THE INFLUENCE OF THERMAL RESISTANCE AND THERMAL MASS ON THE SEASONAL PERFORMANCE OF WALLING SYSTEMS IN AUSTRALIA

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ABSTRACT

This paper describes an experimental investigation of the thermal performance of four Australian domestic walling systems (cavity brick, insulated cavity brick, insulated brick veneer and insulated reverse brick veneer) having various combinations of thermal insulation and of thermal mass location within the wall. This experimental analysis extends further the previous studies of the benefits of thermal mass on the overall thermal performance of building enclosures (Gregory et al. 2008, Luo at al. 2008, Alashaary et al. 2009). The comparison is based on the time required to maintain thermal comfort for free-floating internal conditions. The results clearly show that internal comfort levels are influenced by both the thermal resistance of the walls as well as the extent and location of the thermal mass, with neither parameter being the sole predictor. The best thermal performance is therefore obtained by an appropriate combination of thermal mass and resistance, rather than focussing on the overall wall thermal resistance (R-value) alone. A new approach of density temperature plots for comparison of temperature variation is also used in the assessment of module thermal performance.

KEYWORDS

thermal mass, thermal performance, thermal resistance, building enclosure, temperature plots

1. INTRODUCTION

In the major Australian population centres, the typical forms of domestic construction are brick veneer, cavity brick or some form of lightweight walling system. These walling systems have a wide range of thermal resistance and thermal mass, with both properties being a function of the materials used and the levels of insulation. Australia also has climates ranging from

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tropical, with humid summers and warm winters, to alpine conditions; however, the bulk of the population centres are located in moderate climate zones, and the investigations presented in this paper are therefore based on "temperate" conditions.

Thermal mass is a thermo-physical property which is proportional to the density and the specific heat of the material. The benefits of this heat storage capacity have been already recognized, especially in relation to passive solar design. Thermal mass can be installed externally and/or internally within the walls and floor using brick, concrete or stone (Florides 2002, Hoseggen 2009).

Previous studies highlighted the ability of thermal mass to significantly diminish the diurnal (day to night) temperature swings, creating internal conditions more consistent with the ideal human comfort zone (Gregory et al. 2008). This is because the solar energy received by the building during the day can be stored in building elements with high thermal mass and then gradually released overnight. Whilst it is well-know that buildings with high thermal mass will suppress maximum indoor temperature (Cheng and Givoni (2005), there is a lack of understanding about the interaction between thermal mass and insulation.

In fact, previous studies (Gregory et al. 2008, Luo at al. 2008, Alashaary et al. 2009) in the Australian context have confirmed that thermal mass performs well within envelopes; however, the best combinations and locations of thermal mass and insulation within the walls have not been confirmed using experimental data. It was also found that energy consumption could be significantly decreased by installing better performing walling types on the eastern and western walls.

It should also be noted that thermal mass is not a substitute for insulation, since insulation has a direct influence on the extent to which heat flows into or out of the building. Therefore to achieve the best performance, an appropriate combination of thermal mass and insulation should be used.

An extensive research program on the thermal performance of Australian housing has been carried out for more than 10 years at the University of Newcastle in collaboration with Think Brick Australia (Page et al. 2011, Gregory et al. 2008, Luo at al. 2008, Alashaary et al. 2009). This paper describes an experimental investigation of the thermal performance of four walling systems used in Australian housing: cavity brick (CB), insulated cavity brick (InsCB), insulated brick veneer (InsBV) and insulated reverse brick veneer (InsRVB). All of these walling systems were part of the larger study, and selected because of their varying combinations of thermal mass and insulation. These systems have a range of thermal resistance (R) values and varying degrees of external and internal thermal mass properties (see Table 1). The R-values of each wall were first determined using a Guarded Hot Box Apparatus. They were then incorporated into four housing test modules built on the University of Newcastle campus and the detailed thermal performance of each system was observed over a range of seasonal conditions. In the tests, the interior of the module could be allowed to "free float", or be controlled within a comfort range by a heating/cooling system with the energy consumption being measured. Only free floating conditions are considered in this paper.

2. GUARDED HOT BOX INVESTIGATIONS

The guarded hot box facility (GHB) measures the thermal resistance (R-Value) or conductance of walling elements by establishing a steady-state temperature gradient across the wall whilst measuring the energy flow through the wall. An in-house facility conforming to ASTM C 1363–97 (ASTM, 1997) was developed and used to obtain the R-Value of each

TABLE 1. Description and Thermal Characteristics of Module Walling Systems.

Wall Type	Wall Sections	R-value [m²K/W] surface to surface	R-value [m²K/W] air to air	Weight [kg/m²]	Specific Heat [kJ/kgK]
Cavity Brick (CB)	*110mm external brick skin; *50mm cavity; *10mm internal cementicious render ***110mm brick masonry skins**	0.44	0.62	400	0.90
Insulated Brick Veneer (InsBV)	*110mm external brick skin; *50mm cavity; *pine stud frame with low glare reflective foil and R1.5 insulation glasswool batts; *10mm interior plasterboard	1.58	1.72	210	0.97
Insulated Cavity Brick (InsCB)	*110mm external brick skin; *50mm cavity; *R1.0 rigid expanded polystyrene sheets in cavity fixed to interior masonry skin; ***110mm brick masonry skins**; *10mm cementicious render on external face of interior skin	1.30	1.48	401	0.90
Insulated Reverse Brick Veneer (InsRBV)	*7mm external fibro-cement sheeting finished with polymer render; *breathable membrane fixed to pine stud frame; *R1.5 glasswool batts in frame; ***110mm brick masonry internal skin,** *10mm cementicious render	1.57	1.93	217	1.01

Note: Air-to-air R-Values measured and compered with AU Standard (AS/NZS, 2002): 0.04 externally and 0.14 internally; an internal masonry skin is indicated in bold

of the four wall types described in Table 1. The test walls were 2.4 m (high) by 2.4 m (wide) with the guarded hot box occupying the central 1.2 x 1.2 m area of the test panel. The R-values obtained for Δ18°C temperature differential (AS/NZS, 2002) (air to air across each wall thickness) for the four wall types used in this study are shown in Table 1 (air to air values are used for subsequent comparison in this paper)

3. HOUSING TEST MODULES

The housing module tests were used to provide qualitative and quantitative data on the thermal performance of the walling systems under real climatic conditions. The modules were comparable in size to other buildings used in similar studies in North America (Burch et al., 1982). Note that the intent of the module tests was not to reproduce the behaviour of an actual house but rather to observe and quantify the typical heat flow mechanisms for walls in a realistic context.

The modules were constructed on the University of Newcastle Campus (Newcastle is located in a temperate climate zone on the east coast of Australia at latitude 33°south). This temperate climate is typified by mild to warm summers and cool winters with a considerable diurnal temperature variation of 11 to 16 degrees Celsius that requires winter heating and occasional cooling in summer.

Over the testing period, a range of walling systems have been used (cavity brick (CB), insulated cavity brick (InsCB), brick veneer with and without insulation (BV and InsBV), lightweight construction (LW) and insulated reverse brick veneer (InsRVB)). This paper focuses on a study of the interaction between thermal mass and insulation by considering data for the CB, InsCB, InsBV and InsRBV modules. In each case the response of the modules was observed with the interior being in a 'free-floating' state where the response of the module is influenced by the weather conditions and the recent thermal history (other studies, not reported here, were also carried out with the interior heated or cooled to pre-set levels of temperature (Page et al, 2011).

The modules had a square floor plan of 6m x 6m and were spaced 7m apart to avoid shading and minimise wind obstruction. With the exception of the walls and roof, the buildings were of identical construction following normal Australian practice, being built on a concrete slab-on-ground and aligned in a manner so that the north wall of each building was perpendicular to astronomical north. Timber trusses were used to support the roof which consisted of tiles for the CB, InsCB and InsBV modules and steel sheeting for the InsRBV module, in both cases placed over a layer of sarking. The buildings had a ceiling height of 2450 mm. The ceiling consisted of 10mm thick plasterboard with glasswool insulation batts (R3.5 $m^2.K.W^{-1}$) placed between the rafters. Since the emphasis of the investigation was on wall performance, the R3.5 insulation was selected to minimise the "through-ceiling" heat flow. Entry to the buildings was via tight fitting, solid timber doors with a 75mm thick layer of polystyrene foam insulation (R3.0) located on the southern face of the buildings. The roof was supported by an independent steel frame which allowed the removal and replacement of walls as required.

The tests reported here were performed with a major window opening (a 3 panel sliding door assembly, 2050 high x 2840 wide) incorporated in the northern wall of each module to allow solar ingress and to better reflect solar passive influences. The dimensions of the eaves were typical for Australian domestic construction, and the same for all modules, thus ensuring that solar effects from the eaves were the same for all the modules. The modules are shown in Figure 1.

4. INSTRUMENTATION

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

Figure 1: Housing Test Modules (with window in north wall), (a) Insulated Brick Veneer (b) Insulated Cavity Brick (c) Cavity Brick and (d) Insulated Reverse Brick Veneer.

internal air temperature and relative humidity. Heat flux sensors (100x100mm with sensitivities 25μV/W/m^2) were placed on the walls, ceilings and concrete slab, adjacent to the window (in direct sunlight) and at the rear south-east corner (see Figure 2). Thermocouples (Type T with accuracy of 0.5°C) were placed on the surface of the slab at various locations between the window and the centre of the room. For the window, three net radiation sensors were placed at heights of 600, 1200 and 1800mm up the glass panel to assess the incoming/outgoing radiation. The surface temperature of the glass was recorded and additional heat flux sensors were placed on the aluminium frame to assess the influence of the frame itself. Internal air space temperatures were also monitored at heights of 600, 1200 and 1800mm with the relative humidity and globe temperatures being measured centrally. In total, 105 data channels were scanned and logged every 5 minutes, 24 hours per day for each of the modules for the duration of the testing program.

5. SEASONAL ANALYSIS

The analysis is based on the assumption that the internal conditions were comfortable when the internal air space temperature was in the 18-24°C range (Rahman et al. 2007, ANSI/ASHRAE, 2004). It is recognised that other factors also affect thermal comfort (Olesen and Brager, 2004) but this temperature range was used for convenience. The analysis of the

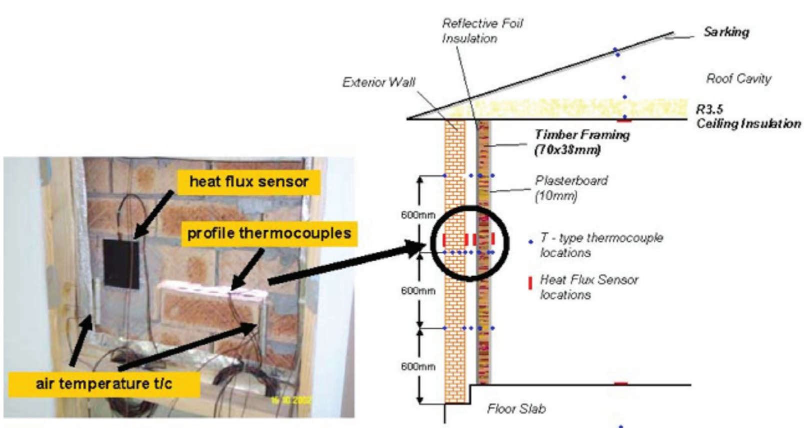


Figure 2: Typical thermocouple and heat flux sensor arrangements for the InsBV module.

‘free-floating’ data involved studying the diurnal behaviour of the ‘free-floating’ modules for typical spring, summer, autumn and winter periods across 2008 and 2009. The analysis therefore allows the potential year round performance to be assessed, by examining the relevant number of hours each of the modules sat within the comfort zone for the “snapshot” of each season.

5.1. Performance During Spring Conditions

The spring data was obtained for a 4 week period from 02/10/2008 to 30/10/2008. Generally over the spring collection period the conditions were sunny with over half the days being clear. An average external temperature of 18.2°C was recorded. Daily external temperatures nearly always exceeded 20°C, occasionally peaking over 25°C. Minimum night external temperatures typically ranged between 5-10°C. The typical diurnal response of the modules is presented in Figure 3, together with the external temperature distribution across the season in Figure 4.

During the spring period for all four modules, the majority of the time was spent within the 18-24°C temperature zone (over 86% for InsCB, CB and InsRBV modules, and 75% for the InsBV module as seen in Figures 5). Despite the large differences in R-value (ranging from 0.62 to 1.93), the performance of all modules with internal thermal mass (i.e. InsCB, CB and InsRBV) was relatively similar, with only slight differences as a result of the difference in the distribution of mass and insulation throughout the wall thickness. It can also be seen that due to the lack of internal thermal mass, the InsBV module exhibited the longest periods above 24°C and below 18°C, with higher temperature swings and a correspondingly lower proportion of time in the comfort zone.

The cumulative time spent above, below and within the 18 – 24 degree temperature zone for the 4 week period for each of the modules is shown in Figure 6.

Figure 3: Typical thermal behaviour for a randomly selected 3 day cycle.

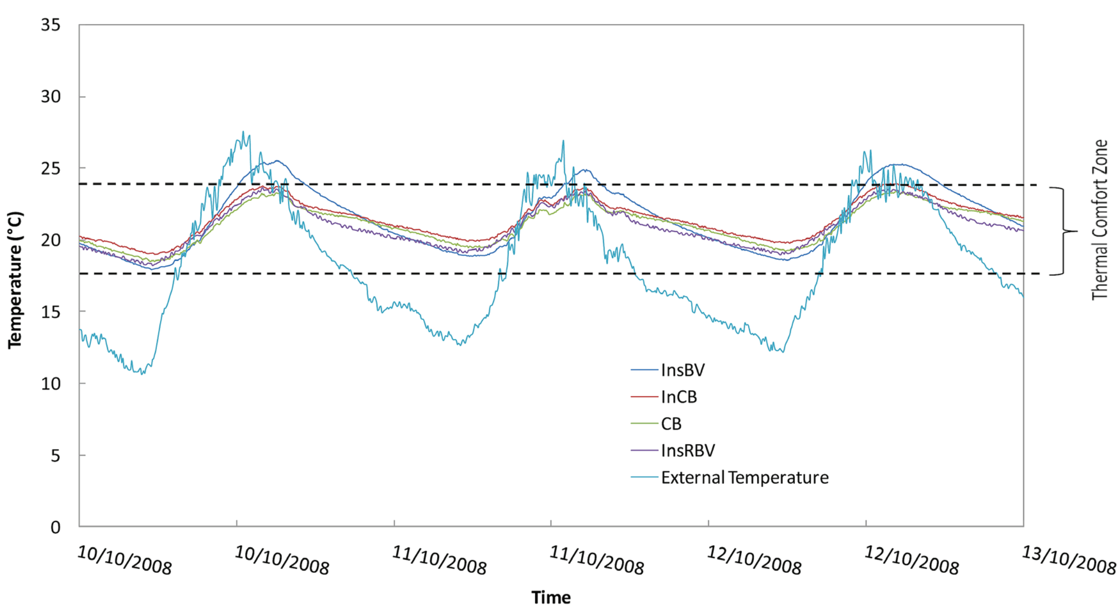


Figure 4: External temperature distribution for the spring period.

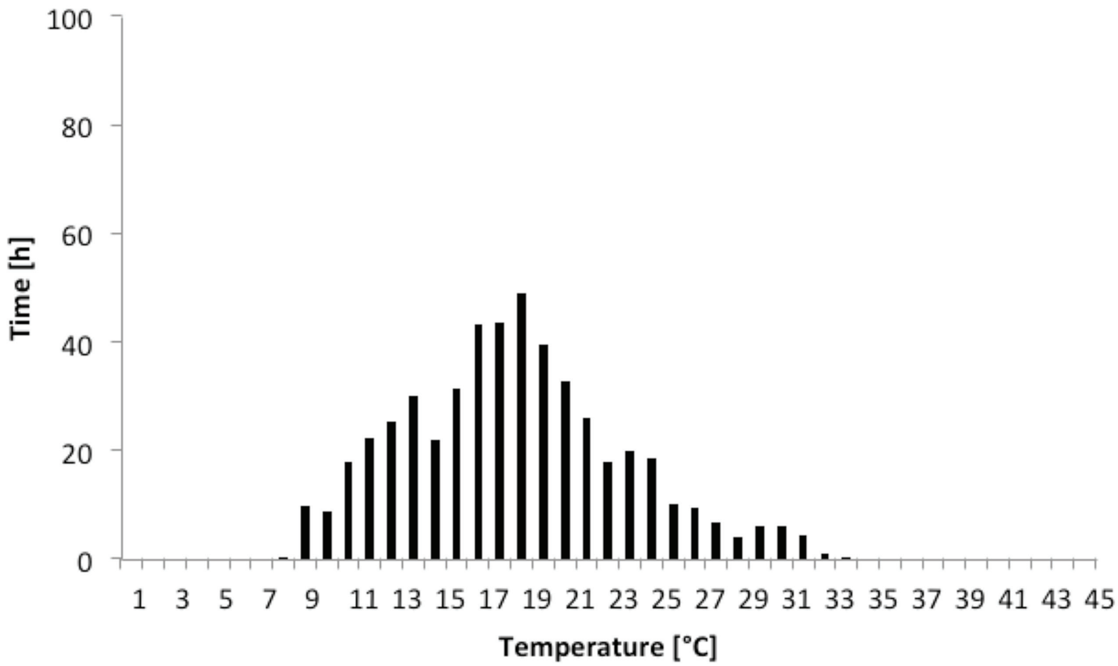


Figure 5: Internal temperature distribution for modules: (a) InsRBV, (b) InsCB, (c) InsBV, (d) CB – spring period.

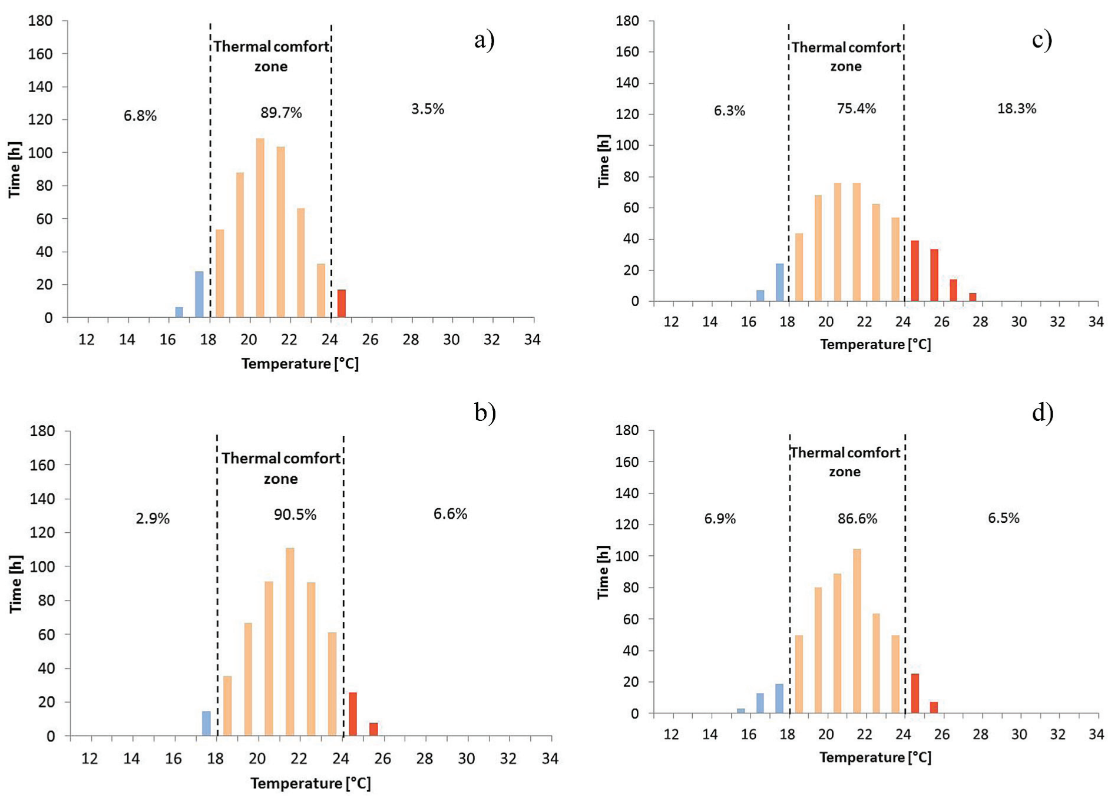
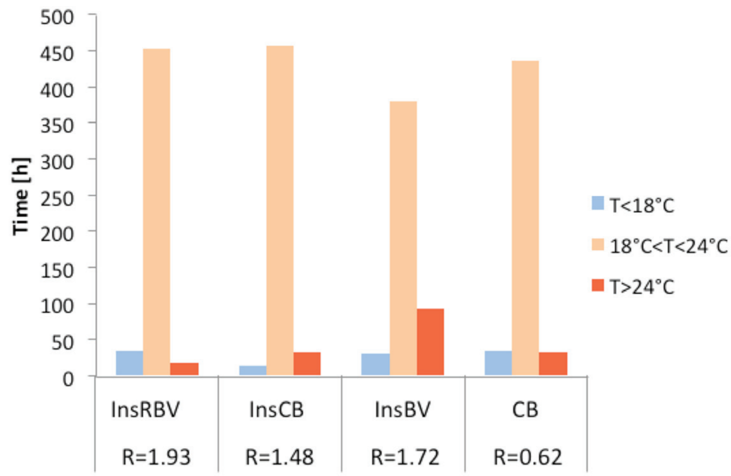
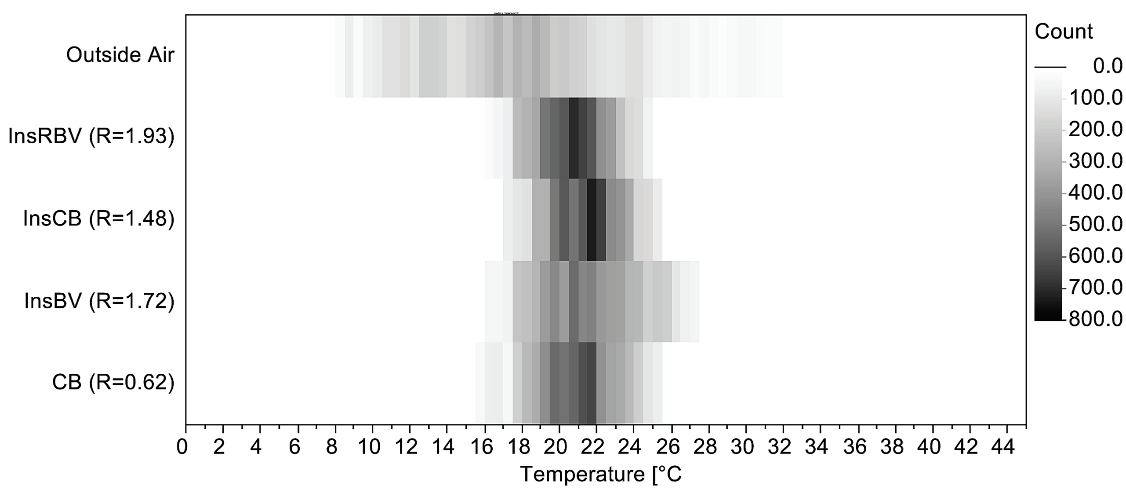


Figure 6: Hours within and outside the comfort zone – spring period.



Another way of presenting and interpreting the above results using temperature density plots is also presented here (Figure 7). Every bar indicates the number of counts (for 5 minute intervals) for a given range of temperature, with the darker bars indicating higher density of counts and lighter of lower density. The plot allows the easy comparison of the thermal performance of the modules for the full range of temperatures across a day, month, season or year.

Figure 7: Temperature density plot for every module across spring conditions.



5.2 Performance During Summer Conditions

The summer data was obtained for a 4 week period from 11/12/2008 to 08/01/2009. External conditions varied from over 35°C for 20 days with an average daily temperature of 23.2°C to several cooler periods of around 20-25°C. The maximum peak external temperature of 41.8°C was recorded with the minimum temperature being 12°C in the period. The typical diurnal response of the modules for a 3 day period is presented in Figure 8, together with the external temperature distribution across the season in Figure 9.

During the summer period, the relative periods within and outside the comfort zone for the 4 modules are shown in Figure 10, with the InsRBV and InsBV modules having the

Figure 8: Typical thermal cycles for all modules under external temperature.

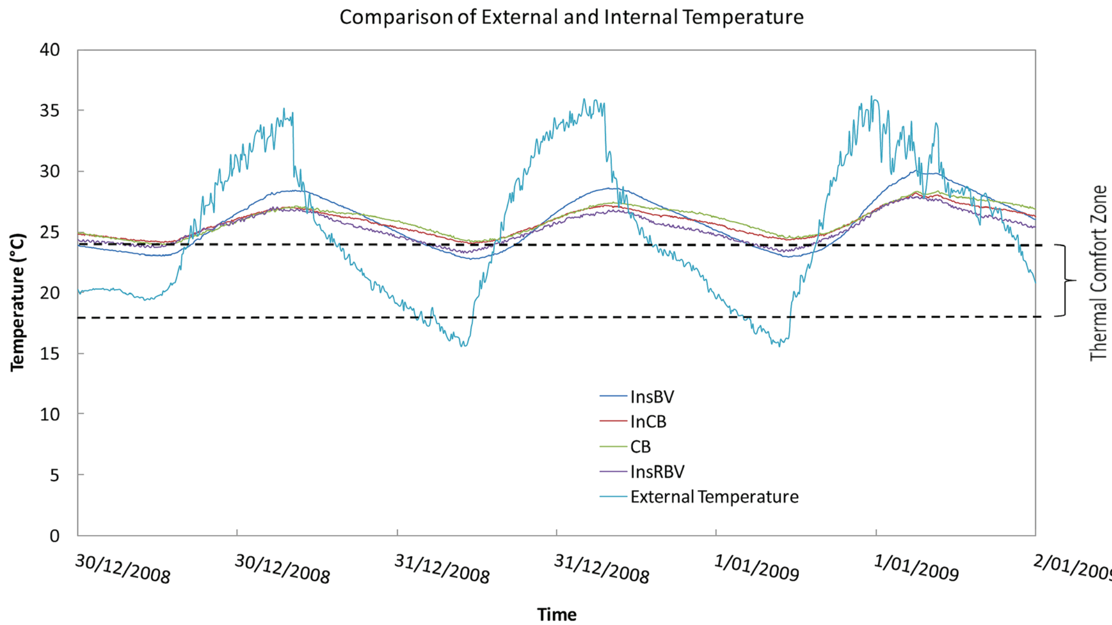


Figure 9: External temperature distribution for the summer period.

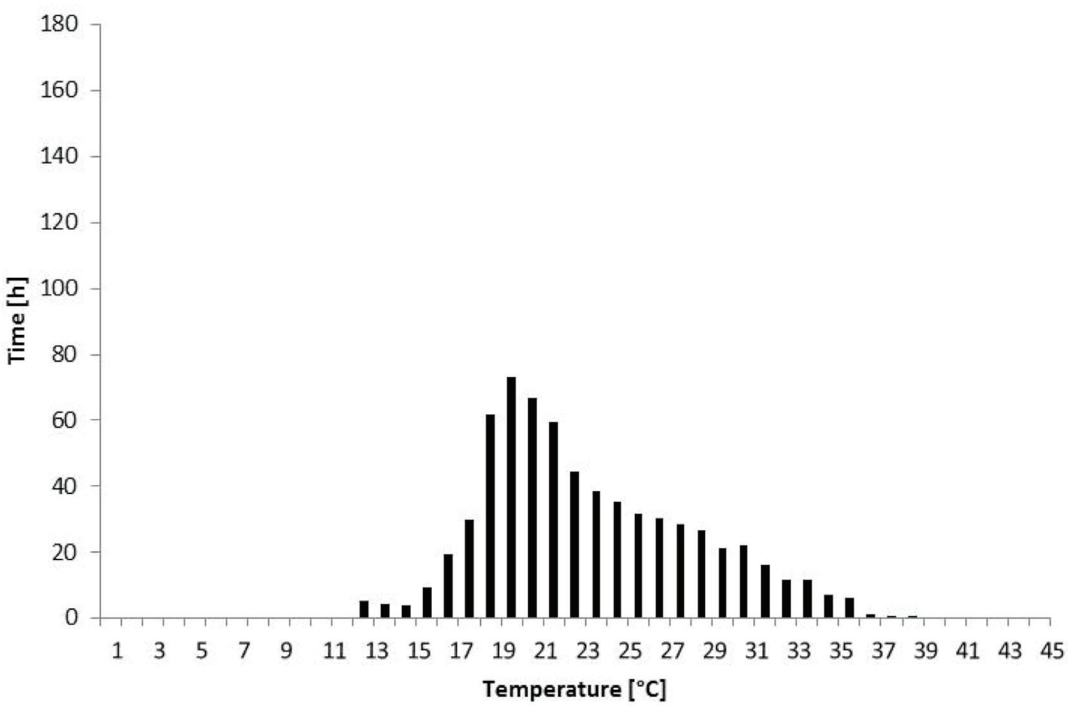
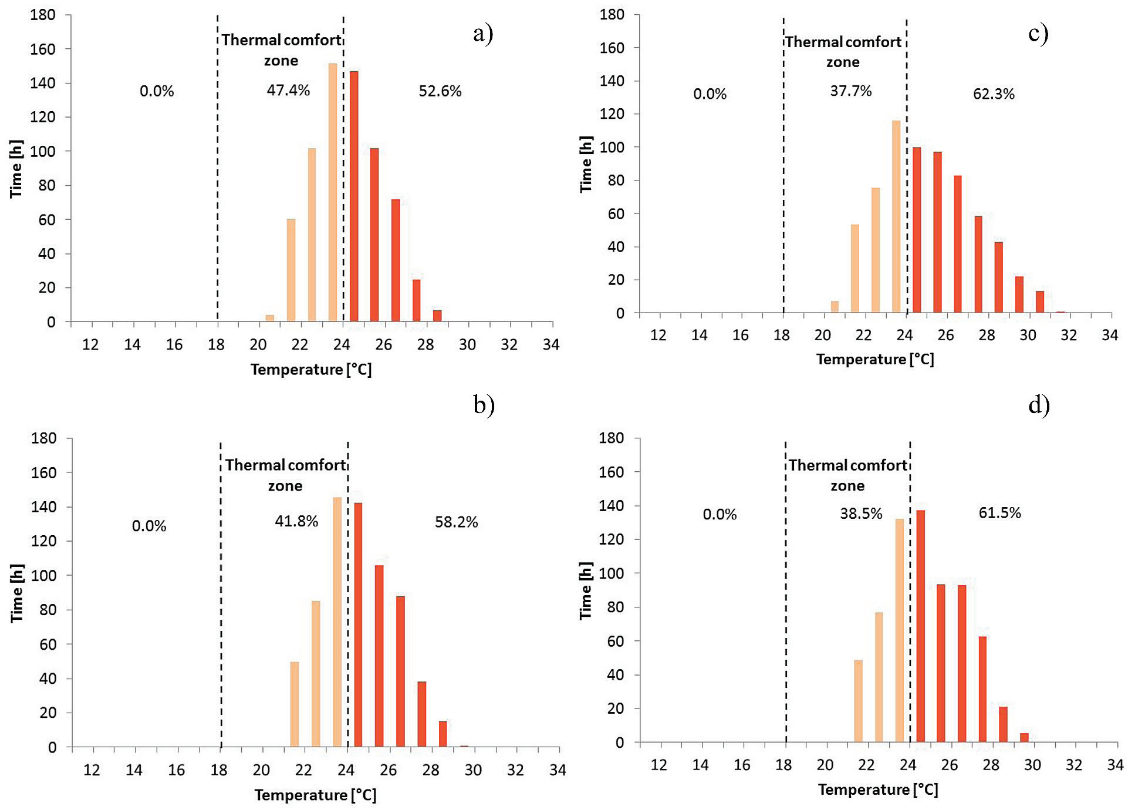


Figure 10: Internal temperature distribution for modules: (a) InsRBV, (b) InsCB, (c) InsBV, (d) CB – summer period.



greatest and least time in the comfort zone respectively. It is interesting to note that over the 4 week period, the InsBV and CB modules had similar percentages of time within the thermal comfort zone yet exhibited different behaviour in responding to the changing external diurnal conditions, with the maximum internal temperature of the CB module being 29.5°C compared to 31.5°C for the InsBV module. The InsRBV module was also consistently cooler than all the other modules; however, its internal temperature dropped more rapidly than both the InsCB and CB modules which had an internal skin with thermal mass.

As illustrated in Figures 10, 11 and 12, and observed for the entire season, the InsBV module consistently exhibited larger temperature oscillations than the three modules with thermal mass in their internal skins. This illustrates the ability of the internal thermal mass to provide a dampening effect on the internal temperature swings.

Both, the histogram and temperature density plots shown in Figures 11 and 12 indicate that the InsRBV module was the best performer of the four modules for summer conditions, with almost half of the time spent in the comfort zone for the observation period. The InsRBV module also had the lowest day and lowest night temperature variations which would be desirable during summer conditions. The InsCB module with an insulation layer between two skins was generally slightly warmer as it released more heat into the room at night compared to the InsRBV module.

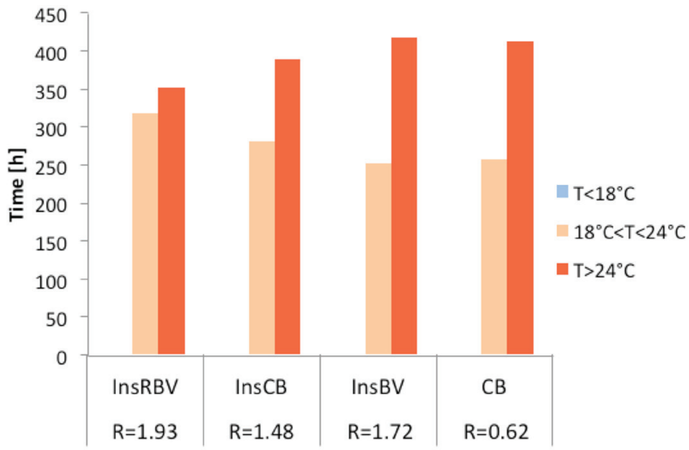
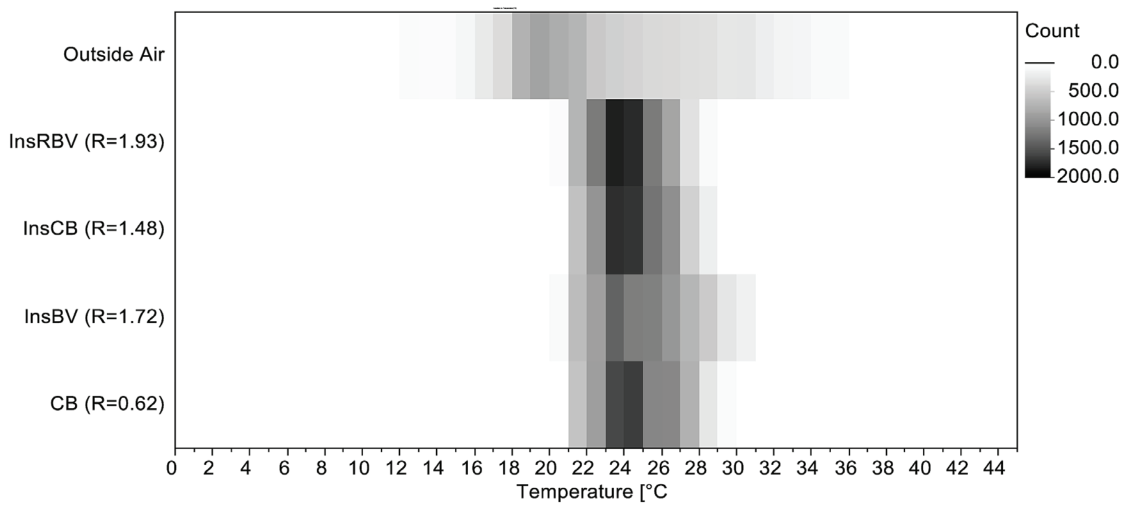


Figure 11: Hours within and outside the comfort zone – summer period

Figure 12: Temperature density plot for every module during summer conditions



5.3 Performance DuringAutumn Conditions

For the 4 week autumn period from 05/03/2009 to 02/04/2009, the weather was quite warm, with maximum external temperatures ranging predominately between 30°C and 33°C. Night time minima had a greater variation and ranged from cool nights close to 12°C to warmer temperatures of 20°C. External average temperatures were lower than summer by 1.7°C on average, but the north vertical plane solar radiation was almost three times greater than summer due to the reduced solar angle. The solar radiation on the roof was slightly less than summer as was that for the south wall due to lower solar angle. East and West wall surface radiation remained very similar to that for summer. The typical response of modules is presented in Figure 13, together with external temperature distribution across the season in Figure 14.

Despite the external temperatures being lower overall, these conditions resulted in much higher temperatures within the modules due to the greater solar gain through the northern window. This indicates that autumn conditions can potentially produce higher internal temperatures than summer, and reinforces the need for counteracting the heat gain for this period with better design for the impact of solar gain.

Figure 13: Typical thermal cycles for all modules under external temperature.

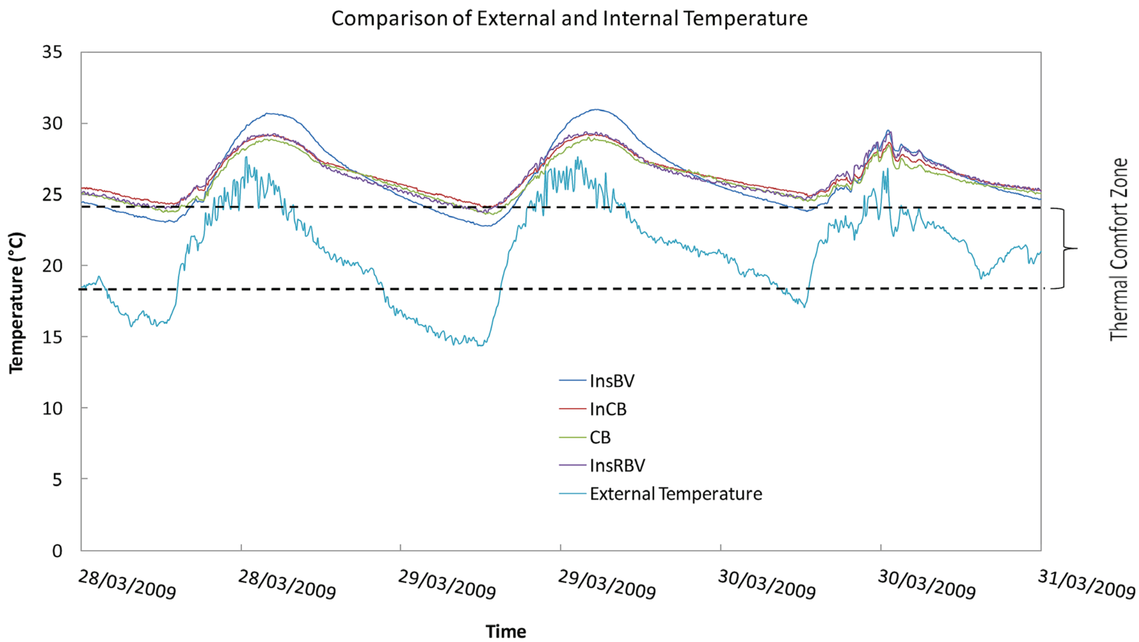
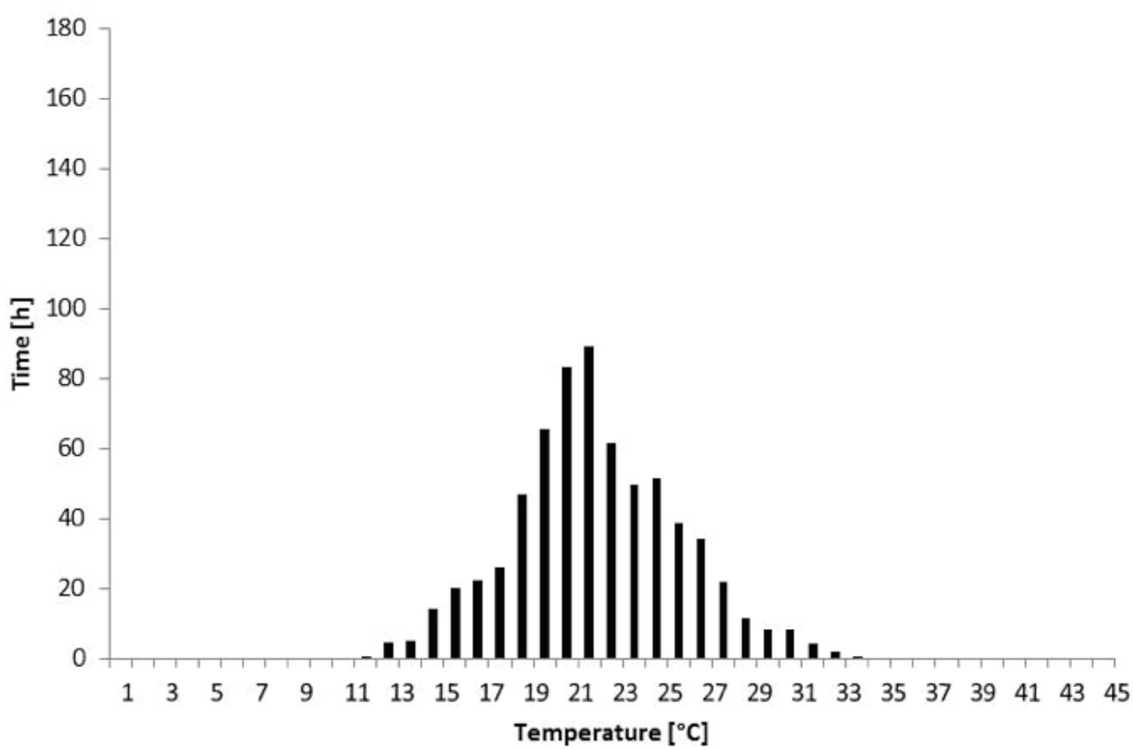


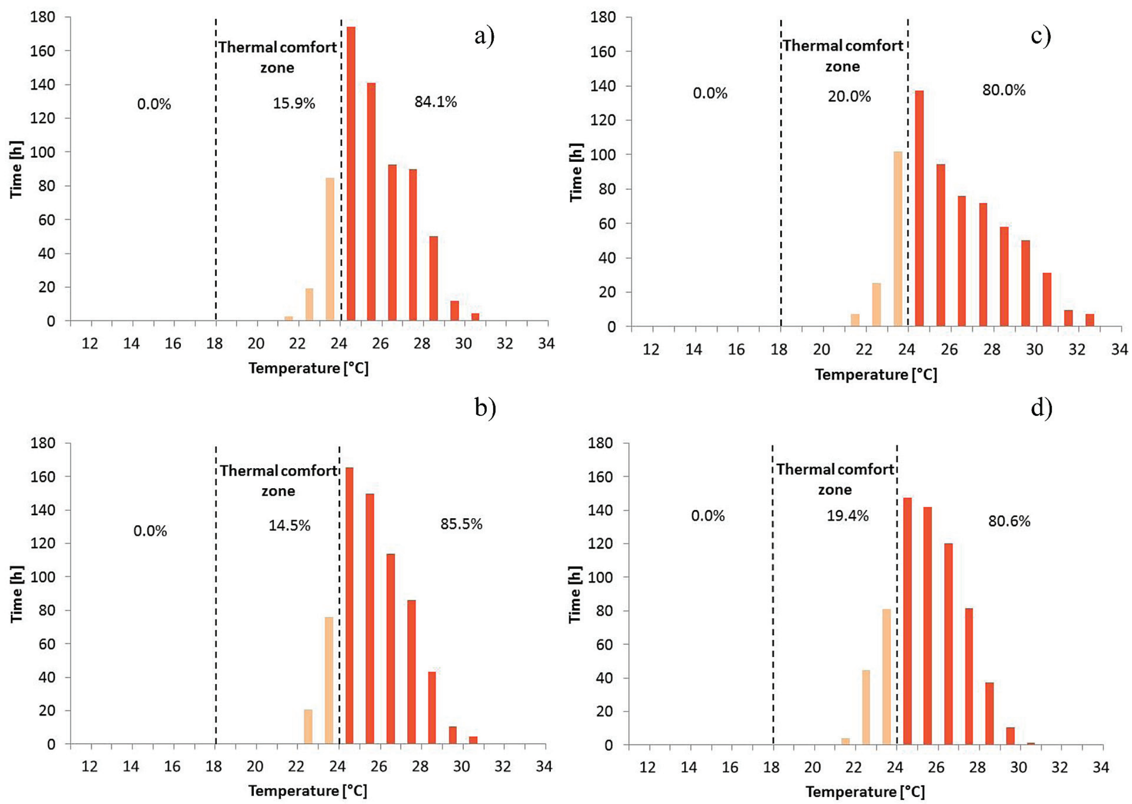
Figure 14: External temperature distribution for the autumn period.



During the autumn period, the temperatures in all modules were regularly above 24°C which resulted in little time being spent within the comfort range (see Figure 15). The InsBV spent a greater amount of time (about 20%) within the comfort zone due to its higher rate of temperature decrease with the lack of thermal mass being an advantage in this case. As can be seen in Figures 15a and 16, due to the faster reduction in temperature of the InsBV module during evenings, its internal temperature drops to within the comfort zone for a short period, whereas the modules with internal thermal mass (with accompanying stored heat) remain at a higher level, with a corresponding higher accumulation of degree hours above 24 degrees. However, it is also important to note that the InsBV module peaked at greater temperatures during the day.

The InsCB and InsRBV modules had the highest peak temperatures and a larger rate of temperature change during the night with lower minimum temperatures. The InsRBV module did exhibit slightly more rapid initial cooling into the evening, yet the minimum temperatures are similar to the InsCB module. The main contributor to the temperature rise was the solar gain through the north facing window. In addition, the wall insulation would act as a

Figure 15: Internal temperature distribution for modules: (a) InsRBV, (b) InsCB, (c) InsBV, (d) CB – autumn period.



thermal barrier resulting in more heat being retained within the room. Controlled ventilation would have the potential to negate some of this heat gain. However, this study was focussed on the study of the role of insulation and thermal mass with all modules nominally sealed and with no capacity for controlled ventilation.

Figure 16: Hours within and outside the comfort zone – autumn period.

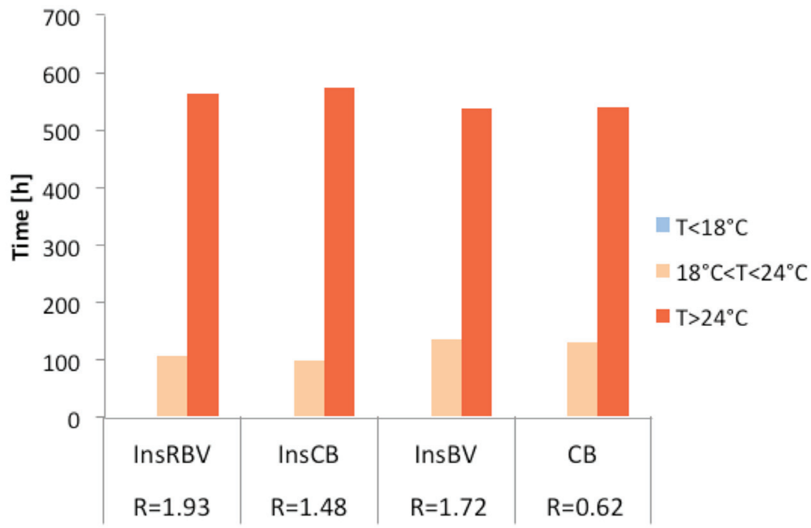
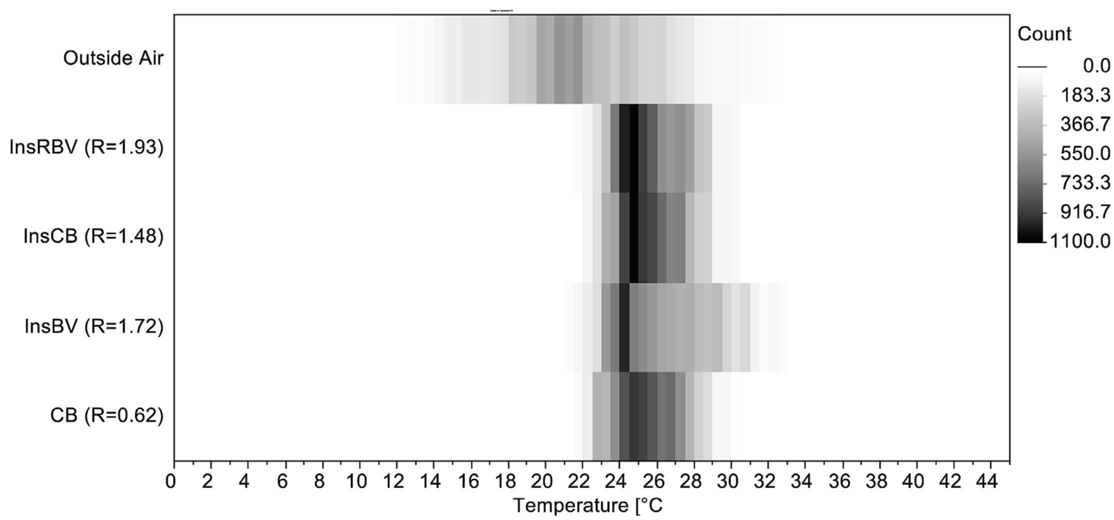


Figure 17: Temperature density plot for every module across autumn conditions.



The fact that all four modules spent little time within the comfort zone is also confirmed in the temperature density plots in Figure 17. Note: imposed ventilation might improve the performance of all modules however this is not considered in this paper.

5.4 Performance During Winter Conditions

Except for the first week of the observation period, the period of the winter collection from 21/05/2009 to 18/06/2009 (4 weeks) consisted of external temperatures below 20°C. The overall trend of temperatures was a gradual reduction over the 4 weeks as the middle of the winter season approached. Towards the end of the collection period, night time minima regularly approached 4°C. On average the external air temperature was 13.6°C. The typical response of the modules is presented in Figure 18, together with the external temperature distribution across the season in Figure 19.

The CB together with InsBV modules experienced the least time in the thermal comfort zone. The uninsulated cavity of the CB module remained cool under the conditions promoting

Figure 18: Typical thermal cycles for all modules under external temperature.

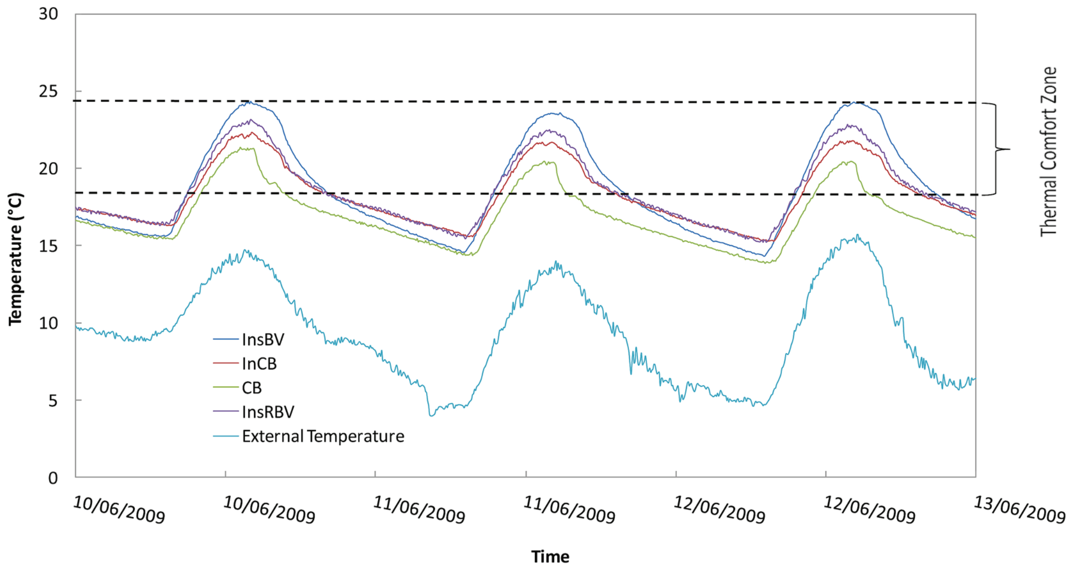
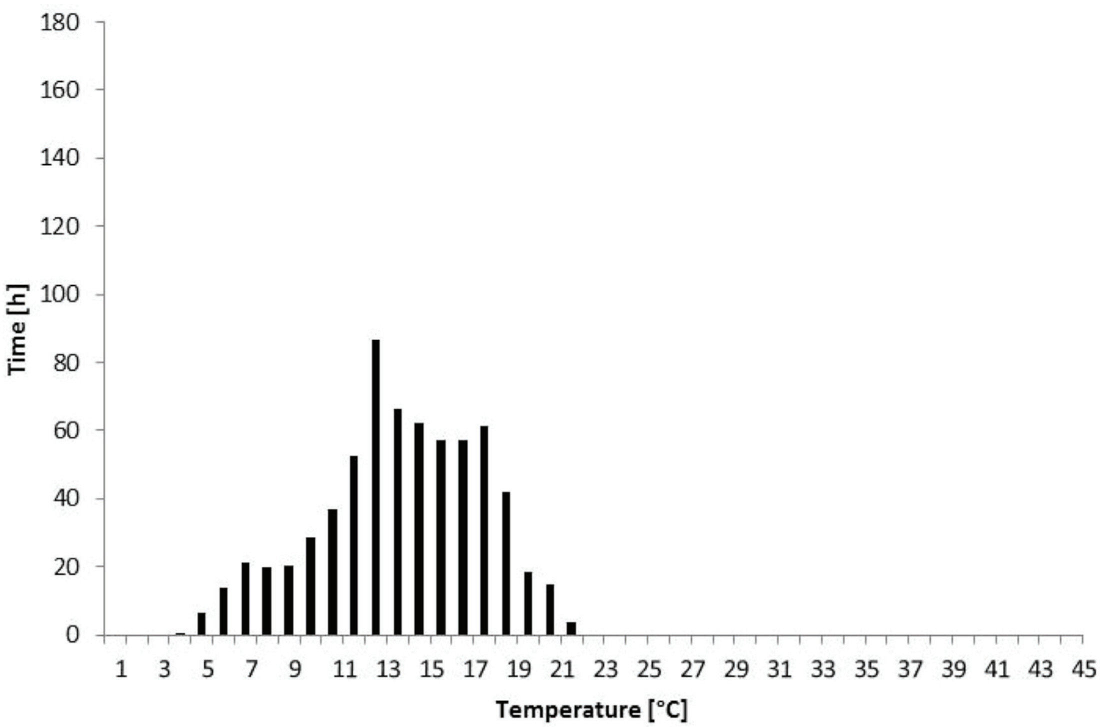


Figure 19: External temperature distribution for the winter period.



a continual outward flow of heat through the inner leaf of the wall (see Figures 20 and 21). The CB module also had the smallest internal diurnal swing of the modules but had both the lowest daytime peak temperature and lowest evening temperature; the InsBV module exhibited the largest diurnal swings.

From the observed temperature variations of the modules, the InsRBV module clearly had the highest time spent within the thermal comfort zone. It also had almost 20% less counts below 18°C, which was more than twice as small as its InsBV counterpart. During this winter collection period all the modules spent a much greater percentage of time within the comfort zone compared to summer and autumn. Comparison between the InsCB and CB modules with temperatures below 18°C indicated that the former spent almost twice the time in the comfort zone, highlighting the advantage of an insulation layer in the winter period. It is also apparent from Figure 22 that all three modules with wall insulation (InsBV, InsCB and InsRVB) spent

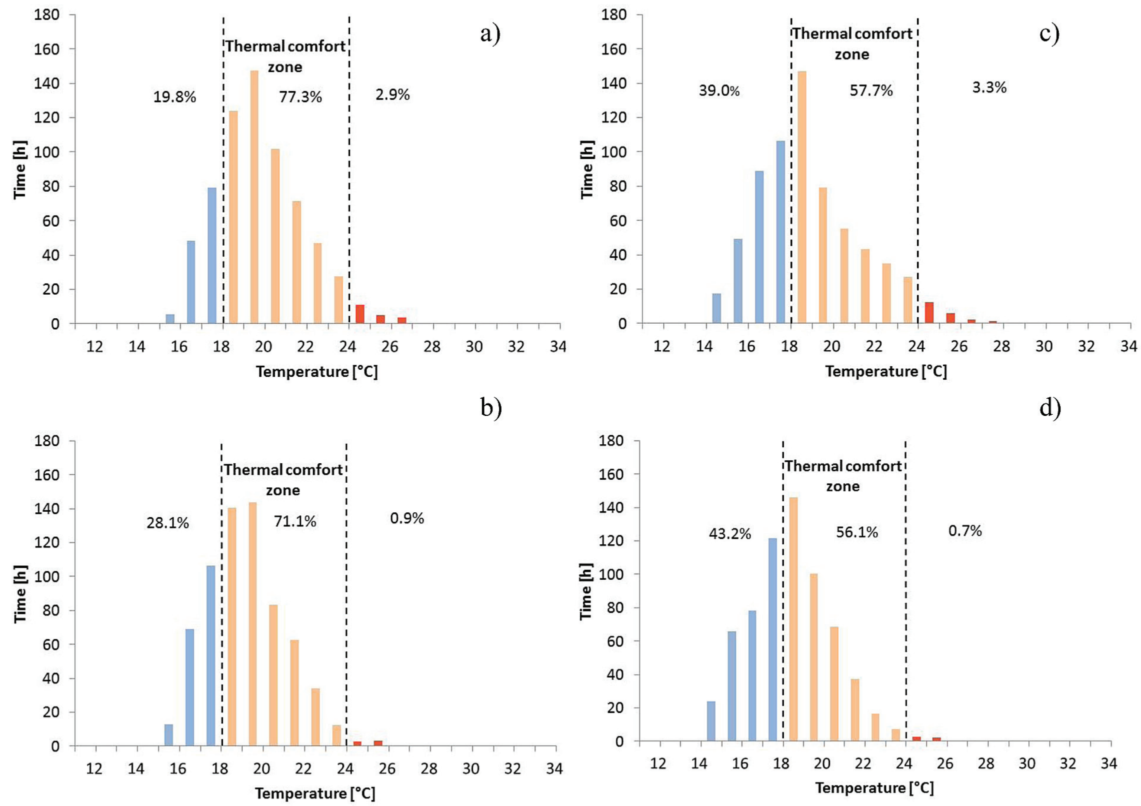


Figure 20: Internal temperature distribution for modules: (a) InsRBV, (b) InsCB, (c) InsBV, (d) CB – winter period.

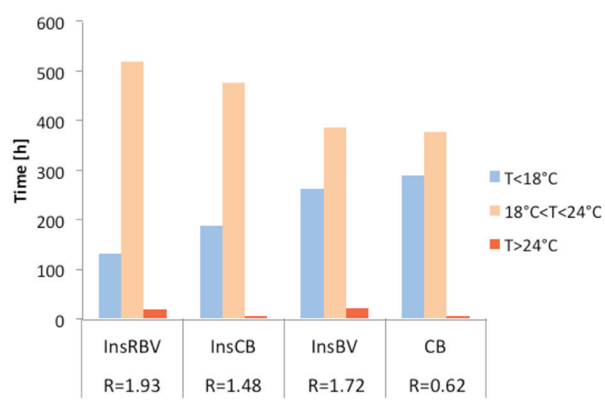


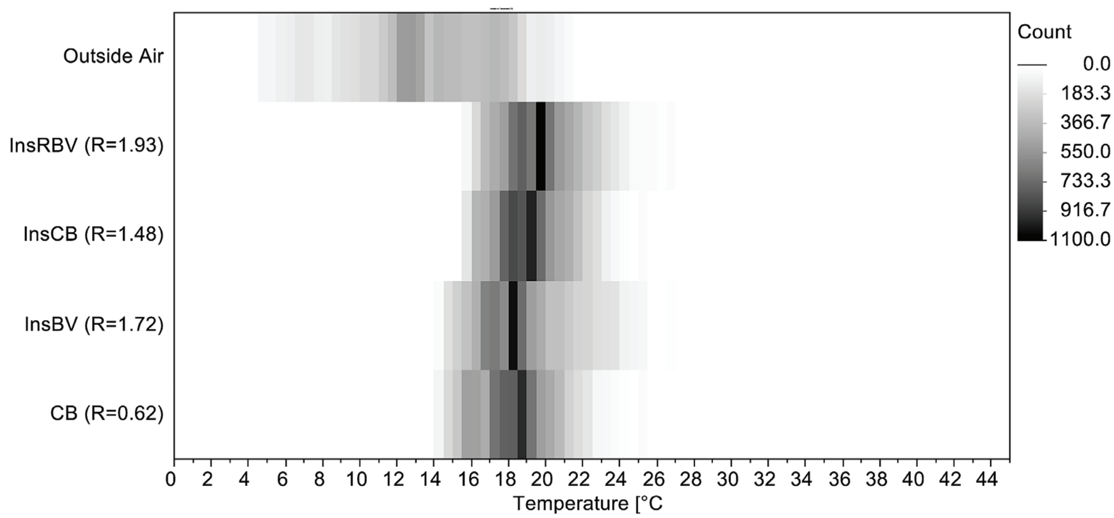
Figure 21: Hours spent in every three periods (including the comfort zone) for all modules.

greater periods in the comfort zone than the uninsulated CB module. This highlights the importance of insulation in the winter period in minimizing the loss of stored and released energy. Of the three insulated systems, the InsCB and InsRBV outperformed the InsBV, illustrating the additional contribution of the thermal mass of the internal skin. As can be seen from Figure 21, the InsRBV module exhibited the best overall performance. Some preliminary findings of this aspect of the study have been previously published (Alterman et al., 2012).

5.5 Overall Annual Performance

The overall comparison for the entire year confirmed that thermal mass is most effective when located on the inner side of the insulation in the building envelopes such as for the InsCB or InsRBV modules as presented in Figure 23 and Figure 24.

Figure 22: Temperature density plot for every module across winter conditions.



An insulation layer on the internal side of the masonry (as for the InsBV module) results in the less effective utilization of thermal mass. Due to the absence of internal thermal mass, the Ins-BV module modules (with walls with a high R value of 1.72), developed higher variations in temperature than other modules, including the CB modules with walls with much lower thermal resistance values (R values of 0.62). This indicates that the Ins-BV module was heated and cooled at the highest rate.

Note: In passive solar design applications, the impact of thermal mass could also be increased in summer by the use of night ventilation, purging the heat built up and creating a more comfortable environment with a lower inertia for the following day; in winter, thermal mass can be used to store energy from the solar radiation heat gains during the day, which can then be slowly released to the interior overnight. However this aspect is not considered here, since the focus if this study is on the contribution of thermal mass and insulation to the thermal performance.

6. CONCLUSIONS

A study of the thermal performance of full scale housing test modules incorporating a range of typical Australian walling types has been described. The interior of each module was allowed

Figure 23: Internal temperature distribution for modules: (a) InsRBV, (b) InsCB, (c) InsBV, (d) CB – annual performance.

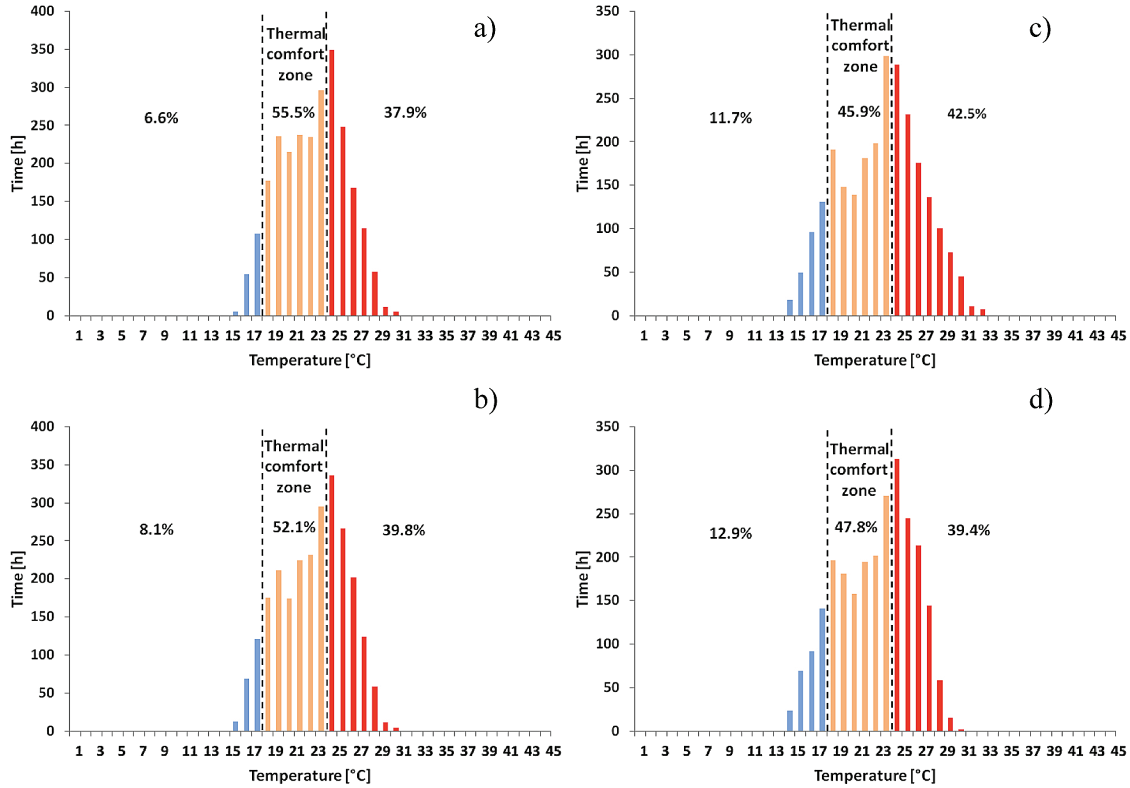
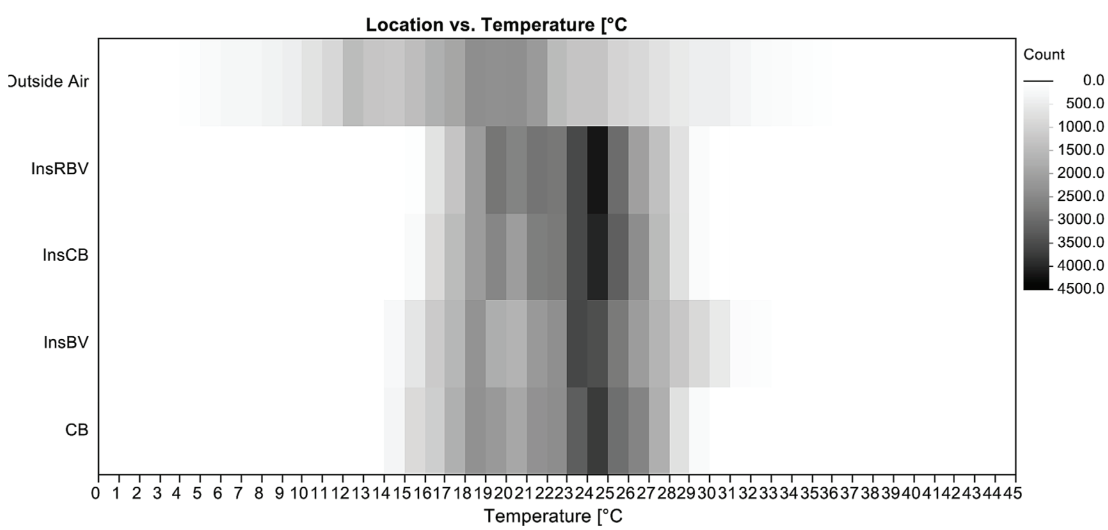


Figure 24: Temperature density plot for every module for entire year.



to “free float” and the period of time spent within a nominal comfort zone of 18 to 240C was used as a measure of comparative performance. The walls had varying combinations of insulation and thermal mass ranging from brick veneer (with negligible internal thermal mass) to cavity brick module (with high inherent thermal mass, but no additional insulation). The following is a summary of the key conclusions:

- The wall R-value was clearly not the only parameter influencing the thermal behaviour and the interior conditions. No direct correlation of wall R-value and thermal performance was obtained due to the additional influence of thermal mass (with that influence varying with the location of the thermal mass within the wall).
- Due to the lack of thermal mass, the interior of the InsBV module reflected the external conditions more rapidly. In contrast, systems with appropriately located internal thermal mass attenuated the diurnal temperature swings and delayed the achievement of minimum and maximum internal temperatures. This was best illustrated by comparison of the performance of the InsBV and InsRBV modules which had different arrangements of essentially the same walling components.
- The interaction of thermal mass and thermal resistance is a function of the relative locations of the wall components and the wall insulation as this controls the flow of heat from the enclosing walls both into and from the interior of the building. Because the mechanism of this interaction is influenced by the seasonal conditions, the optimum combination and location of thermal mass and thermal resistance within a wall will vary. However, the contribution of thermal mass to the overall thermal performance is clear.
- The use of temperature density plots facilitated the comparison of the performance of the various modules, as they clearly show the full range of interaction between the external and the resulting internal air temperatures. This provides more a more comprehensive picture than comparisons of the average temperatures alone without the diurnal temperature variations.

In summary, the results clearly show that internal comfort levels and energy demands are influenced by both the thermal resistance of the walls as well as the extent and location of the thermal mass. Work is continuing on the development of a single measure for wall performance which reflects the contribution of both thermal mass and thermal resistance under the dynamic temperature conditions of a diurnal temperature cycle.

7. ACKNOWLEDGEMENTS

This research project has been supported by the Australian Research Council (LP 120100064) and Think Brick Australia and their support is gratefully acknowledged. Their support and the assistance of the Civil Engineering laboratory staff and the past and present members of the Thermal Research Group are gratefully acknowledged.

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