winter) as shown in Table 4.

Table 4. Percentage of the number of hours where temperature difference falls within 0- 3 ºC between real data and CFD simulation for each module to the total simulation time.

Time step size/ module-season	CFD 60 min	CFD 80 min	CFD 100 min	CFD 120 min
CB summer	90.30%	86.67%	83.64%	84.85%
InsCB summer	98.79%	95.15%	88.48%	87.27%
InsBV summer	88.48%	87.27%	80.00%	79.39%
InsRBV summer	95.15%	88.48%	84.85%	85.45%
CB winter	96.36%	93.33%	94.55%	84.85%
InsCB winter	92.12%	92.73%	90.30%	85.45%
InsBV winter	50.91%	70.30%	80.61%	83.03%
InsRBV winter	76.97%	87.88%	94.55%	89.70%
Average	86.14%	87.73%	87.12%	85.00%

Larger time steps will speed up the simulation (less computing time), with the most accurate simulations resulting from the 80/100 time step where more than 87% of the results fall within 3 ºC of the real data.

4. CONCLUSION

Weekly, monthly and annual CFD simulations of thermal performance using smaller time steps result in excessive computing times as well as unrepresentative (smaller) daily internal temperature fluctuation ranges when compared with the real temperature fluctuation data. To solve these issues a larger time step can be used to speed up computing time and increase the temperature fluctuation range.

Replicating the external air temperature for different time intervals used in these simulations, resulted in less than 2% error between maximum and minimum temperatures for any given time interval. To study the effect of larger time steps on the temperature fluctuation range, CFD simulations were performed for different time step sizes. It was found that using larger time steps for CFD analysis increased the temperature fluctuation range and better reproduced the variation of real fluctuations. Increasing the time step to 80 and 100 minutes resulted in more than 87% of the results lying within a 3°C range of the real data.

Using larger time steps also speeds up the simulation process because of the reduced computing time. For instance using 100 minute time steps reduced the computing time by more than 99% compared to a 1 minute time step. This facilitates the use of desktop PC's to run the CFD simulations for long periods.

This technique (using larger time steps to speed up the simulations and obtain larger fluctuation range) can be applied to different buildings in different locations resulting in more effective and efficient simulations. The study of the fluctuation range involved the performance of four modules (each with a different walling system) through different times of the year (summer and winter), indicating that this technique is applicable to any buildings type.

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