Yanni Papadopoulos, Veronica Soebarto

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INVESTIGATION OF THERMAL COMFORT AND AIRFLOW IN A NATURALLY VENTILATED LIGHTWEIGHT HOUSE IN A BUSH FIRE PRONE AREA

Yanni Papadopoulos[1], Veronica Soebarto[2]
[1]School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, Australia
[2]School of Architecture & Built Environment, University of Adelaide, Adelaide, Australia

ABSTRACT

Building performance simulation has been utilised for the investigation of thermal comfort and airflow within a naturally ventilated, self-sufficient house in a bushfire prone area. Lightweight construction with Phase Change Materials (PCM) was proposed as an appropriate solution to respond to the brief. The simulations modelled the effects with and without PCM, to demonstrate the reduction in temperature swings throughout design days. Computational Fluid Dynamics (CFD) was used to graphically model the air velocity and temperature gradients and produced results to highlight design parameters that can assist airflow. Limitations of the software are discussed particularly in relation to assisted ventilation from ceiling fans, and miscellaneous heat gains of a fire stove, which could not be simulated effectively.

INTRODUCTION

This paper presents a design solution and the building performance simulation results of a bushfire resistant, residential building design that aims to achieve passive heating and cooling by using a lightweight construction. Bushfires are considered to be the fourth most hazardous natural disaster in Australia (Haynes et al, 2010) and there is an apparent and necessary demand to investigate residential building designs that are capable of withstanding the intensity of a bushfire and protecting the occupants within. Conversely, it is imperative that such designs minimise the adverse impact on the environment.

Using the Solar Decathlon 2014 competition brief as a point of reference (Solar Decathlon, 2014), this research-by-design project explores a sustainable design solution that also mitigates the threat of this constant natural disaster. Solar Decathlon 2014 is a competition open to the public to design, build, and operate a solar-powered residential building. This competition defines the global pursuit in achieving sustainability and minimising the effect on the environment. The design must address the ten main elements addressing architecture, engineering and construction, energy efficiency, electrical energy balance, comfort conditions, house functioning, communication and social awareness, urban design – transportability and affordability, innovation, and sustainability.

The inherent focus of this paper will be on only three of these elements: engineering and construction, comfort conditions and sustainability. While the original Solar Decathlon brief calls for the building to be built in a defined location, it will be omitted from this study.

SITE AND CONTEXT

The site chosen for the project is within a bush fire prone area of South Australia at 35°01’33” SL and 138°40’10” EL. It is located in a warm, temperate climate with hot, dry summers and cold winters with moderate rainfall (Sturman & Tapper, 1996). The average temperature during summer is 29 °C; however, the most recent summer recorded thirteen days of temperatures greater than 40 °C, with five of those days being consecutive (Bureau of Meteorology, 2014). Winter is typically cold with frequent rain periods, averaging 75 mm a day. The average minimum temperature can drop to approximately 7.5 °C throughout winter, with intermittent snowfall in the Adelaide Hills (Bureau of Meteorology, 2014). In order to minimise the need for heating and cooling with these climatic conditions, the use of thermal mass and insulation is usually recommended coupled with appropriate shading for summer and night time ventilation (Shaw et al, 1994).

The design team argued that reducing heating and cooling is not the sole objective of a sustainable design. Lowering the embodied energy of the building materials as well as minimising the energy used for the construction process is also one of the main objectives (Hammond & Jones, 2008). Therefore to respond to this challenge, it was decided that lightweight construction and structure would be used for the building which is likely to minimise the immediate impact on the ground.

An issue arises with lightweight construction, as this form does not utilise heavyweight materials for thermal mass. Insufficient thermal mass reduces the capacity of heat storage within a building (Shaw et al, 1994) and while this can be regarded as a benefit in hot and humid climates, this is generally not a recommended design strategy for warm temperate climates. In this climate, thermal mass is required to absorb, store and emit latent heat energy to minimise the need for heating and cooling.

In view of the need for lightweight construction and structures while at the same time lowering the need for heating and cooling, it was decided that the building must use materials that still provide adequate latent heat exchange when discharging heat energy into or out of a building envelope. Phase Change Materials (PCMs) were considered to provide the building with thermal mass, whilst still a lightweight material (Vineet & Buddhi, 2007). The provision of sufficient latent heat storage capacity is critical in achieving a passive building design.

PCMs have been trialled and tested as integrated building materials. The two main categories of PCMs are organic and inorganic. This study applied organic PCMs integrated into the building's construction, due to the added benefit of lower embodied energy. Advantages of this form of PCM include: recyclable after primary usage, solidify with minimal supercooling, and customisable to serve various temperature ranges. However, disadvantages include: lower thermal conductivity (compared to inorganic PCMs), and low volumetric latent heat storage capacity in comparison to inorganic PCMs (Kuznik et al, 2011). Many studies have aimed to understand how to effectively utilise the latent heat capacity of PCMs during summer, and their results generally determine night purging to 'reset' the PCM and encourage the release of heat energy stored during the previous daytime (Evola et al, 2011).

METHODOLOGY

Reducing the need for heating and cooling means trying to create internal spaces whereby the thermal condition is acceptable for the occupants. Thermal comfort is a psychological equilibrium within a thermal environment that does not cause an occupant to feel cold nor hot. Some of the factors that influence this psychological state are the surrounding air temperature, and the internal surface temperature. (Kuznik et al, 2011). The simulations presented in this paper therefore have modelled these factors in addition to the temperature swing effects of PCM and the velocity and temperature gradients of the building envelope.

The design process was assisted by simulation using the EnergyPlus simulation engine and Computational Fluid Dynamics (CFD) analysis modules within the DesignBuilder software package. The EnergyPlus model was used to simulate the building's thermal performance to determine the success of the building's passive heating and cooling system. Weather data for the simulations were obtained from the local bureau of meteorology (Bureau of Meteorology, 2014).

The CFD simulation created a 3-dimensional visualisation of the internal velocity and thermal gradients, which in turn highlighted airflow in and out of the building envelope. Both these simulation models played an important role in analysing the effectiveness of PCM and natural ventilation on the operative temperature. DesignBuilder's in-built PCM algorithms were utilised during simulations.

The passive heating and cooling strategies employed within this building design were deemed effective if the internal operative temperatures lay within the 80% acceptable limits outlined within ASHRAE 55 (2013). For the mean monthly outdoor air temperatures of this region, the lower and upper 80% acceptability limits of the indoor operative temperature during summer and winter, are 19.4°C, 26.3°C and 16.6°C, 23.6°C respectively. Table 1 summarises the thermal comfort zones in summer and winter.

Table 1: Thermal comfort zones for summer and winter based on mean monthly outdoor air temperatures. (ASHRAE, 2013).

80% Acceptability Limit	***Summer Comfort Zone**	****Winter Comfort Zone**
Upper Operative Temperature (°C)	26.3	23.6
Lower Operative Temperature (°C)	19.4	16.6

**summer mean monthly outdoor air temperature (min 15.0°C, max 17.5°C)*
***winter mean monthly outdoor air temperature (min 6.8°C, max 7.6C)*

BUILDING DESIGN SOLUTION

The slope of the site was approximately 13° and surrounded by dense Eucalypt forest. An elevated structure that minimises site excavation was under those circumstances seen to be the most effective approach, to reduce both construction labour and impact on the natural environment.

A simple building footprint not only maximised internal floor area, but also minimised the external surface area that would have otherwise been exposed during a bushfire. The footprint fit a recycled shipping container as a structural support, which simultaneously provided some form of bushfire protection to the building services stored within, such as a battery farm for solar panel generated electricity, tanks for rainwater storage, and waste treatment. A recycled shipping container has the added benefit of reducing the embodied energy of construction.

Figure 1 displays the building design, highlighting the dynamic shading device on the northern façade, and the shipping container supporting structure on the southern base.

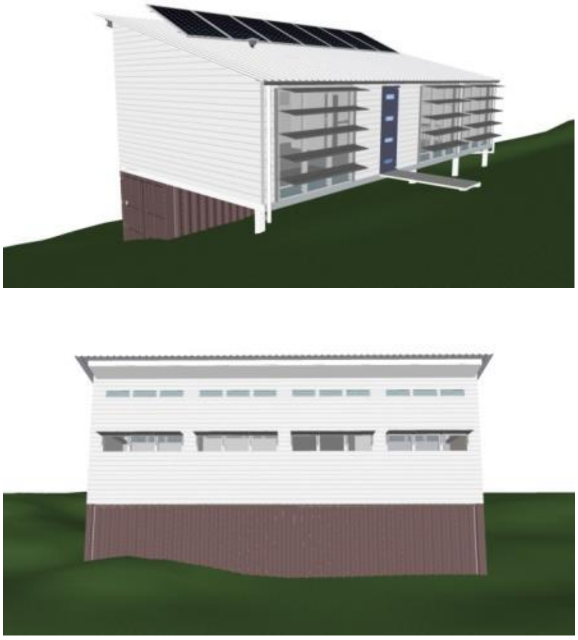


Figure 1: Computer modelled building design; front perspective (top), rear perspective (bottom).

The design attempts to achieve complete fire resistance and a lightweight construction. Previous research has found that a single mono-pitched roof form minimises wind turbulence, which drastically minimises the possibility of ember catchment (Rogleff & Gnankrishnan, 1987). The single mono-pitched roof has also created a mono-pitched ceiling, which in turn assists heat stratification create a north to south airflow through the strategically placed internal and external vents. Figure 2 shows the expected heat stratification and airflow that would occur from this design.

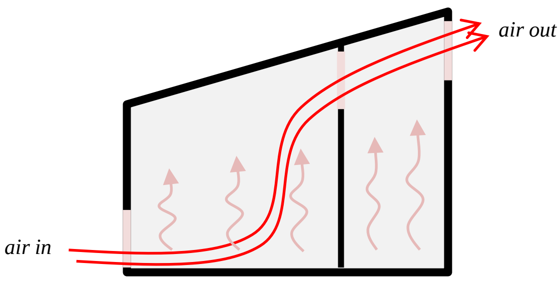


Figure 2: Airflow path from north to south, assisted by heat stratification.

The building's construction composed of materials that had to meet three main selection criteria: fire resistance, thermal performance, and embodied energy. These materials are listed in Table 2.

Table 2: Construction materials of the design solution.

Application	Construction Material	Description
External Cladding	10mm Fire Resistant Plasterboard	Magnesium oxide composite board with fire resistance properties
Internal Cladding	10mm Fire Resistant Plasterboard	
Floor Surface	20mm Fire Resistant Plasterboard	
Ceiling Lining	10mm Fire Resistant Plasterboard	
Roof Cladding	Corrugated Steel Roof Sheeting	Economically viable construction material
Insulation	External Metal Frame Wall Insulation Batts	Combination of glass and rock wool insulation that exhibits great fire resistance and environmental benefits
	Internal Wall (Acoustic) Basic Insulation Batts	
	Mono-Pitched Roof Insulation Batts	
	Underfloor Insulation Batts	
Glazing	Double Glazed Fire Resistant Glazing with 12mm Air Gap	Composite glass which creates a fire resistant barrier against radiant heat and smoke

PCM was modelled within all internal surfaces of the building, as the incorporation of PCM provides thermal inertia for the lightweight construction to achieve a passive design. The floor plan plays a critical role in maximising the PCM exposed to direct solar gain during the winter; for this reason, the internal partition wall was orientated to face the northern glazed façade. Figure 3 displays the internal layout of the building within a sectional model. Without the incorporation of PCM within the construction, this building would not be capable to achieve passive heating and cooling within this climate.

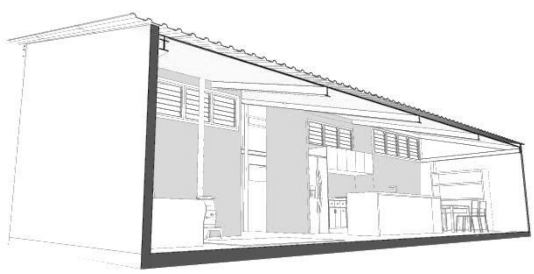


Figure 3: Computer modelled building design, internal floor plan perspective.

Table 3 identifies the properties of the PCM utilised and their specific placement within the building's construction. This was strategic in maximising the efficacy of each PCM to shift the peak heating and cooling loads.

Table 3: Placement and properties of each PCM within the building design.

		Freeze Pt. (°C)	Melt Pt. (°C)
Ext. Walls	M91/Q23	18	23
Int. Partitions	M91/Q25	18	25
Ceiling	M91/Q25	18	25
Floor	M91/Q23	18	23

Overall, the passive design strategies were found to be restricted by the design strategies implemented to achieve bushfire resistance, and vice versa. This is even more the case when the bushfire prone area is deemed Flame Zone (BAL-FZ), the most extreme Bushfire Attack Level (BAL), placing a greater priority on achieving bushfire resistance. For example, the northern glazed façade was required to maximise internal solar gains, whilst simultaneously this reduced the building's integrity to withstand a bushfire, which was similarly the case for the northern vents. The intense heat, flame impingement, and ember attack of a bushfire could penetrate the vents and glazing if not protected appropriately. Therefore, the shading device required to control the solar gains throughout the year served a double purpose, shading during the summer and protecting the glazing and vents during a bushfire.

SIMULATION RESULTS

Simulations were conducted to predict the airflow in the building and the thermal performance of the building design during design summer and winter weeks.

Summer and Winter Performance

Thermal performance was assessed during both the summer and winter; however, due to the harsh, hot, and dry conditions that are unique to Australian bushfire prone areas, summer was a focus within this study. The simulations performed were during the summer and winter design weeks, as specified in Table 4.

Table 4: Summary of winter and summer design weeks (as per EnergyPlus - Mount Lofty weather file).

	Winter Design Week	Summer Design Week
Time period	12 Jun – 18 Jun	11 Jan – 17 Jan
Min. Outdoors DBT	2.4	-
Max. Outdoors DBT	-	29.9

Table 5 outlines the parameters of the building simulations. These parameters include construction material properties and internal heat gains of the building envelope. Some of these parameters were based on assumptions which aimed to simulate optimal conditions, such as, an airtight building envelope and natural ventilation achieving an air exchange of 10 ac/h. Construction material parameters were otherwise based on products found within the current market.

Table 5: Building simulation parameters.

General	
Floor Area (m^2)	75
Mechanical Heating & Cooling	*OFF*
Natural Ventilation Rate (ac/h)	10.0
Airtightness	*infiltration disregarded*
Shading Device Louvre Angle from the horizontal (°) - Summer	*60*
Shading Device Louvre Angle from the horizontal (°) - Winter	*Shading device removed*
Internal Gains and Profiles	
Occupancy Density (people/m^2)	*0.027*
Occupancy Profile	*7:00 – 8:30 (100%) 18:00 – 23:00 (100%)*
Operable Vents Profile	*Summer – ON (100%) Winter – OFF (0%)*
Lighting Heat Gain (W/m^2)	*3.30*
Lighting Profile	*6:00 – 7:00 (100%) 18:00 – 23:00 (100%)*
Winter Fire Stove Miscellaneous Heat Gain (W/m^2)	*60*
Construction - Insulation	
External Walls Insulation Batts R-Value (m^2-K/W)	2.0
Internal Walls Insulation Batts R-Value (m^2-K/W)	1.8
Roof Insulation Batts R-Value (m2-K/W)	3.5
Underfloor Insulation Batts R-Value (m2-K/W)	2.1
Construction – Double Glazing	
Inner and Outer Pane Thermal Conductivity (W/m.K)	0.054
Inner and Outer Pane Thickness (mm)	10
Inner and Outer Pane Transmissivity	0.87
Inner and Outer Pane Outside Reflectivity	0.09
Inner and Outer Pane Inside Reflectivity	0.10
Air Gap Thickness (mm)	12

The building simulation results summarises the influence of each of the simulation parameters previously discussed. Figure 4 compares the outdoor dry-bulb temperature and the indoor operative temperature during the summer design week. The maximum and minimum operative temperatures are 25.9°C and 21.5°C respectively, which remain within the summer thermal comfort boundaries; 26.3°C (upper boundary) and 19.4°C (lower boundary) as previously stated in Table 1. The air temperature was noted to be effectively equal to the internal operative temperature; therefore, the internal surfaces, which contain the PCM, exhibited temperatures that were on average 1°C higher than the air temperature. This was considered the direct result of latent heat storage beneath the internal lining.

Even though the internal operative temperature remains within the 80% acceptability limits, the relative humidity during the summer design week as seen in Figure 5 peaks at 100% on 12 January at approximately 10:00AM, whereas ASHRAE recommends the relative humidity to range only between 30 and 60% for residential buildings. Due to this peak in relative humidity, the maximum operative temperature of 25.9°C feels closer to 29°C, which is beyond the thermal comfort boundaries. The absence of mechanical air-conditioning within this building also limits the possibility of a mechanical dehumidification process, and consequently, the relative humidity cannot be mechanically maintained. Greater airflow through the building envelope via natural ventilation is then necessary to maintain the relative humidity between 30 and 60%.

Figure 6 displays the simulation results of when the PCM was removed from the model's construction and it is evident that the operative temperature began to reflect the temperature fluctuations of the outside dry-bulb temperature. Without PCM, the building envelope experienced an approximate 9°C temperature swing during the summer design week, whereas with PCM this was reduced to approximately 5°C, a difference of approximately 4°C during the summer design week. The presence of PCM has maintained a better quality thermal environment by providing thermal inertia within the lightweight construction and subsequently reducing temperature swing.

Figure 7 presents the winter simulation results which demonstrates solar heat being retained within the building envelope; however, as the temperature fluctuations do not appear to reduce considerably it suggests that insufficient heat gains were received to reach the melting point of the PCM for it to be effective as thermal mass. For this reason a fire stove was added to the building model as a uniform miscellaneous heat gain of 60 W/m^2, which had positive influences over the thermal comfort and temperature fluctuations. The additional internal heat gain increased the maximum and minimum operative temperatures to 29.2°C and 18.5°C respectively, which only exceeded the upper winter thermal comfort boundary as defined in Table 1. In reality, the fire stove could simply be not used if the indoor operative temperature rises above the acceptable thermal comfort limit in winter.

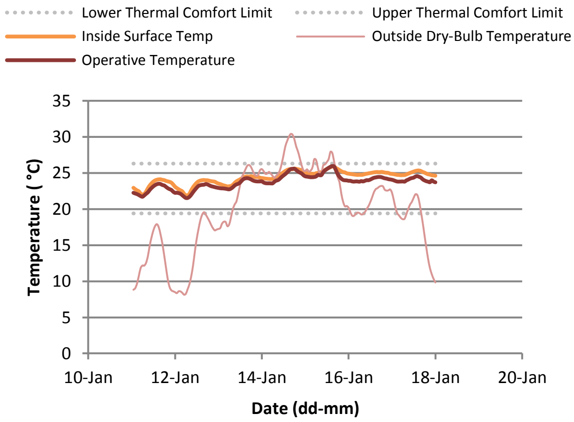


Figure 4: Outside design dry-bulb temperatures compared to indoor operative temperatures during summer design week (results from EnergyPlus).

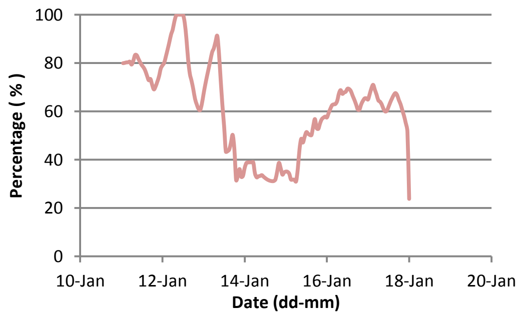


Figure 5: Relative humidity during summer design week (results from EnergyPlus).

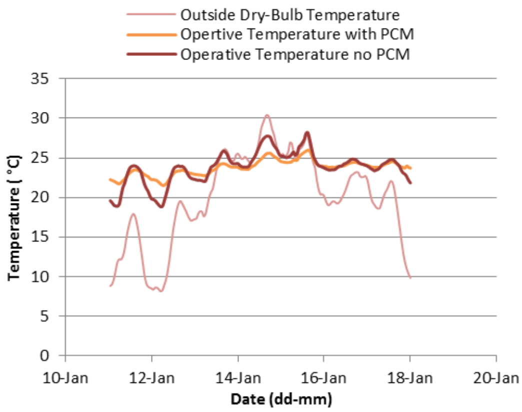


Figure 6: Internal operative temperatures demonstrating effect of removing PCM during summer design week (results from EnergyPlus).

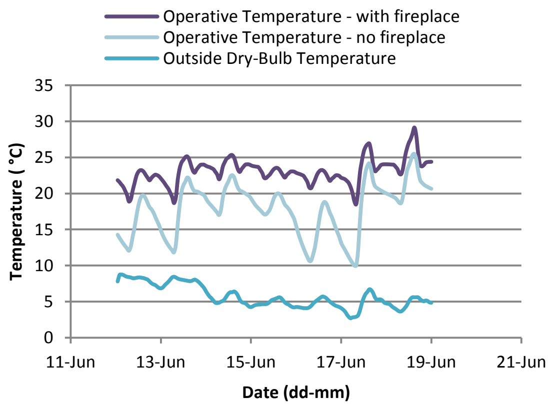


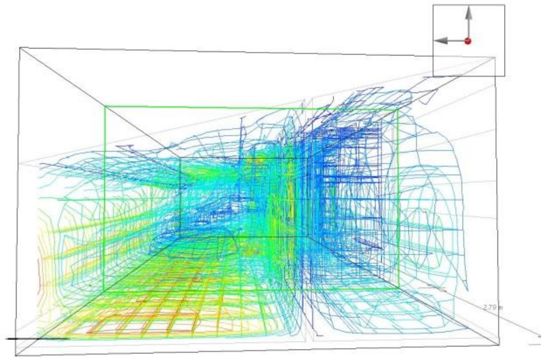
Figure 7: Internal operative temperatures demonstrating effect of fire stove during winter design week (results from EnergyPlus).

A bushfire at close proximity would cause a spike in internal heat gains via convective, conductive, and radiant heat transfer through to the building envelope. The reaction of the PCM during these conditions is unknown; in those circumstances, provided the cladding utilised has adequate fire resistant properties to protect the PCM within the wall cavity, flame impingement should not cause an issue. Rigorous testing is required to evaluate the reaction of PCM when exposed to intense radiant heat as a simulation of the conditions within a bushfire.

CFD Analysis Results

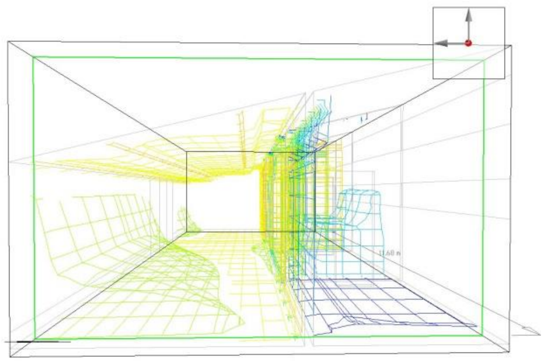
The CFD analysis was performed for the particular day of 12 January at 10:00AM when the relative humidity was at its maximum of 100%. The intention of this analysis was to assess the cause of the peak in relative humidity and understand the subsequent effect on the internal air temperature. Figure 8 presents the velocity distribution throughout the building envelope, which depicts an airflow from the northern vents deemed negligible. Airflow was assessed as stagnant at ceiling level due to the negligible airflow from the northern vents. Effectively no circulation of the internal air was achieved; however, ceiling fans within this model would mitigate this stagnant air and improve the overall indoor air quality.

It appeared that the vented openings did not induce adequate internal airflow but instead created low-pressure vortices at low level. The air that the occupants would utilise would be of poor quality as it appeared to be stagnant, as the natural ventilation throughout the envelope relied heavily on the external wind speed and direction. Airflow over the internal surfaces with PCM was not regarded to be optimised, thus, reducing the PCM's thermal inertia.



Velocity							m/s
	0.00	0.01	0.01	0.02	0.02	0.03	
	0.03	0.04	0.04	0.05	0.05	0.06	

Figure 8: Summer 3-D velocity contours at the cross section on 12 January 10:00AM. (results from CFD analysis)



Temperature							°C
	21.57	21.80	22.04	22.27	22.50	22.74	
	22.97	23.20	23.44	23.67	23.91	24.14	

Figure 9: Summer 3-D temperature contours at the cross section on 12 January 10:00AM. (results from CFD analysis)

Figure 9 presents the temperature distribution throughout the building envelope, highlighting the inflow of cooler air via the lower northern vents. The air temperature surrounding internal surfaces, where PCM was modelled, appeared to be slightly higher than inflowing air. The higher temperature was seen to be the result of the time of day, as the peak internal heat gain has not yet been reached and outside air temperature is still low on a summers morning.

As the summer conditions were the main focus of this study, the operable shading device was modelled at 60 degrees from the horizontal. At this angle, an 80% reduction of solar gain via the northern window was achieved during the summer. Hence, in these conditions the PCM interacts mainly with internal air via convective heat transfer and not direct radiant solar gains. It is critical that sufficient airflow convectively interacts with the PCM during summer conditions to absorb heat during the hot day and purge heat during the cool night. Without the ceiling fans present, the model was not considered to allow sufficient airflow for the PCM to perform at its optimum.

It is difficult to evaluate the interaction of the PCM and dynamic airflow through the building envelope. Conversely, hourly CFD analysis would provide a clearer image to identify stagnant air throughout all periods of the day, and the location and intensity of vortices that form. Theoretically, added air circulation from ceiling fans and added heat gains from fire stove would be sufficient in enhancing the thermal comfort of this building design solution.

Limitations of Simulation Results

The passive thermal performance of the building was simulated using the EnergyPlus and CFD modules in the DesignBuilder software package. It is important to keep in mind the limitations of these software modules and the assumptions that were made throughout the simulation process.

The simulation of PCM within this building envelope has proved to contribute thermal inertia to this lightweight construction which aims to achieve passive thermal comfort. The PCM models utilised were considered to be well tested and formed part of DesignBuilder's Materials library. The installation of this material within reality could potentially produce different results compared to those presented within this paper. To ensure the accuracy of this prediction, this solution should be tested in the future.

As previously discussed, ceiling fans would assist the passive system by circulating stagnant air within the building envelope, in particular at ceiling level. This influence could affect both the summer and winter indoor air quality; regardless, both EnergyPlus and CFD software modules do not have the ability to simulate the influence of rotating ceiling fans.

Simulations that were performed during winter conditions also highlighted limitations of the software package. Simplifications to the simulation model during these conditions included creating a number of schedules for the shading device with a variety of rotating angles of the louvres. This is because both EnergyPlus and CFD are not capable of simulating a continuously dynamic shading device which is operated to adjust to the changing solar angles.

Another limitation experienced was the simulation of a fire stove during winter conditions. The thermal performance of the building required a supplementary heat gain during the coldest days of the winter design week, whereas, this could only be modelled as a miscellaneous heat gain. This assumed a uniform radiant heat would be generated by the fire stove throughout the entire building envelope, although, in reality it would radiate heat from a single point source. The schedule of the fire stove was similarly difficult to define, as it would only be used to the occupants discretion during times of thermal discomfort.

CONCLUSION

This paper has discussed simulations used to verify the building design that tries to achieve both fire resistance and passive heating and cooling in a lightweight construction using PCM. The results indicate relative success in thermal comfort. In summer conditions, the use of PCM successfully reduce the peak operative temperature resulting in a thermal environment considered acceptable according to the adaptive model in ASHRAE 55 (2013). The use of a ceiling fan would although, still be needed to improve air circulation and reduce relative humidity. Similarly, in winter conditions the application of PCM assisted the increase in peak operative temperature to achieve a relatively comfortable indoor environment, which was supplemented by a wood-fuelled fire stove.

This study has highlighted an important issue for residential building design located within a bushfire prone area. These buildings can be subject to extreme conditions of flame impingement, ember attack, and intense radiant heat which with careful planning and design can be mitigated by strategic selection of construction materials, envelope layout, and protection of openings. Simultaneously aiming to achieve passive heating and cooling has meant natural ventilation within this building design has been limited as openings were minimised to increase the building's bushfire resistance. This was apparent as relative humidity was not maintained and air circulation was not satisfactory. Therefore, it is evident that natural ventilation of the building envelope is the critical factor of a building design solution which has priorities in achieving both bushfire resistance and passive heating and cooling in a lightweight construction. Natural ventilation must be maximised to achieve a passive building design and minimised to achieve bushfire resistance, hence achieving both in equilibrium would provide the optimum design solution.

Limitations of the software package utilised to analyse the building design solution have been discussed and it is recommended that further study be undertaken to assess the effects of intense radiant heat on PCMs experienced during a bushfire.

ACKNOWLEDGEMENTS

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