# II

# RESEARCH ARTICLES

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# WARMING ISSUES ASSOCIATED WITH THE LONG TERM SIMULATION OF HOUSING USING CFD ANALYSIS

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## ABSTRACT

The determination of internal building air temperature has an impact on the design and performance of a building in measuring thermal comfort and heating and cooling loads. There is software to assist with measuring internal building air temperature such as Autodesk CFD simulation. However, the use of Autodesk CFD simulation for the analysis appears to have an issue with simulations extending over a long term (i.e. months or years) as the internal air temperature in a building keeps rising with time. This paper addresses the challenges encountered using CFD simulation in the modelling of a building for long term performance. A new method to overcome the issue of the progressive rising of internal air temperature using two external air boundaries, one for the external volume (sky boundary) and the other surrounding the building, is suggested in the paper.



## KEYWORDS

thermal performance; CFD analysis, long term simulation, building enclosure, external boundary


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## 1. INTRODUCTION AND HYPOTHESIS

According to the Worldwatch Institute about 40% of the world's total energy usage is dedicated to the construction and operation of buildings [1]. The massive amounts of energy required in residential buildings for space heating and cooling, lighting and water heating can be saved by the application of appropriate climate interactive and passive solar energy design principles. The growing demand for energy and controlling fuel price increases, secure energy supplies, climate change and ways to reduce greenhouse gases (GHG) all accentuate the need for the design of energy efficient buildings with accompanying regulatory measures, including an energy star rating system for all new residential developments in Australia.

Using thermal simulation to determine the accurate temperature inside a building helps to define the thermal comfort, indoor air quality and building energy consumption. The


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accuracy of any thermal simulation will therefore have direct implications on the prediction of the operational energy costs for the life of the structure. Computational Fluid Dynamics (CFD) is a powerful tool that is playing a progressively more important role in achieving a comfortable, healthy, and energy-efficient building design. CFD can be used in a wide range of applications in building design, from building site layout design to individual room planning. It can also be used for active heating, ventilating and air-conditioning system design [2]. CFD analysis, following its continuing development for decades, can be used to analyse the internal air temperature at any point within the building space.

Autodesk CFD Simulation software has the advantage of decreasing the design risks and avoiding costly inaccuracies while facilitating innovation and easy improvements. CFD turns any CAD drawing (a technique widely used by building designers) into fully interactive zero-cost prototypes showing immediate critical engineering information and data not accessible from physical experiments [3]. Some thermal modelling programs couple Building Energy Simulation (BES) and CFD analysis; however, CFD uses a small time-step whereas BES handles the long-term simulation [2, 4, 5, 6, and 7]. Calculating building internal air temperatures for long term simulations (one day to several days) require lengthy computing time, an issue that can be solved for CFD analysis by using a larger time step [8].

However, there is an issue with modelling using CFD analysis that affects the accurate validation of the simulation results because the air temperature inside the building keeps rising with time. The main reason for this rise is because in the real environment the modules emit some heat back to the outer space during the night. However, in the simulation, since the CFD volume is limited, it does not allow all that heat to be dissipated back to the outer space. Therefore, the main goal of this paper is to find a new method to accurately predict the internal air temperature using CFD Simulation and thereby avoiding the increasing temperature issue.

## 2. METHODOLOGY

An extensive research program on the thermal performance of Australian housing has been underway in The Priority Research Centre for Frontier Energy Technologies & Utilisation, for the past 10 years. This has involved the construction and monitoring of the behaviour of four full scale housing modules (with walling systems of Cavity Brick, Insulated Cavity Brick, Insulated Brick Veneer and Externally Insulated Brick) under a range of seasonal conditions. For the current study, the performance of each of these four modules is replicated and analysed using the Autodesk CFD software and the temperature results of the simulations compared those observed in the test modules to determine the accuracy of the CFD's simulations.

### *2.1 Full-Scale Test Modules*

By having four differing construction systems each case of the internal air temperature for each module can be compared with the simulated CFD results. The modules were chosen to represent typical forms of domestic construction in Australia and were located on the University of Newcastle, Callaghan Campus (Longitude 151.7 degrees and latitude 32.89 degrees S). The four modules were as follows:

- Cavity Brick (CB)
- Insulated Cavity Brick (InsCB)
- Insulated Brick Veneer (InsBV)
- Insulated Reverse Brick Veneer (InsRBV)

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The modules had a square floor plan of 6m x 6m as shown in Figure 1 and were spaced 7m apart to avoid shading and minimise wind obstruction. Details of the walls and roof systems used are summarised in Table 1.

**TABLE 1.** Summary of wall and roofing systems for all modules [9].

| Module Types Element | Configuration of walling systems |
|---|---|
| Cavity Brick wall (+Insulated cavity brick wall) | 2x110 mm brickwork skins with 50mm cavity; 10mm internal render. Standard 50mm cavity or 50mm cavity with R1 polystyrene insulation fixed to cavity side of interior brick skin. |
| Insulated Brick Veneer wall | 110 mm external brickwork skin; 50mm cavity; internal timber frame; 10mm plasterboard. Low glare reflective foil on timber frame with or without R1.5 glass wool batts |
| Insulated Reverse Brick Veneer wall | 2-3mm acrylic render on 7mm fibro-cement sheets on timber stud frame; internal 110mm brick skin; 10mm internal render. R1.5 glass wool batts insulation. |
| Glass sliding door | Clear, 6.38 mm laminated glass set in a light coloured aluminium frame. |
| Ceiling | 10mm plasterboard. R3.5 glass wool batts between rafters insulation. |
| Tiled roof | Clay and concrete. Foil sarking insulation. |
| Metal roof | Coated corrugated steel. Foil sarking insulation. |

To more realistically reflect the contribution of the various walling systems to passive solar behaviour a major window opening was installed in the northern wall of each module representing approximately 20% of the floor area (a typical living room/floor area ratio).

The instrumentation recorded the external weather conditions, ground temperature, wind speed and direction, air temperature, relative humidity, as well as the incident solar radiation on each wall surface (vertical plane) and roof (horizontal plane). For each module, temperature and heat flux profiles through the walls, slab and ceiling were recorded in conjunction with the internal air temperature and relative humidity [9].

A total of 105 sensors were installed in each module to monitor internal and external conditions as well as temperature and heat flux gradients through each wall, roof and floor. These were recorded every 5 minutes for 24 hours per day over the testing period. The data was recorded using Datataker DT600 data loggers as shown in Figure 2. The interior of the modules were in a 'free-floating' state, where the temperature in the module was determined solely by the influence of the external weather conditions [9]. The internal temperature was measured at a 1200mm height and no ventilation in the modules was provided [9, 10, and 11].

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**FIGURE 1.** Floor and front plan for all modules [9].

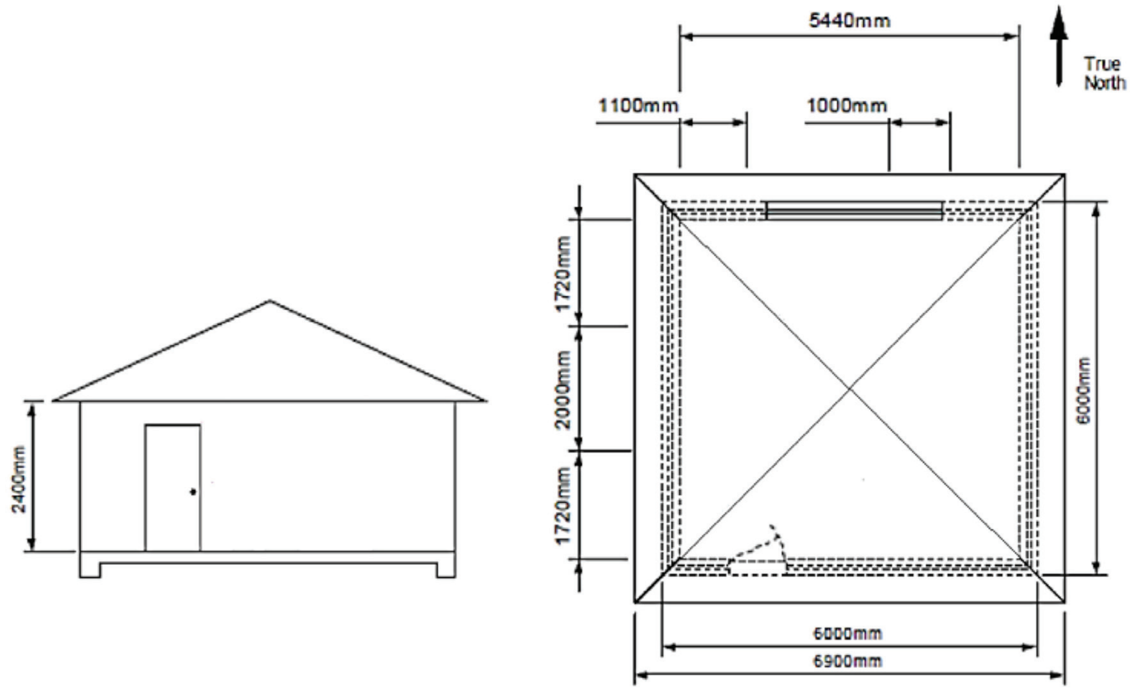


**FIGURE 2A.** Layout of the cavity brick module with the sensor locations [9].

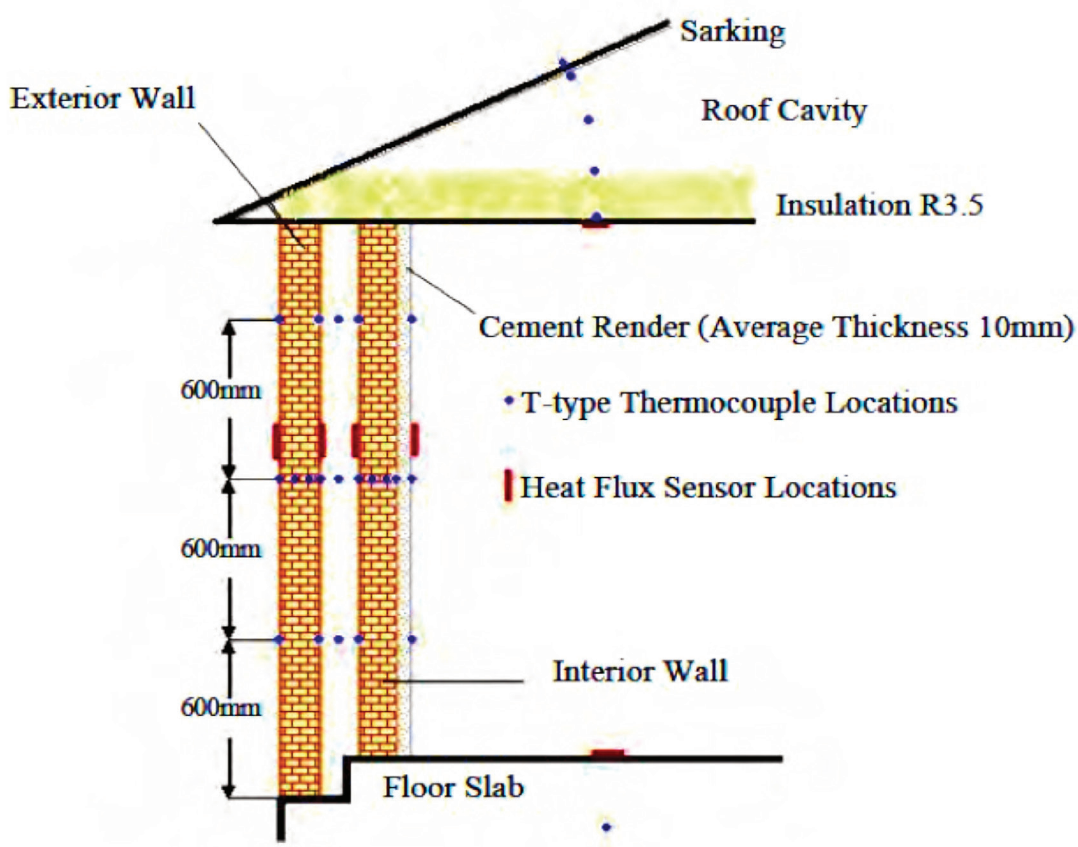




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**FIGURE 2B.** Layout of the insulated brick veneer module with the sensor locations [9].

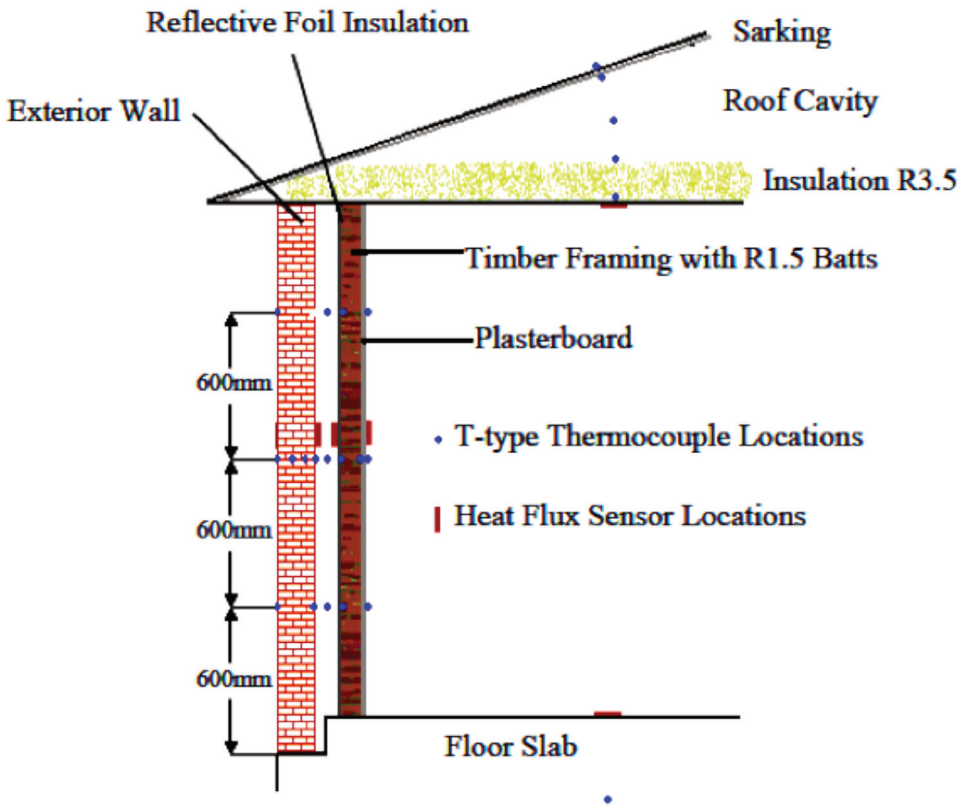


**FIGURE 2C.** Layout of the insulated cavity brick module with the sensor locations [9]

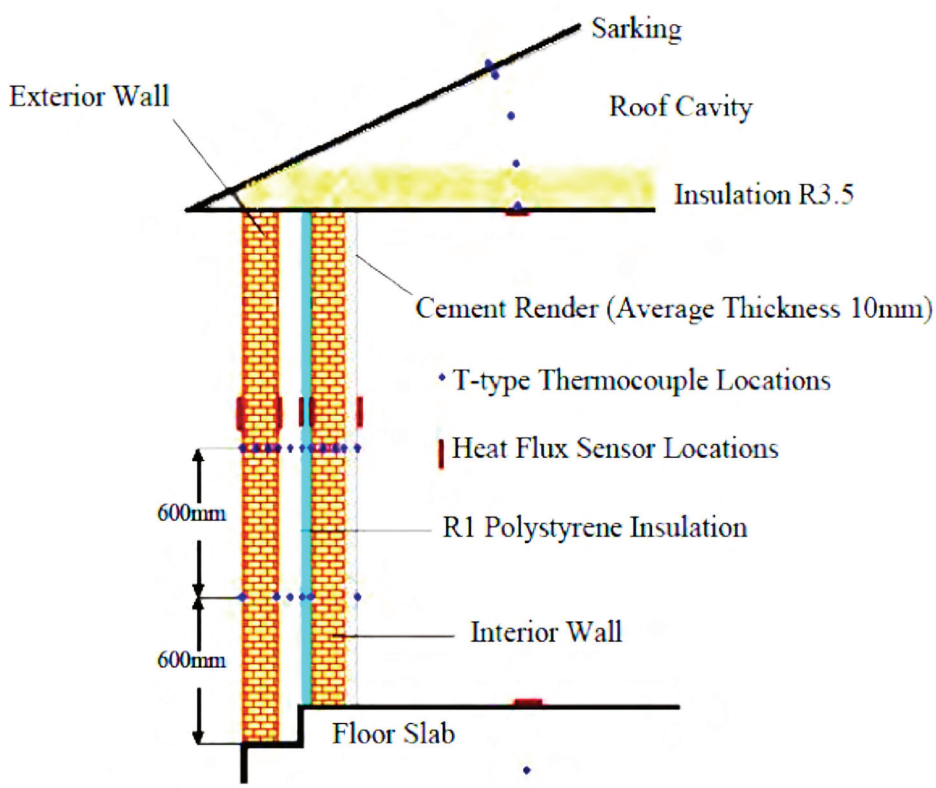


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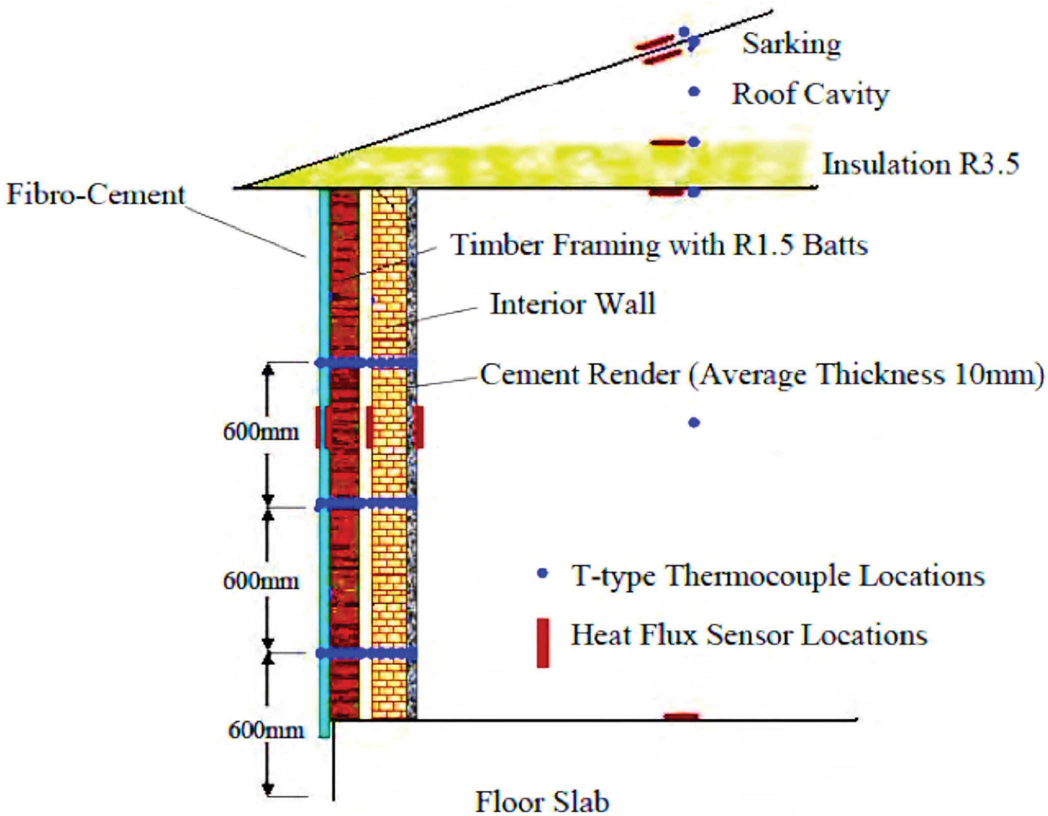
**FIGURE 2D.** Layout of the Insulated Reverse Brick Veneer module with the sensor locations [9].




### *2.2 CFD Analysis*

Computational Fluid Dynamics (CFD) is a simulation technique that mathematically simulates fluid flow and heat transfer using numerical methods and algorithms to solve and analyse problems that involve fluid flows. A CFD Simulation package [12] is not specifically designed to calculate the module internal air temperature over the long term (e.g. months, or years) due to the lengthy computing time involved. However, for this study, the various issues involved with this type of simulation have been addressed, with the characteristic of each module (geometry and material configuration) replicated in the CFD environment and the results compared with the full-scale experimental test modules.

#### *2.2.1 Temperature Boundary Conditions and Issues*

To properly simulate the effects of reflected and emitted radiative heat transfer between the object and its surroundings, cube environments extending 10 times the height of the modules as per the Autodesk guide [12] were adopted as shown in Figure 3. The sky radiation temperature to the exterior surface of the dome, temperature boundary conditions and emissivity for both the ground and the sky are shown in Figure 4.

Simulations were carried out for a one week period in summer (southern hemisphere) between 14/01/2010 to 22/01/2010 using the following assumptions: grass surface emissivity of 0.3, sky emissivity of 1, the real ground temperature and 1 minute time step interval. The CFD results for a one week period (7 days) revealed an issue with the internal air temperature which kept rising in comparison to the actual (stable) internal air temperature for all modules.



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**FIGURE 3.** Geometry from Autodesk instruction [12].

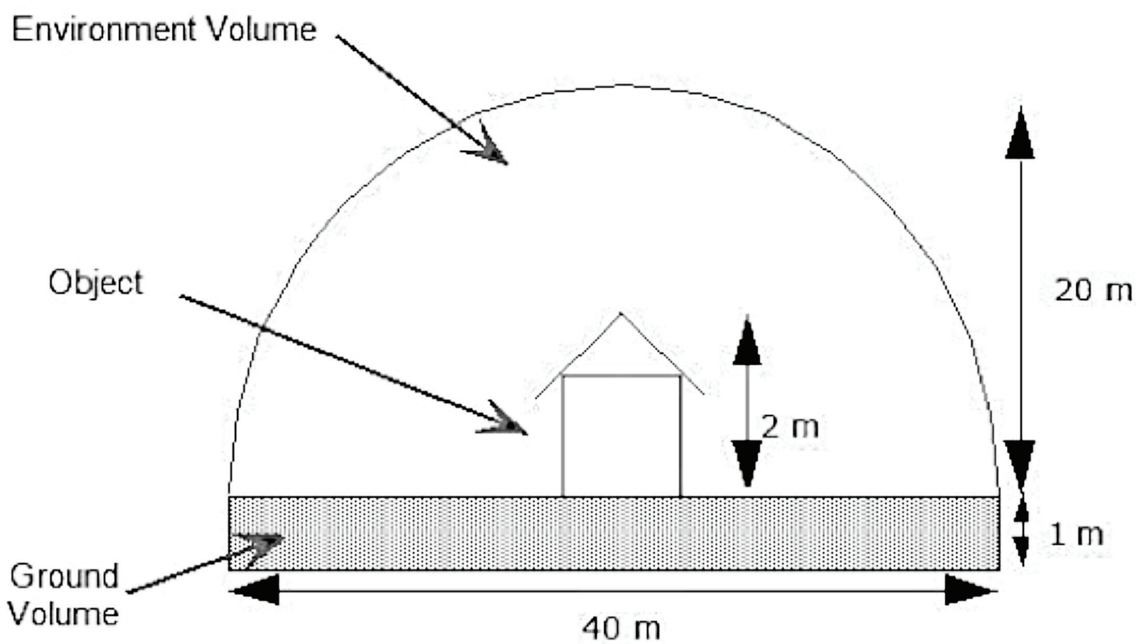
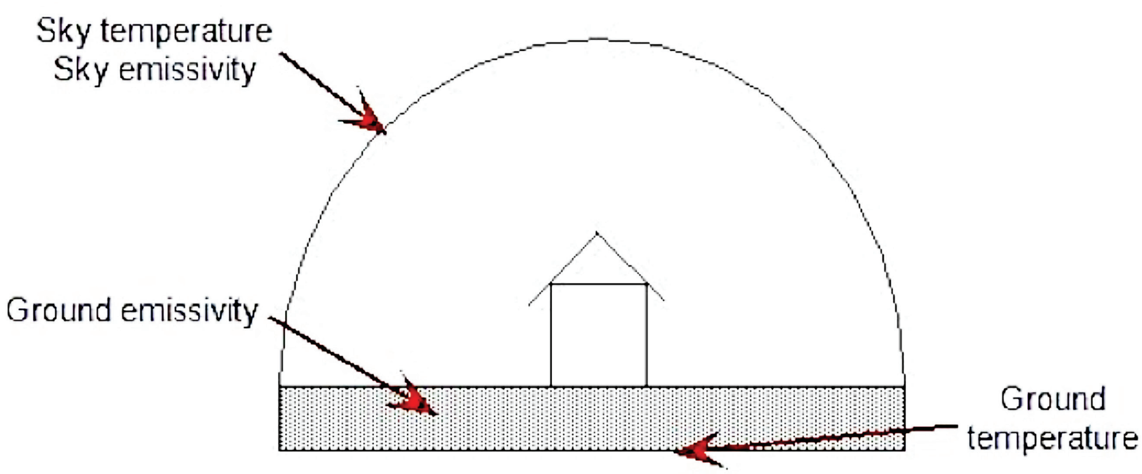



**FIGURE 4.** Temperature and emissivity for both the ground and sky [12].




When applying this approach (just one external boundary/sky boundary) for shorter periods (less than 9 hours) the simulation gave reasonable results. However, for a longer period (several days, weeks, months), the internal air temperature inside each module kept rising as shown in Figure 5.

The sharpest rise in internal air temperature for all modules occurred in the first week. The temperature then kept increasing but at a slower rate. The study focuses on a week in January by comparing real and simulated temperatures.



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**FIGURE 5.** The effect of rising internal air temperature inside the modules for longer period CFD simulation.

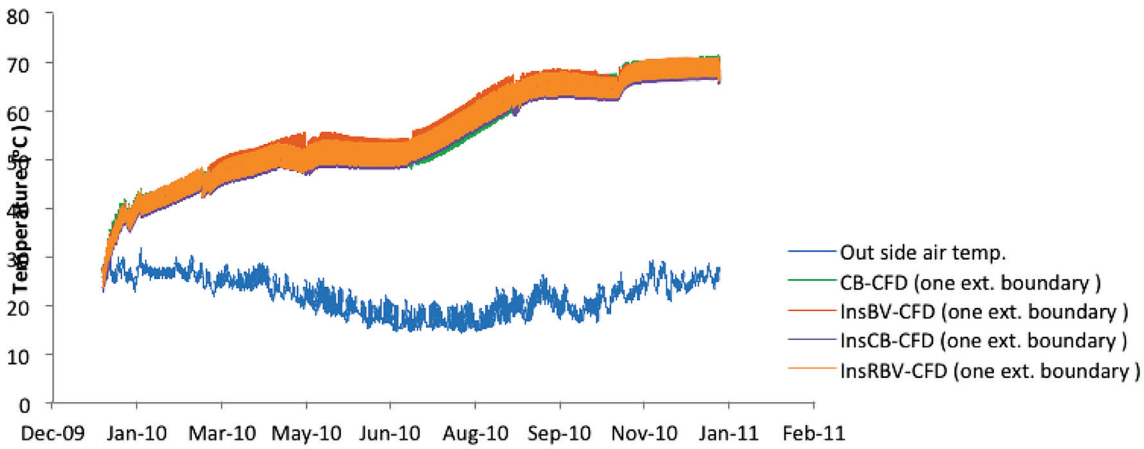
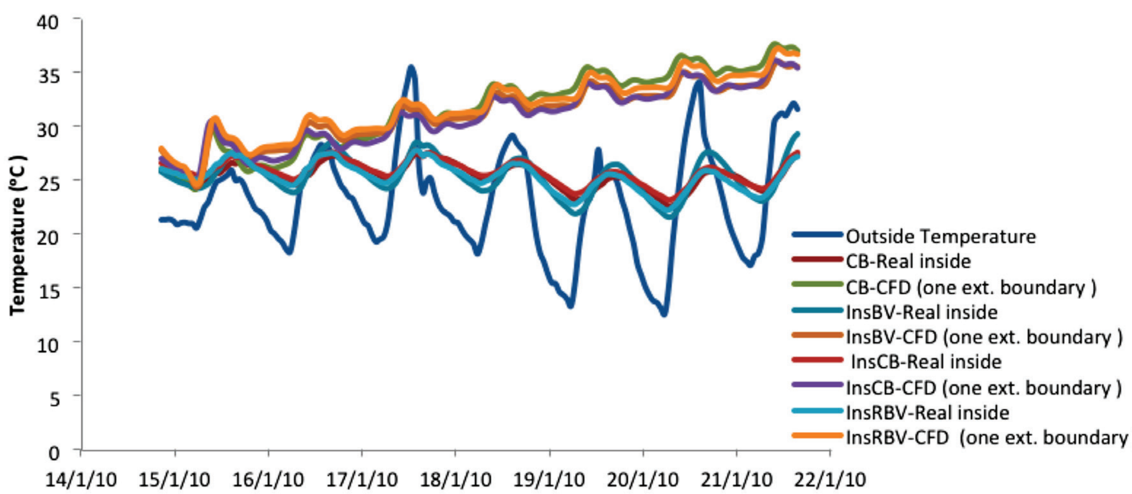



**FIGURE 6.** Comparison between real internal air temperature and CFD simulated internal air temperature for the InsBV, CB, InsCB and InsRBV modules.




## 3. DISCUSSIONS AND RESULTS

When using CFD analysis, there is an increasing internal temperature issue which affects the validation for long term simulations. The main reasons are as follows:

- In the real environment because of low night time temperatures, little heat is emitted back to the sky. In the simulation, the CFD volume is limited and therefore does not allow all that energy to be dissipated back to the outer space; that energy therefore keeps accumulating in the CFD environment space, and hence the module internal air temperature keeps rising.
- For CFD simulations, the numerical methods and algorithms involve fluid flows for shorter simulation periods (milliseconds, seconds, minutes, hours and multiple days), but are not normally suited for long term simulations involving months or years. Therefore, CFD simulations provide reasonable results for shorter periods (less than 9 hours).



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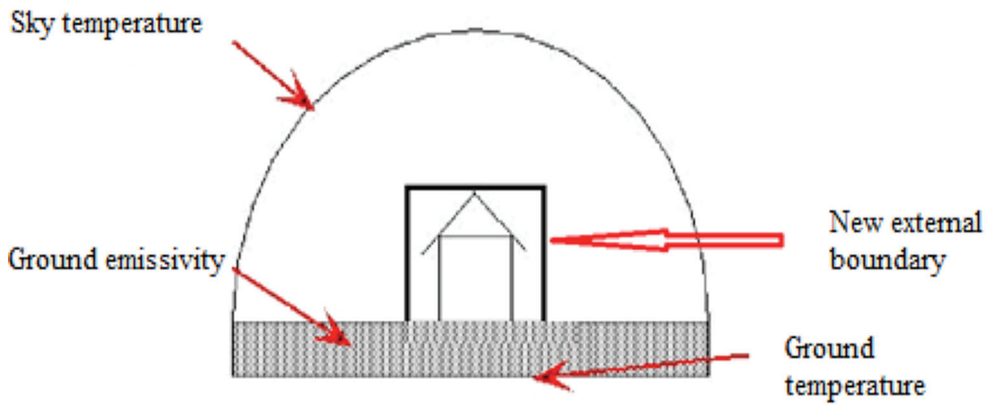
To avoid the rising internal temperature effect for the simulation of the behaviour of the modules, a new method to measure internal module air temperature for a long term (weeks and months) using CFD simulation is proposed. This uses two external air boundaries: one for the external volume (sky boundary); and a second new volume (new external boundary).

It was noticed from the CFD analysis that the progressively rising internal air temperature can be minimized by addition of a new external boundary (less than 1m thick) surrounding a module as shown in Figure 7.

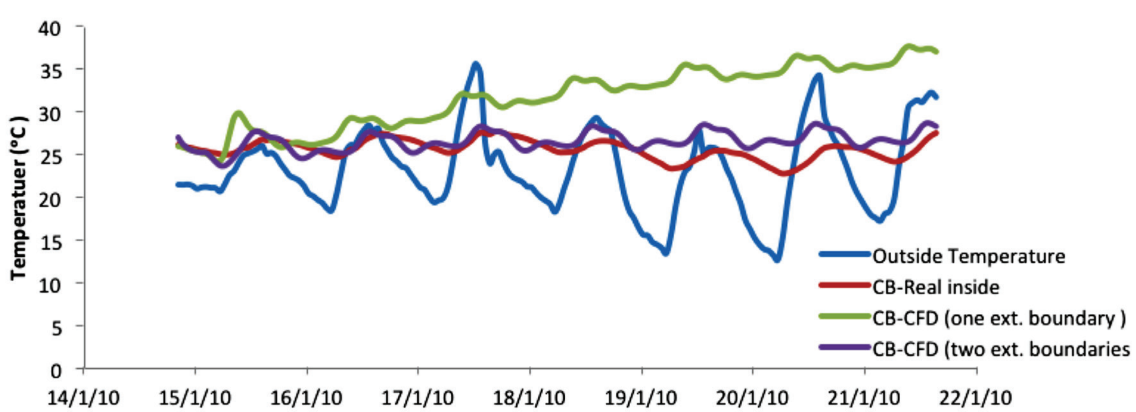
**FIGURE 7.** New external boundary applied to the module.




The external air temperature is then applied to the new external boundary rather than applying it to the sky boundary. This does not affect the solar radiation received by the module. The dimensions of the new external boundary are 7m in length, 7m in width and 3m height in this analysis and the new space is filled with the same atmospheric air as the surrounding space.

As can be seen from Figures 8(a) to 8(d), the addition of this new volume (external air layer) which surrounds the module with the ambient external air temperature consistently helps to stabilise the internal temperature.

**FIGURE 8.** Comparison of actual and CFD simulated internal air temperature for all the modules.




**(a.) Cavity Brick module.**



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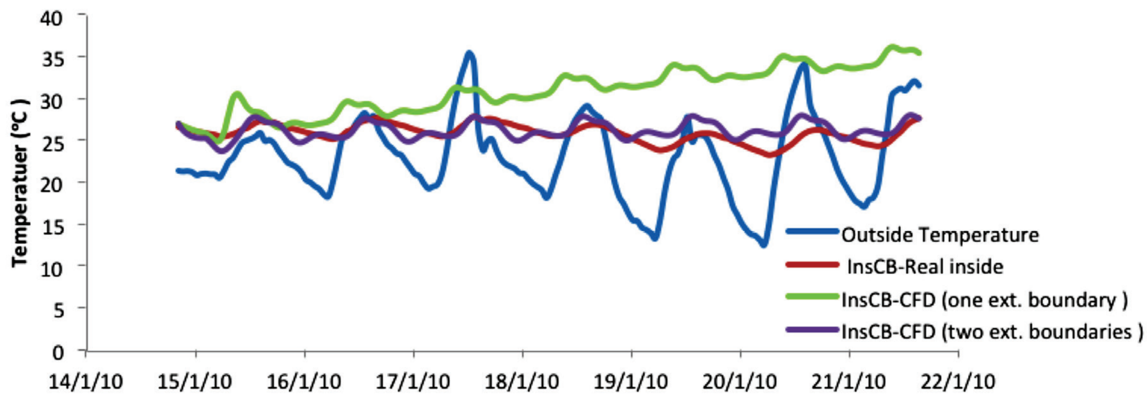
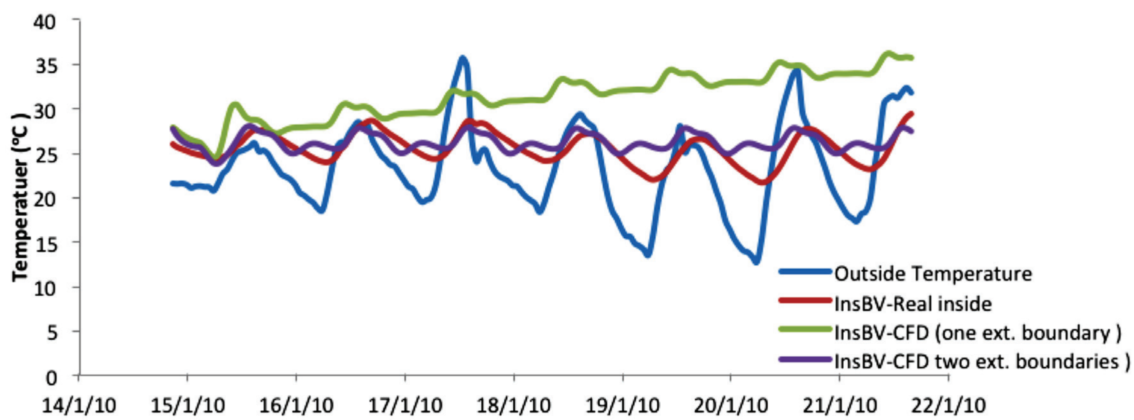
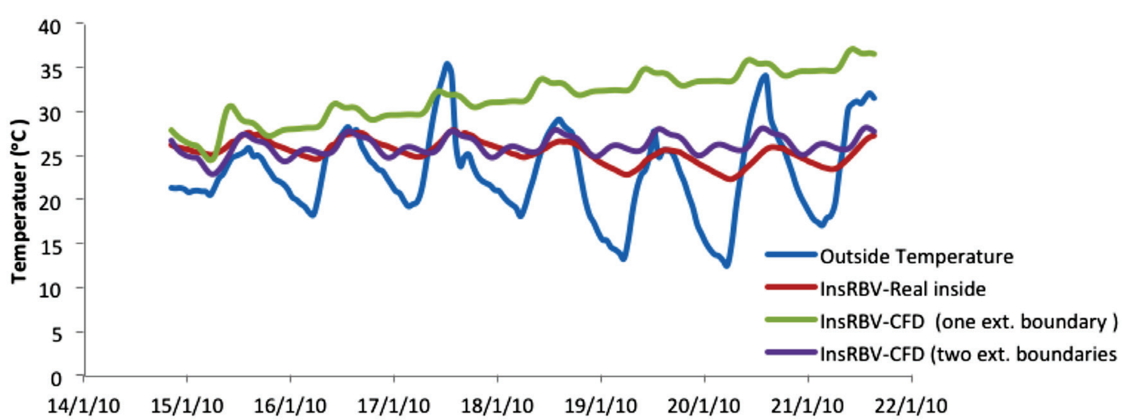



**(b.) Insulated Cavity Brick module.**




**(c.) Insulated Brick Veneer module.**




**(d.) Insulated Reverse Brick Veneer module.**

By comparing the number of hours that each module falls within the temperature difference between the CFD simulation and the real internal air temperature, it can be seen that the new external air boundary stops the temperature increasing with time. For example, a value of 16 hours (total simulation time 164 hours) for the CFD simulation using one external boundary for the

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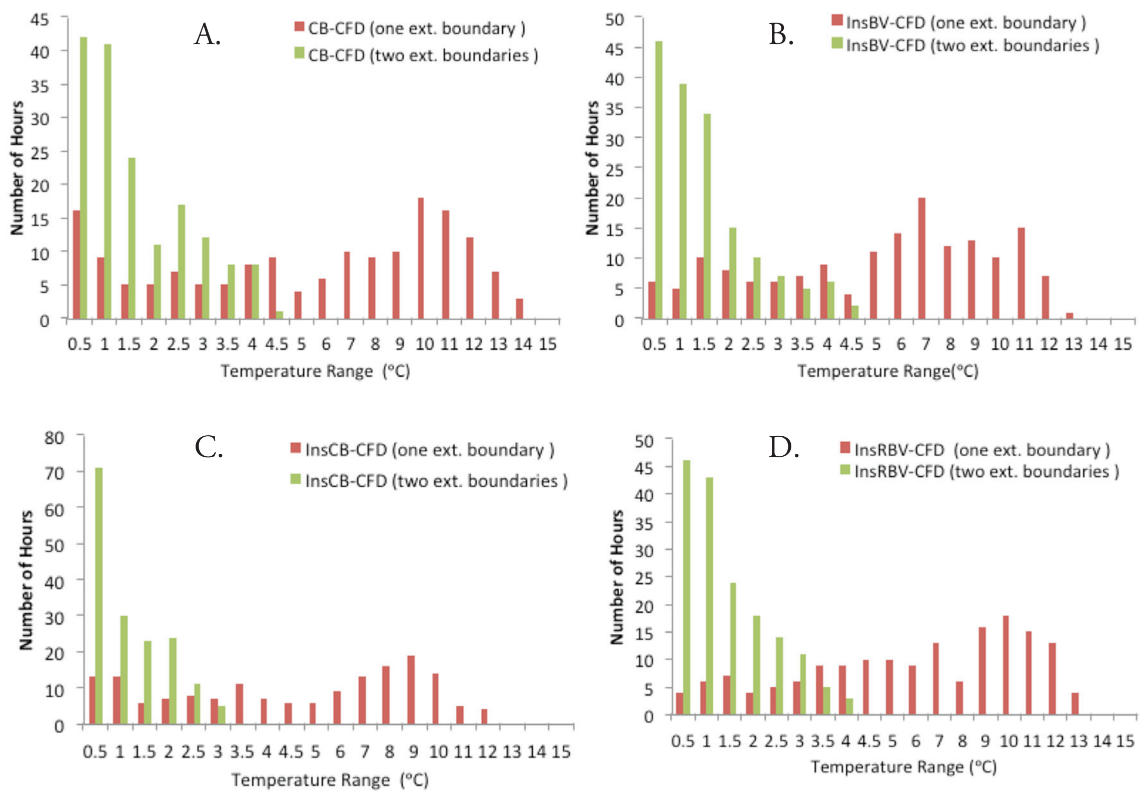
Cavity Brick module (CB- CFD (one ext. boundary) falls within a 0 - 0.5°C range with the real inside air temperature, while the CFD simulation using two external boundaries for the Cavity Brick module (CB- CFD (two ext. boundaries) 42 hours falls within that range (0 - 0.5°C).

It can be seen in Figure 9 that all modules with two external boundaries performed much better. With two external boundaries the maximum difference between the simulated and real internal air temperature was 4.5°C, compared to 14°C with one external boundary.

**FIGURE 9.** Number of hours for each temperature range between real data and the CFD simulation for all the modules ((a) Cavity Brick module, (b) Insulated Brick Veneer module, (c) Insulated Cavity Brick module, (d) Insulated Reverse Brick Veneer module). Note: 0.5, 1, 1.5, 2 temperature range for the number of hours falls within 0-0.5, 0.5-1, 1-1.5, 1.5-2°C range respectively.




It is clear that a CFD simulation with two external air boundaries gives more accurate results compared to one external air boundary. This provides a better representation of the real air temperature inside the module with all results falling within a 0-4.5°C temperature difference with the real air temperature as shown in Table 2 and Figure 10.

The comparison between the CFD simulation and the real data inside each module shows that the average accuracy for simulations using two external boundaries at any given time during one week is around 95% for all modules compared to a 74% - 84% average accuracy with one external boundary as shown in Figure 11.

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**TABLE 2.** Percentage of the number of hours for each temperature range (bin) between real data and CFD simulation (with one and two external boundaries) for each module to the total simulation time (164 hours).

| Temperature Range (ºC) | CB- CFD (one ext. boundary) hours | CB- CFD (two ext. boundaries) hours | InsBV-CFD (one ext. boundary) hours | InsBV-CFD (two ext. boundaries) hours | InsCB-CFD (one ext. boundary) hours | InsCB-CFD (two ext. boundaries) hours | InsRBV-CFD (one ext. boundary) hours | InsRBV-CFD (two ext. boundaries) hours |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 15.24% | 50.61% | 6.71% | 51.83% | 15.85% | 61.59% | 6.10% | 54.27% |
| 0-2 | 21.34% | 71.95% | 17.68% | 81.71% | 23.78% | 90.24% | 12.80% | 79.88% |
| 0-3 | 28.66% | 89.63% | 25.00% | 92.07% | 32.93% | 100.00% | 19.51% | 95.12% |
| 0-4 | 36.59% | **99.39%** | 34.76% | **98.78%** | 43.90% | **100.00%** | 30.49% | **100.00%** |
| 0-5 | 42.07% | **100.00%** | 37.20% | **100.00%** | 47.56% | **100.00%** | 36.59% | **100.00%** |

**FIGURE 10.** Percentage of the number of hours for each temperature range between real data and the CFD simulation to the total simulation time for each module. modules ((a) Cavity Brick module, (b) Insulated Brick Veneer module, (c) Insulated Cavity Brick module, (d) Insulated Reverse Brick Veneer module).

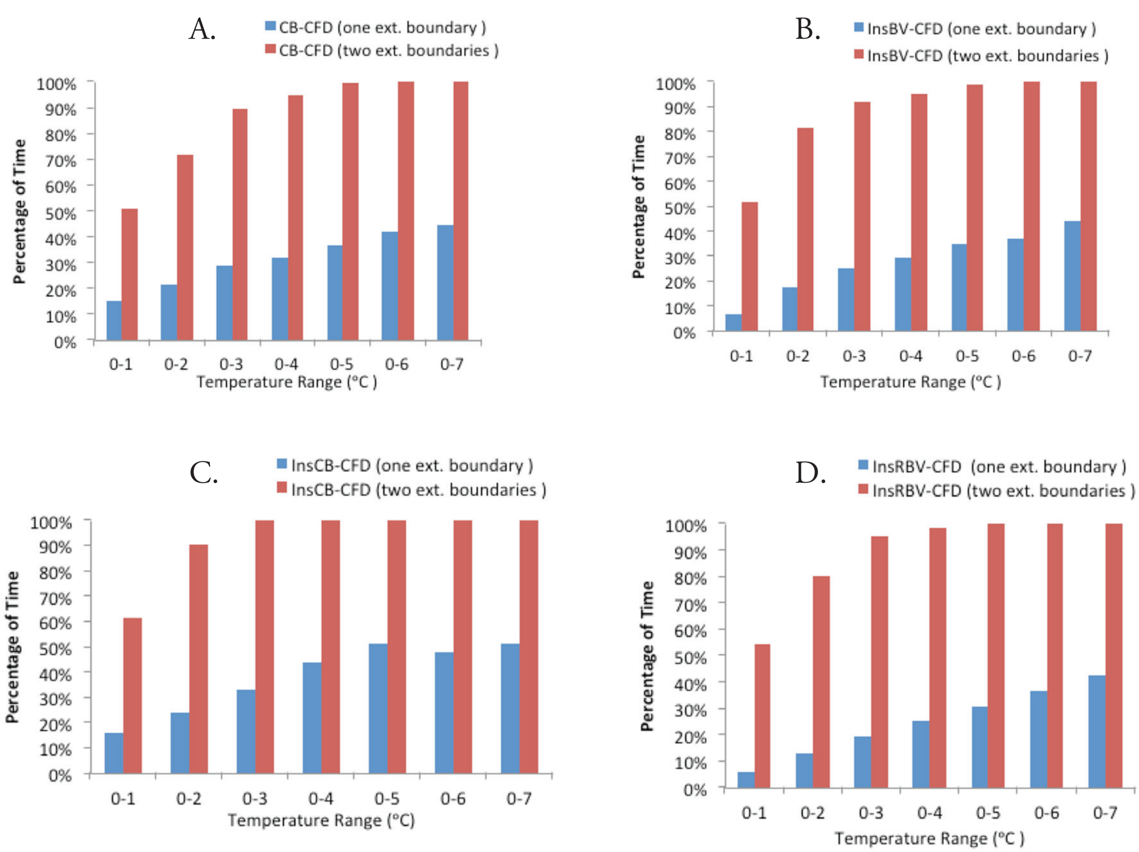




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**FIGURE 11.** Average accuracy at any given time during one week simulation.

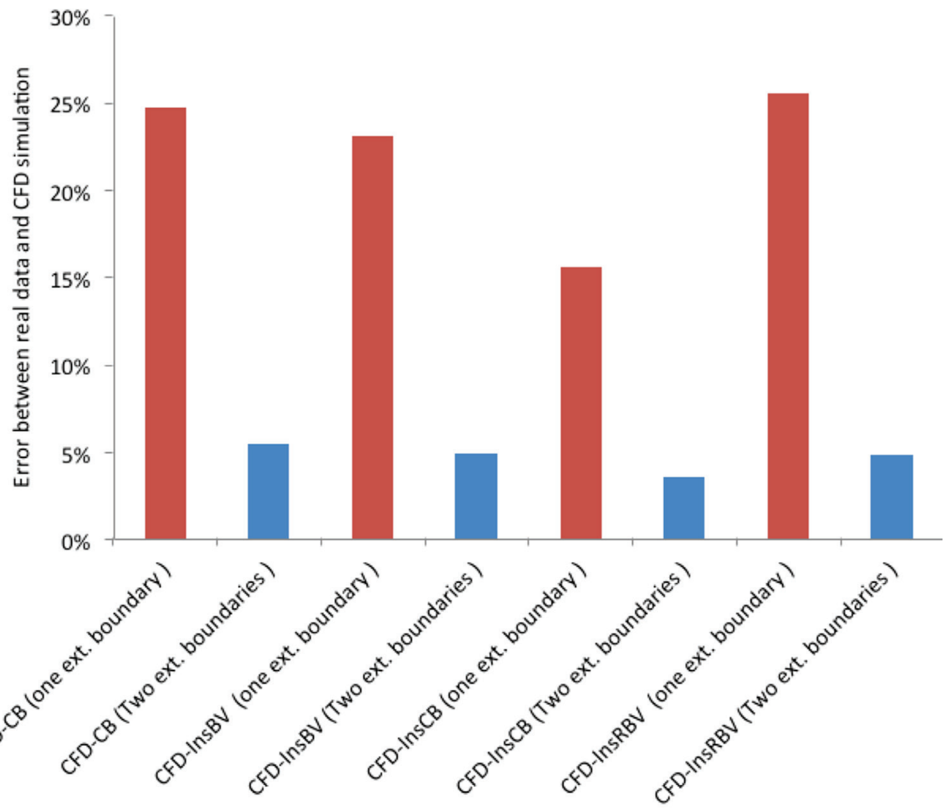
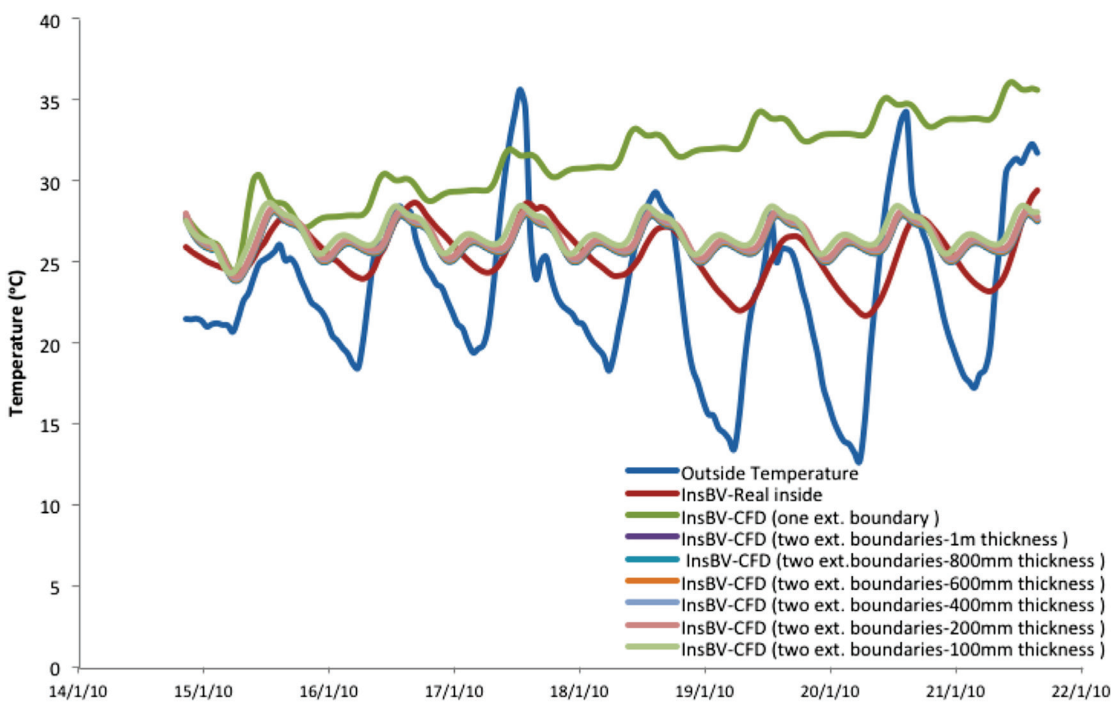



**FIGURE 12.** Internal air temperature for different wall thickness for the new external boundary.

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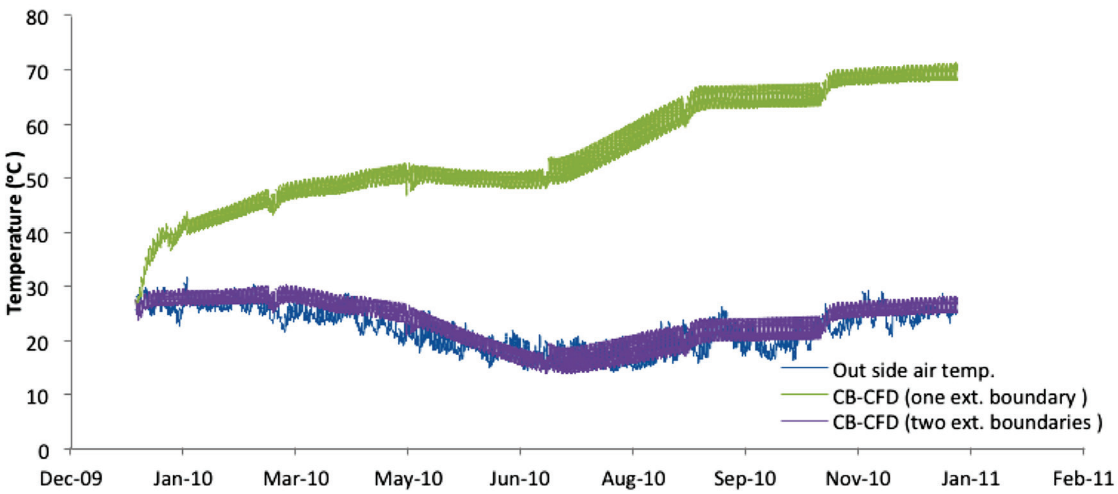
Using different thicknesses for the new external boundary, 1m, 800mm, 600mm, 400mm, 200mm and 100mm shows that there is a minimal effect (less than 5.5%) of the new external boundary layer thickness on the internal air temperature as shown in the Figure 12. This is due to the nature of the new external boundary which is filled with the same atmospheric air as that surrounding the module.

The effect of one external air boundary for a longer period (one year) is shown in Figure 13; the internal air temperature for all modules stabilised and followed real trends with more accurate simulations.

**FIGURE 13.** CFD simulations for one year using one and additional boundary for the CB module. Note: The same trends were observed for the rest of the modules (InsCB, InsBV and InsRBV).




## 4. CONCLUSION

There is an issue using CFD analysis which affects the validation of the simulated results when the internal air temperature is analysed for the long term (i.e. week, month or years) because the temperature keeps rising with time. This rise is created by the CFD environment which does not allow the entrapped energy to be dissipated back to the outer space resulting in inaccurate predictions for long term simulations. A new method to more accurately predict the internal air temperature by adding a new volume, an external air layer surrounding the module with ambient external air temperature, is presented in this paper. This results in a significant improvement of the internal air temperature predictions for 89.6%-100% of the time within a 0-3°C difference when using two external air boundaries compared to 19%-33% of the time within that temperature range when using one external boundary.

The CFD simulation with two external air boundaries therefore gives more accurate predictions compared to one external air boundary, and thus provides a better representation of the real air temperature inside the module.

### *Abbreviations Used In the Paper*

| | |
|---|---|
| Outside Temperature: | Outside air temperature (°C) |
| CB-Real inside: | Real internal air temperature for cavity brick module (°C) |



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| | |
|---|---|
| InsBV-Real inside: | Real internal air temperature for Insulated Brick Veneer module (°C) |
| InsCB-Real inside: | Real internal air temperature for insulated cavity brick module (°C) |
| InsRBV-Real inside: | Real internal air temperature for Insulated Reverse Brick Veneer module (°C) |
| CB- CFD (one ext. boundary ): | CFD simulation using one external boundary to measure internal air temperature for cavity brick module (°C) |
| CB- CFD (two ext. boundaries ): | CFD simulation using two external boundaries to measure internal air temperature for cavity brick module (°C) |
| InsBV- CFD (one ext. boundary ): | CFD simulation using one external boundary to measure internal air temperature for Insulated Brick Veneer module (°C) |
| InsBV- CFD (two ext. boundaries ): | CFD simulation using two external boundaries to measure internal air temperature for Insulated Brick Veneer module (°C) |
| InsCB- CFD (one ext. boundary ): | CFD simulation using one external boundary to measure internal air temperature for insulated cavity brick module (°C) |
| InsCB (two ext. boundaries ): | CFD simulation using two external boundaries to measure internal air temperature for insulated cavity brick module (°C) |
| InsRBV- CFD (one ext. boundary ): | CFD simulation using one external boundary to measure internal air temperature for Insulated Reverse Brick Veneer module (°C) |
| InsRBV- CFD (two ext. boundaries): | CFD simulation using two external boundaries to measure internal air temperature for Insulated Reverse Brick Veneer module (°C) |

## 5. ACKNOWLEDGEMENTS

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