Investigating the use of earth tubes for passive cooling and ventilation through thermal modelling

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Abstract

Household energy use accounts for 25.4% of energy end-use in Australia. A large proportion of this energy use comes from the use of heating and cooling appliances. This research investigated the application of 'earth tubes' as a strategy to minimise cooling and heating energy use in two hypothetical buildings in Adelaide, South Australia. Thermal simulation was used to model a base case of each building before applying the earth tubes. Improvement strategies, such as double-glazing, *Timbercrete SIS* walls, rammed earth walls, and higher insulation in the roof, were first tested and provided minor thermal improvement. The year-round indoor temperature stabilized dramatically with the application of the earth tubes and appropriate natural ventilation operation, with no cooling and minimal heating appliance use, thus, reducing total energy use and the associated greenhouse gas emissions.

Introduction

This paper is primarily based on an assignment brief given as part of an environmental design course in the Bachelor of Architectural Design at the University of Adelaide. The aim was to improve the thermal performance of a small building to better respond to the site context and the occupants' thermal comfort requirements, reduce the life cycle energy and costs, minimise environmental impact, and be self-sufficient in electricity and water as much as possible. The ideal situation was to produce an improved design where no mechanical cooling was needed and minimal heating energy was required to maintain thermal comfort.

The site was in Adelaide, South Australia (34.9º South Latitude, 138.6º East Longitude, 51 m above sea level). Adelaide's climate varies from mild winters to warm dry summers. It has an average mean maximum temperature of 22.4°C and a mean minimum temperature of 12.3°C annually (Australian Government Bureau of Meteorology 2017). Applying external shading, thermal insulation and thermal mass are the ideal strategies to achieve thermal regulation and comfort in this location; however, these do not always occur in existing houses and heavy use of energy-demanding appliances is a common practice (ABS 2009).

A base case building was given with a footprint of 8000 mm x 6000 mm (figure 1) and its orientation was predetermined at 30 degrees north-east. This initial design had a lightweight construction, see table 1.

Based on solar shading analyses, a shading structure was designed and added (figure 2). This was modelled to test and ensure that it would block summer sun and enable winter sun access through the entire glazed facade.

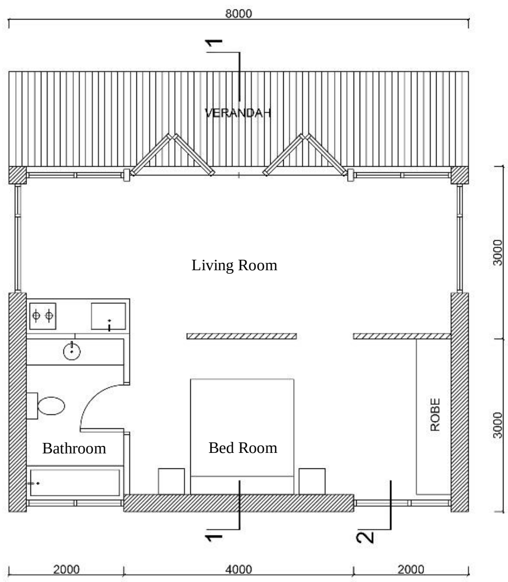


Figure 1: Floor plan – model 1 base building

Figure 2: Front elevation of model 1 with shading structure highlighted red

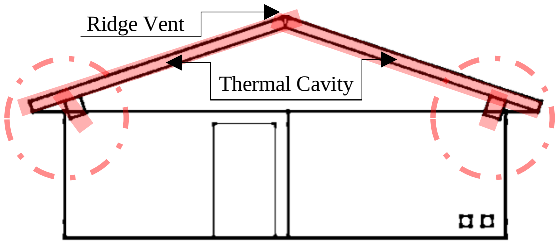


Figure 3: Section cut showing ceiling ducts and gable roof channel/cavity of model 2.

In order to achieve the low energy performance requirements of the brief, passive design techniques from 'earthship' architecture were used as precedents. The primary principles and strategies behind the earthships design, i.e. increasing thermal mass and the use of 'earth tubes' as a thermal regulation strategy (Ip and Miller 2009; Grindley and Hutchinson 1996), informed design outcomes. These strategies will be further explained in the paper.

In order to test the application of these strategies in more common designs in Adelaide, a second building was modelled. It is a typical suburban two- bedroom house, elongated on the north-south direction, as opposed to a north-facing orientation, as in reality many houses in Adelaide do not necessarily have the "ideal" north (sun)-facing orientation. In this building an insulated metal gable roof with an 18.5-degree pitch was modelled. This roof utilizes two layers of steel sheeting with a thermal wrap under the bottom layer to create a 241 mm thermal cavity/channel along the entirety of the roof area (figure 3). It was hypothesized that this thermal cavity paired with the 18.5-degree pitch of the gable roof would cause natural ventilation to occur and this was investigated in conjunction with the earth tubes once they were applied. For the sake of this paper's clarity, the modified base building will be referred to as model 1 and the second building as model 2. The main objective of this paper is to give insight specifically into the application of 'earth tubes' and their effectiveness in Adelaide's climate.

Earthships

The 'earthship' is a passive solar design developed by US architect Michael Reynolds (Freney, Soebarto, Williamson 2013). Earthship buildings are completely off grid and address 6 human needs: heating and cooling, electricity, sewage treatment, building with natural and recycled materials, water management, and food production. It has been said, "The earth ship is the epitome of sustainable design and construction. No part of sustainable living has been ignored in this ingenious building" (Earthship Biotecture, n.d.). An earthship utilises an equator-facing greenhouse to enhance food production and to heat and cool the house**.** The greenhouse enhances performance of earthship built in the original climate of Taos, New Mexico, USA. The back and sidewalls of earthships are typically made from used tires, which are compacted with dirt and clay from the site to achieve high thermal mass.

Earth tubes

Earth tubes are pipes buried underground used to vent cooler air into a house. The low stable temperature below the earth's surface cools the warm or hot outside air as it passes through these pipes. As the openings on the equator-facing facades are heated by the sun they draw warm air out from the building and at the same time pull the cool air from the pipes into the living space within the house (figure 4). This naturally regulates the indoor temperatures throughout summer and winter. While such a technique has been used in vernacular buildings in the Middle East, known as *qanat* (English 1968) and has been implemented in earthship buildings in Taos, New Mexico (Freney, Soebarto and Williamson 2013), their application as a 'passive' cooling (and heating) strategy in contemporary buildings throughout Australia is less established.

Table 1. Thermal properties of construction layers - Base case of model 1

Construction Layers (from outside to inside)	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
Insulated Timber Stud Walls:				
• Steel cladding	3.0	50.00	7800	480
• Insulation	89	0.025	20	1030
• Plasterboard	10	0.210	700	1000
Concrete Floor:				
• Clay	150	1.410	1900	1000
• Reinforced Concrete	100	2.300	2300	1000
Single Glazed Windows: (60% of floor area)				
• Clear Float	6	1.060	-	-
Insulated Metal Cladding Roof:				
• Steel	3	50.00	7800	480
• Cavity	140	-	-	-
• Glass-Fibre Slab	100	0.035	25	1000
• Plasterboard	10	0.210	700	1000

Table 2. Thermal properties of construction layers - Base case of model 2

Construction Layers (from outside to inside)	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
Insulated Timber Stud, Brick Veneer Walls:				
• Brick	101	1.331	2083	921
• Insulation	89	0.025	20	1030
• Plasterboard	10	0.210	700	1000
Rammed Earth Internal Partitions				
• Rammed Earth	250	1.300	1540	1260
Concrete Floor:				
• Clay	150	1.410	1900	1000
• Reinforced Concrete	100	2.300	2300	1000
Single Glazed Windows (Accounting for 19.6% of floor area)				
• Clear Float	6	1.060	-	-
Gable Roof with Thermal Cavity				
• Steel	3	50.00	7800	480
• Cavity	241	-	-	-
• Polyurethane Board	100	0.025	30	1400
• Plasterboard	10	0.210	700	1000

Design Strategy

The thermal properties of the envelope of base models 1 and 2 are presented in Tables 1 and 2. From the base design of model 1, several strategies were applied to maximise the building's thermal performance and give comparative evidence for relativity of certain strategies. *Timbercrete SIS (Super Insulation Series)* walls, a lightweight masonry building product with thermal resistance of R4 (R value = 4 m^2.K/W), replaced the lightweight timber stud walls, while double-glazed windows were applied in place of the original single glazing. The floor construction was changed to slab on ground, and the roof was further insulated with R3 insulation. Trial and error with material properties of the roof and slab continued, as well as altering the internal partition materials and adding further internal glazing to pair the internal partition with the roof; however, significant heating and cooling loads were still required to reach thermal comfortability.

Three 30 m long, 241 mm diameter tubes were additionally implemented and simulated at 2 metres below the ground surface, to act as earth tubes. "Arranging two earth tube pipes of *ø241* mm shows superior heat transfer capacity in both natural ventilation and mechanical ventilation mode, and superior capacity in flow rate for both modes" (Pangolin Associates, 2013). Hence, this informed the tubes utilized for simulation.

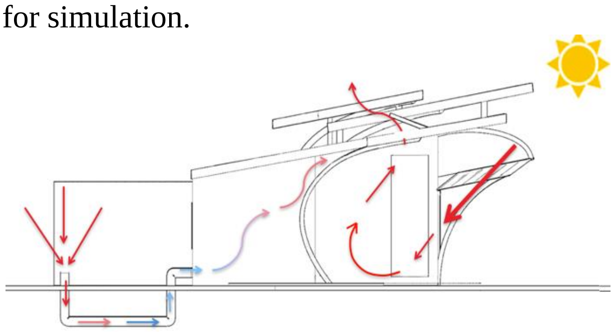


Figure 4: Diagram of earth tube implemented in model 1

Model 2 followed a similar strategy. 250 mm Rammed earth external walls with a U-value rating of 2.32 (U value = 2.3 W/m^2K) were added in place of the original brick veneer as the first alteration from the base case. Internal partitions were then changed to this same material (rammed earth) to increase heat storage. Due to the low percentage glazing area, it was then decided for external walls to be altered once more to a high insulation wall. The super-insulated external wall used held a thermal resistant rating of R4.36 (R-value = 4.36 m^2.K/W). Double glazed windows replaced the original single glazing and six 241 mm diameter tubes were further implemented as the earth tubes.

Methodology

The modelling was entirely conducted through simulation given the scope of the research project. The above design strategies were simulated using Integrated Environmental Solutions Virtual Environment (IESVE) Version VE 2016 (hotfix 1). Standard weather files in EPW format enabled the computational climate to represent Adelaide's weather from the weather station at Kent Town, about 2 km away from the centre of Adelaide. Using the Apache simulation module embedded within the program, the base case of each building was tested. A time step of 10 minutes and an hourly reporting interval was set. Results of each improvement strategy were then noted and compared. Model 1 was analysed as facing 30 degrees north-east. This was a given limitation of the design brief and if the building was to face closer north to north-west it is likely that the result would differ substantially.

In both cases, simulation of the earth tubes proved to be a difficult process. Many minor settings in the program needed to be altered to enable the active simulation of the earth tubes. The tubes were modelled as unoccupied and unconditioned rooms and each face had to be coupled to the ground. Steel pipe with a heat exchange coefficient of U-value 5.8817 W/m^2K was applied as its thermal construction.

The ground temperatures around the earth tubes were estimated through a soil temperature calculator developed by Aegerter and Meier (2017). This calculator based on IEC 60287 standards is a simplified mathematical model which describes the expected temperature curve in the soil. Climate statistics for Kent Town, the nearest weather station to Adelaide, were gathered from Australian Bureau of

Meteorology and input into the model. Figure 5 shows soil temperature dependant on each day after the coldest day in July, in a yearly cycle. These ground temperature profiles were input into the simulation and assigned in the ApacheSim module as the adjacent conditions for the earth tubes (wall/roof/floor).

The airflow through the earth tubes was simulated to depend on the air drafted out of vents placed in the roof above the living room in model 1, and a vent positioned at the ridge of the gable roof channel in model 2 (loosely depicted in figure 3).

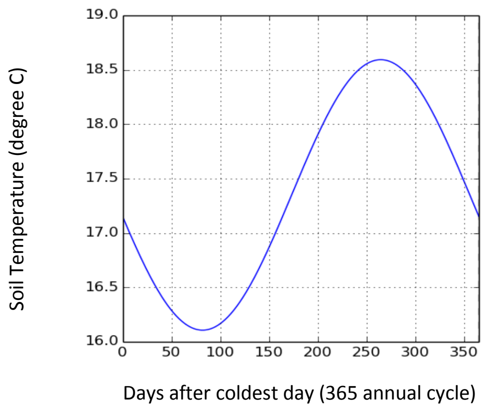


Figure 5: Soil temperature at depth of 2 m

Operational profiles were assigned to each opening type in the Macroflo module within IES. The profiles determined each door/vent to open in accordance with the operation of a real life earth tube system. Adjacent rooms' ventilation profiles were also set in order for each room to receive air from the adjacent earth tubes when the passive system is engaged.

In model 1 the roof vents above the living room were simulated to automatically open when the temperature inside reached 24°C or higher and the outdoor air temperature was warmer (i.e. 25°C or above). The windows above the internal partition were simulated to open in sync with the roof vents; the earth tube inlets were opened in this same configuration. The doors were opened when the outdoor climate was considered comfortable (i.e. between 20-27°C).

Likewise building 2 was scheduled to open the gable ridge vent, the ceiling vents and the earth tube inlets when the outdoor air temperature reached 27°C or higher in order to create the natural convection needed for the active simulation of the earth tubes. External doors and windows were opened when temperatures were considered comfortable (i.e. between 20-27°C). Obviously this operation is required to be adhered to by the operator/user of the building. It is assumed that naturally a person would open doors to allow comfortable temperature inside. The simulation results were used to analyse the changes in indoor operative temperatures, which are found by calculating the average of dry bulb and mean radiant temperature. The hottest period in summer and coldest period in winter, before and after implementing several improvement strategies were analysed.

Results

Each change, as presented in the Design Strategy section above, incrementally improved the buildings performance. As the buildings are naturally conditioned, the adaptive model of ASHRAE 55 (ASHRAE 2013) was used to determine the acceptable indoor operative temperature range for this location. Based on the location's temperature range of the monthly outdoor temperature, the aim was to achieve indoor operative temperatures between 18 and 25°C in winter and between 21 and 28°C in summer.

After the external shading device had been added to model 1, the indoor operative temperatures during the hottest month of the year (February) were analysed. In February, the peak indoor operative temperatures dropped from 46°C (Figure 6A) to 40°C. Initially, the walls were changed from the original lightweight construction to *Timbercrete SIS* blocks. This change decreased the peak indoor operative temperature in February to 38°C while the minimum operative temperature indoors stayed at 19°C. In winter, represented by the coldest month, July, the peak indoor operative temperature dropped from 33°C to 24°C. While this is within the limits for a comfortable condition, some people may perceive this as a 'slightly cool' condition. Double-glazing the windows further insulated the house; however, the results were minimal. This process brought the summer indoor operative temperature range to sit between a minimum of 21°C and a maximum of 38°C while the indoor operative temperatures in winter ranged from 12°C and 25°C. Combining all strategies resulted in a maximum indoor operative temperature of 36°C in February and 25°C in July while the lowest of these temperatures dropped to a minimum of 20°C in February and 14°C in July. These results were still far from ideal and it was not until the earth tubes and appropriate natural ventilation operation were applied that thermal comfort was achieved.

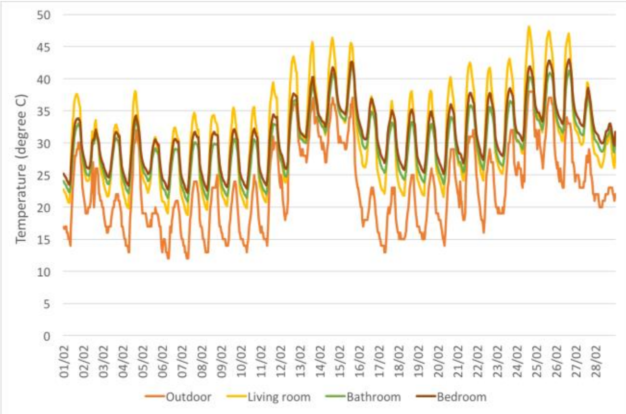
In the final model, all the above strategies and the earth tubes were implemented, and by controlling the inlets and outlets of the tubes and window openings, the indoor temperatures throughout summer (February) were maintained between 21 and 29°C while in winter (July) they remained between 15.5 and 26°C. Note that these temperatures are based on all three rooms collectively; however, during summer the indoor operative temperatures in each individual room varied. As the solar heat radiates through the front facade into the living room there is a greater heat gain. This is used to create natural convection as the heat rises out of the room through the vents in the ceiling above. Therefore, the living room is essentially the 'engine room' of the natural convection. If we look at the results for each room individually (figure 6C), we find the bedroom and bathroom do not spike above 25.5°C. Likewise, the bedroom and bathroom stay about 3-4 degrees warmer on the coldest nights through winter with a minimum operative temperature of 17.6°C (figure 6D).

The initial base case temperatures of model 2, before any changes were made were almost satisfactory. The gable roof construction paired with the north facing orientation and a well-balanced percentage ratio of glazing is assumed to have influenced this. In February, the peak indoor operative temperature was 32°C and the minimum through winter was 18°C (figure 6E-F). The walls were changed from the original brick veneer construction to 250 mm rammed earth. This change increased the peak indoor operative temperature in February to 33°C while the minimum operative temperature indoors increased to 22°C.

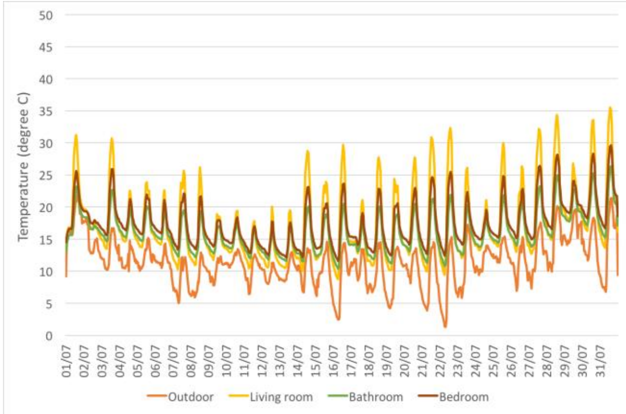
In winter, represented by the month of July, the indoor operative temperature ranged from 15°C to 23°C. After the walls were changed to a high insulation brick and internal partitions were changed to rammed earth the indoor temperatures within February and July regulated. In February temperatures ranged within 24°C and 30°C and July temperatures ranged from 19°C and 24°C. This result was very pleasing as it was acquired without any heating or cooling loads. Double-glazing the windows further insulated the house; however, the results were minimal. This process brought the summer indoor operative temperature range to sit between a minimum of 24°C and a maximum of 30°C while the indoor winter temperatures ranged from 21 and 25.7°C. As the results were already highly promising, the earth tubes and appropriate natural ventilation operation applied, further solidified that thermal comfort was achieved passively.

In the final model, all of the above strategies and the earth tubes were implemented. The indoor temperatures throughout summer were maintained between 21 and 27.5°C while in winter, with the earth tubes closed the temperatures remained between 21 and 25.7°C (see figure 6G-H).

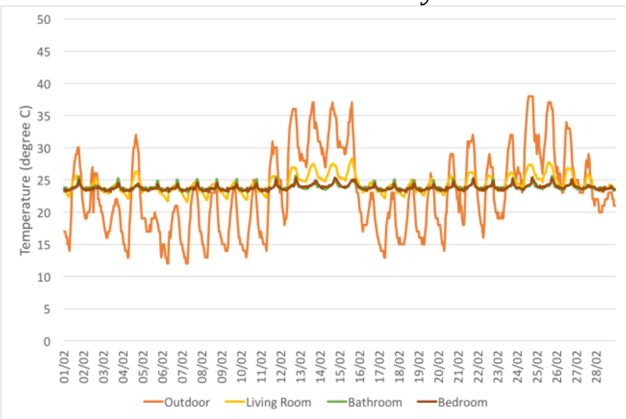
The results of model 2 were achieved entirely passively and minimum energy was required to maintain comfortable winter temperatures in model 1. In model 1 the heating appliance was set to turn on when temperatures indoor dropped below 20°C. This occurred on the colder nights and resulted in only 3.7 kWh/m² of heating energy per annum. In contrast, in the base case of model 1, without earth tubes, 83.6 kWh/m² per year would be required to keep the indoor operative temperatures comfortable. Therefore, the implementation of bioclimatic strategies and primarily the application of earth tubes in this 48 m2 small dwelling equals to savings of approximately $1,265 on heating energy per year (based on a utility rate of $0.32 /kWh), see Figure 7. Based on the last census data, the average floor area of new houses in Australia is 205.7 m2 (ABS 2005). Thus, if similar strategies were implemented in an average or standard Australian home, this saving would relay to be approximately $5,420 per annum.



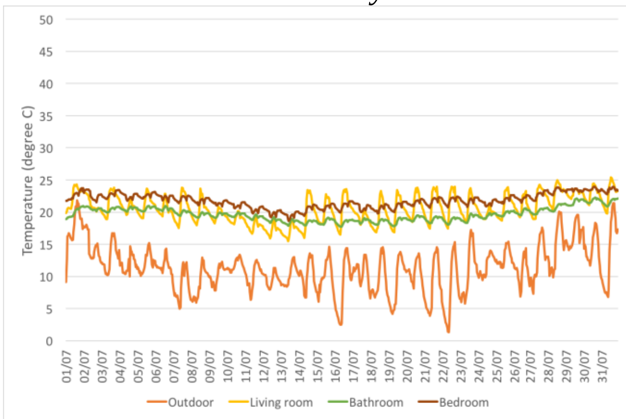
A: *Model 1 base results February*



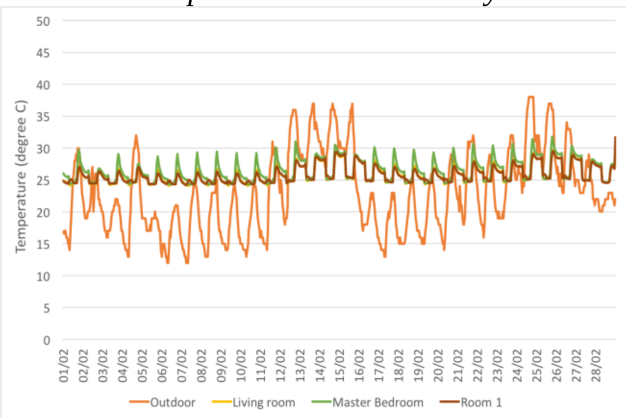
B: *Model 1 base results July*



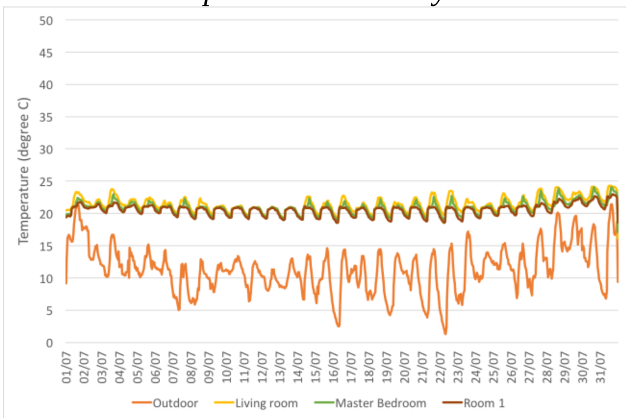
C: *Model 1 improved results February*



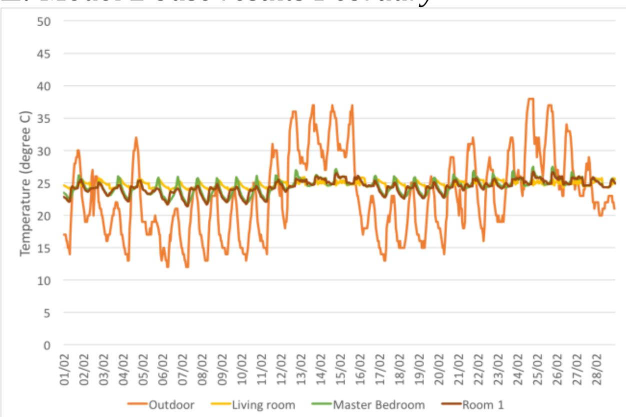
D: *Model 1 improved results July*



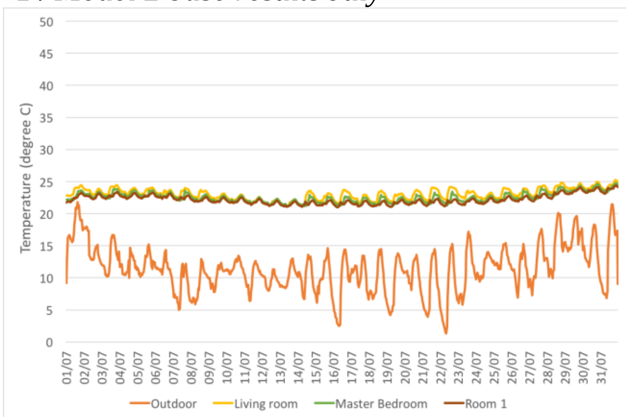
E: *Model 2 base results February*



F: *Model 2 base results July*



G: *Model 2 improved results February*



H: *Model 2 improved results July*

Figure 6: A-H: Model 1 and 2 Results, through Passive Techniques Only

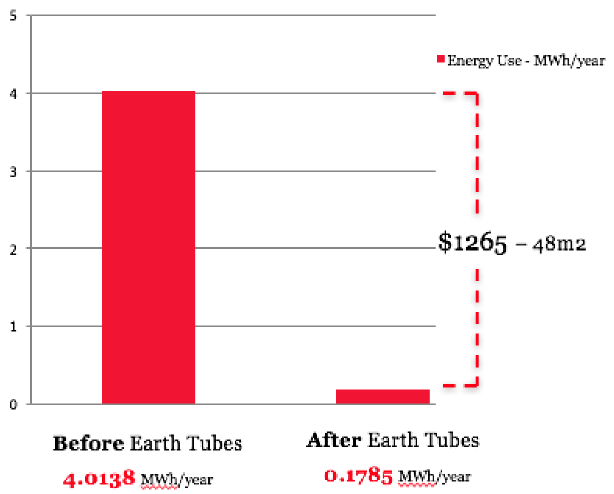


Figure 7: Model 1 Earth Tube Savings Comparison

Discussion

The earthships in New Mexico use an equator facing greenhouse to capture heat in winter and to draft air for passive cooling in summer; however, Adelaide does not have the same climate. In particular, Taos has clearer sky, resulting in high diurnal temperatures, both in summer and winter, and higher solar radiation particularly in winter. In Taos the average direct normal irradiance is 6.22 kWh/m² per day in winter and 9.1 kWh/m² per day in summer whereas in Adelaide it is 3.3 kWh/m² per day in winter and 7.3 kWh/m² per day in summer. (US National Weather Service 2016 and Australian Government Bureau of Meteorology 2016). Thus, the solar radiation impacting the glass façade of model 1 would cause less heat gains in the living room than originally expected, and therefore less convection.

However, compared to the indoor temperatures particularly in winter in an earthship in Taos (Freney, Soebarto and Williamson 2013), the indoor temperatures in model 1 were still lower, proving the glass façade as a viable option to use for natural ventilation when passively drafting air within a small house. In model 2, the gable roof construction was compared as the solar heat radiation in summer is applied almost directly to the normal vector of the roof surface, therefore maximising solar heat gains. This was assumed ideal for Adelaide's climate as the sun is at much higher angle in summer than it is in New Mexico.

Comprehensive analysis on the volume flow out (l/s) of the living room in model 1, and the vent positioned on the apex of the roof channel in model 2 will need to be considered in order to provide conclusive evidence on the preferred strategy of convection for Adelaide's climate, however the pros and cons of each may still be considered, as both are viable strategy's. The intrusiveness of a greenhouse, or a room with a high percentage of glazing on a buildings envelope is much greater than the impact a roof construction alteration would have. The roof channel construction will cool down the temperature of the attic creating a more comfortable space. The gable roof channel construction may be applied as an add-on to any existing home with a gable roof and if modular products were prototyped to achieve this, it would be a highly viable strategy for home owners to reduce their ecological footprint and to save money. Utilizing a glass façade, as in model 1, will cause indoor temperatures in winter to spike higher and lower than a house with minimal glazing (model 2). This comparison can be seen in figure 6D and figure 6H. Another comparison with these results and the results of the gable roof construction techniques is that all rooms are equally ventilated in model 2 as there is no reliance on a 'highly glazed room to create convection. Thus the gable roof technique is less intrusive on the building envelope and there is no room that must negate thermal comfortability as the 'convection energy' is utilised in the roof channel.

Another variable that could affect the performance of the passive ventilation system on model 2 is the thickness of the channel within the gable roof construction. More testing involving trial and error will need to be done to find the superior heat transfer capacity thickness.

It is worth noting however, this analysis is limited as outside wind speed, and rain are not assumed or considered in the simulation and it would be likely for the user to keep windows and/or doors closed if it were a windy/rainy day.

Conclusion

The study has demonstrated that earth tubes offer a great potential to be used as passive cooling and heating strategy for typical suburban residential buildings in South Australia. It is noted that a building firstly designed on “bioclimatic design” principles will easily obtain effective convection of the earth tubes. Further testing (both simulation and real world) is suggested to support the initial conclusions presented in this paper. Globally we are currently using the equivalent of 1.6 planets each year in environmental resources (Global Footprint Network 2016). Heating and cooling energy demands accounts for 11.25% of our global carbon emissions, which are directly responsible for 60% of the worldwide ecological footprint (US Environmental Protection Agency n.d.). Thus, we could reduce our worldwide ecological footprint by 6.75% using passive heating and cooling in place of energy demanding appliances. This study suggests that earth tubes have the potential to be implemented in all suburban and rural houses to reduce our global footprint. On a larger scale, this can be done through developing modular products which can be added to any building to essentially create a convection room. There is high potential for this to work using the gable roof cavity/channel construction in Adelaide’s climate, however, further studies are required to be certain of the applicability of earth tubes in such housing.

By August 2017 comprehensive tests and analysis will be conducted on the passive strategy of using a channel within a gable roof to passively draft air through earth tubes. It is common knowledge that the attics in homes in Australia attract heat. It does not make sense that our air conditioning ducts are placed in this space, as found in almost all houses, when the temperatures just under the earth’s surface are regulated enough to cool down the hot outside air to a similar magnitude as common air conditioning appliances achieve. There are many ways to passively draft this air through a building and this paper has offered evidence of the viability of application of this type of strategy in Australian homes through two simple techniques. Further research is needed in this field to develop sound understanding on how earth tubes can be applied into Australian homes without being intrusive on the building envelope and/or highly priced.

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