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Investigating the impact of earth tubes in an Earthship

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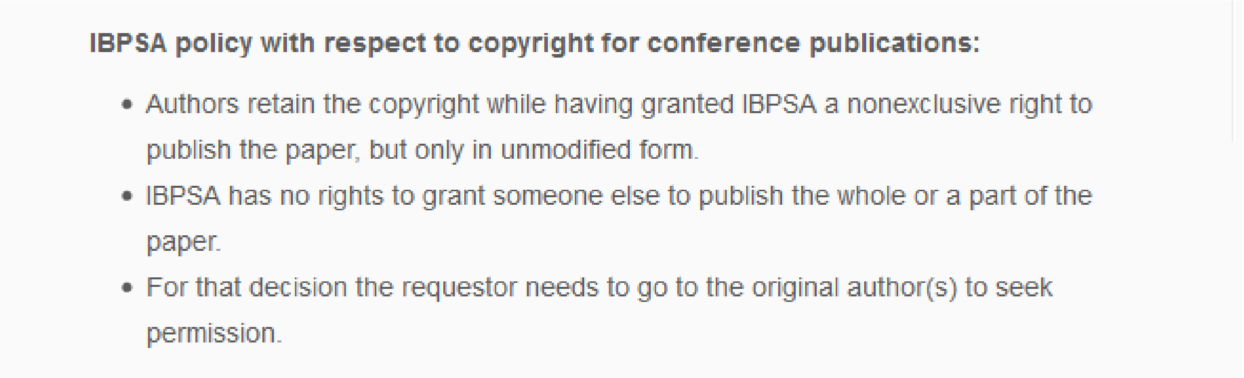

The floor is made of earth (50mm) on a gravel base (75mm). The living space has a vaulted ceiling, constructed of ferrocement (75mm), covered with earth infill (400mm average), expanded polystyrene (150 mm), rubber waterproofing membrane (1 mm), and gravel (100mm). The greenhouse roof is insulated with expanded polystyrene (150mm), clad with corrugated steel on timber frames. All glazed windows and doors use double glazing in hardwood timber frames (5mm clear/10mm argon/5mm clear, U=1.68 W/m^{2}K).

As mentioned, there are two 250 mm diameter PVC tubes, buried underground, to bring fresh air from the outside to the living space. The inlets of these tubes were about 10 meters north of the house, and around 3 meters lower than the ground floor level (Figure 2). The tubes slope upward towards the outlets which are located on the floor of the living space, 600mm from the back (south) wall. The two tubes are spaced at 300mm centre to centre.

The stack effect has been used as an integral strategy to forcing air through the earth tubes. Operable windows (0.81m^2) have been placed above the doors (4.05m^2) connecting the living space and the greenhouse and operable skylights (2m^2) in the greenhouse can also be opened (Figure 2) to provide air flow.

The building was intended to be occupied by one or two people and during the monitoring period the building was mostly vacant. Indoor air and globe temperatures as well as relative humidity of the living space and greenhouse were monitored hourly using data loggers (Onset U30 (Onset 2016)) mounted to the walls at a height of 1200 mm above floor level (Figures 2 and 3).

Modelling the building and earth tubes

Each space in the building was modelled as separate rooms connected by doors, as indicated in Figure 3. As the building was mostly unoccupied during the study period, no internal loads (i.e. occupants, lights and equipment) were entered into the model.

Each of the earth tubes was modelled as a vacant ‘room’. As the earth tubes were exposed to different ground conditions (i.e. outside, under the greenhouse and under the living space), each was modelled as three connecting cylinders with 250mm diameter, with the last part being modelled as a vertical cylinder connected to the floor of the living space. The cooling system was modelled as ‘none’ because there was no space cooling in the actual building. While a space combustion heater exists in the actual building, as it was not used during the study period, the heating system was also modelled as ‘none’.

Building construction

The earth-filled tyre wall construction was modelled as two layers of 10mm thick rubber positioned 650mm apart, with compacted soil/clay in between these two layers and 25mm screed (render) on the internal surface. As the wall is bermed, 1000mm thick compacted clay was added to the wall as an external layer. The entire wall construction was then set to have a ground contact. The other external and internal walls, floor and roof were modelled as per the construction layers in Table 1. The floor is coupled to the ground by setting the ground contact U-value adjustment.

Earth tubes

The ‘wall’, ‘roof’ and ‘floor’ of the earth tube ‘room’ was modelled as 4mm thick PVC with 1000mm thick of soil/clay as an external layer. The entire earth tube wall/roof/floor construction was also set to have a ground contact. The thermal properties of the building construction as modelled are presented in Table 1 while a graphical representation of the model is shown in Figure 4.

To correctly estimate the earth-air heat transfer inside the earth tubes the convection heat transfer co-efficient needs to be determined. The ApacheSim software has a number of options for modelling interior convection heat transfer that apply to building surfaces but gives no specific option applicable to the earth tubes. The following procedure was therefore adopted.

Assuming that the internal surface of PVC pipes used in an earth tube installation is smooth, the Nu correlations given by De Paepe and Janssens (2003) can be used to estimate the convective heat transfer co-efficient h_c defined as,

$$h_c = \frac{N_u k}{D} \qquad (1)$$

Nu is the Nusselt number, k is the thermal conductivity *(W/m^{2}K)*, D is the diameter of the tube *(m)*

The Nusselt number for flow in a tube is given by (2) as,

$$Nu = 3.66 \text{ if } Re < 2300 \qquad (2)$$

$$N_u = \frac{f/8(Re-1000)Pr}{1+12.7\sqrt{(\xi/8)}(Pr^{2/3}-1)} \qquad (3)$$

Where Re is the Reynolds number, Pr is Prandtl number, and f is the friction factor for smooth pipes.

$$\text{With } f = (1.82 logRe - 1.64)^{-2} \qquad (4)$$

If $2300 \leq Re < 5 \times 10^6$ for a fully developed laminar flow and $0.5 < Pr < 10^6$ for turbulent flow with smooth surfaces. The Reynolds number is related to the average air speed and the tube diameter as,

$$Re = \frac{\rho v_{air} D}{\mu} \qquad (5)$$

Where v_{air} is the velocity of air in the tube *(m/s)*, D is the diameter of the tube *(m)* and μ is the dynamic viscosity of the air *(kg/ms)*.

The Prandtl number is given by:

$$Pr = \frac{\mu C_p}{k} \qquad (6)$$

Cp is the specific heat of air *(J/kgK)* and k the thermal conductivity *(W/mK)*.

From the measured speed of air in the earth tubes it was determined that h_c varied in the range 0.5 W/mK to approximately 4.5 W/mK, with an average value of 1.5 W/mK. As ApacheSim allows a user-specified constant convection co-efficient this value was adopted for all simulations.

Modelling the openings

As this building relies on openings to provide natural ventilation, it is critical to model them and their operations as accurately as possible. There are a number of opening types in this building modelled in MacroFlo:

1. Between the living room and green house: there are fixed glass windows as well as top hung operable windows above the doors with maximum angle of opening of 60 degrees and 'sheltered wall' as the exposure type.
2. Roof windows ('skylights') of the greenhouse: these are openable skylights with maximum angle of opening of also 60 degrees and 'exposed long wall' as the exposure type.
3. Earth tube inlets: as there was no cover on the earth tube inlets, the inlets were modelled as having 100% openable area and opened all the time.
4. Earth tube outlets: these outlets have covers and a grille but when opened the opening type was modelled as 'grille' with a coefficient of discharge of 0.25.

Modelling the ground/soil temperature

A critical element in modelling the earth tubes and the Earthship in general is the estimation of ground/soil temperatures as inputs to the model. A series of in-ground temperature sensors were installed during the construction of the building. These sensors (thermistors) were installed at varying depths under the living room, greenhouse and outside to the north of the building. Data from these sensors provided monthly temperature records from October 2015 through October 2016. These data were used to validate the ground temperature models discussed below.

Table 1: Thermal properties of construction layers in the Earthship building

Construction layers (from outside to inside)	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
Earth-filled tyre wall:				
Compacted soil/clay	1000	1.41	1900	1000
Hard rubber	10	0.15	1200	1000
Clay	650	0.7	1280	950
Hard rubber	10	0.15	1200	1000
Screed/render	25	0.41	1200	840
Exterior wall/roof vault:				
Lime render	50	0.41	1200	840
Hempcrete	100	0.07	330	1500
Ferrocement	75	0.22	1500	800
Lime render	10	0.41	1200	840
Earth tube pipe "wall/floor/roof":				
Clay	1000	0.70	1280	950
PVC	4	0.16	1004	0.025
Earth tube box (outlet):				
Clay	1000	0.70	1280	950
Concrete	100	1.13	2000	1000
Internal/external bottle brick walls:				
Screed/Render	10	0.41	1200	840
Cement mortar	100 (internal) 200 (external)	0.72	1860	800
Screed/Render	10	0.41	1200	840
Earth floor:				
Gravel	75	0.35	2080	840
Earth floor	50	1.25	1540	1260
Gravel covered vaulted roof:				
Gravel	100	0.36	1840	840
Waterproofing membrane	1	1.00	1100	1000
Expanded polystyrene	150	0.035	25	1400
Clay	400	0.70	1280	950
Cast concrete	75	1.40	2100	840
Corrugated metal roof:				
Steel	0.6	50.00	7800	480
Cavity	35			
Expanded polystyrene	150	0.035	25	1400

Results: Initial model

Figures 7 to 10 show the comparisons between the hourly measured and simulated indoor temperatures in the living room, green house, inside one of the earth tubes' inlet, and inside the earth tube outlet. These were the conditions when the earth tube outlets were mostly closed. The results show that the simulation model well represents the actual building and its operation during the study period. The CV(RMSE) between the predicted and measured indoor temperatures in the living space, greenhouse, earth tube inlet and earth tube outlet is 3.86%, 6.16%, 3.1% and 3.3%, respectively.

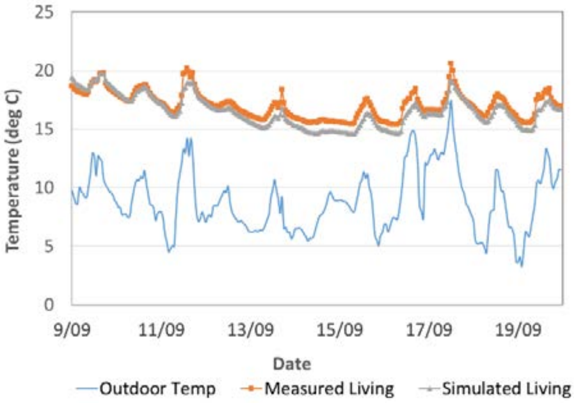

Figure 7: Measured and simulated temperatures in the living space during 9-19 September

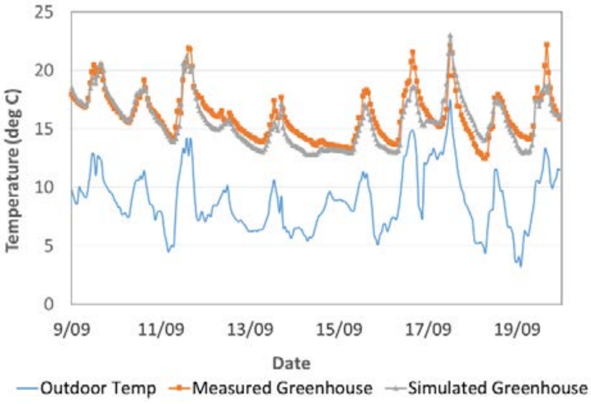

Figure 8: Measured and simulated temperatures in the greenhouse during 9-19 September

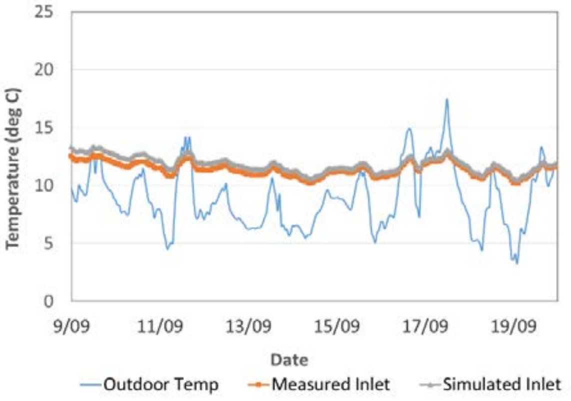

Figure 9: Measured and simulated temperatures in the earth tube inlet during 9-19 September

Note that there are more obvious discrepancies between the simulated and measured temperatures inside the earth tube's outlet box. It is likely that in reality the doors between the living space and the greenhouse were occasionally opened which altered the strength of the stack effect. As a result, more cool air leaking through the earth tubes' outlet doors was being drawn into the living space. In the simulation model, each of the openings (doors and windows) had a set schedule (i.e. either always 'on' or open, or always 'off' or closed), and the earth tube outlet doors had a constant value of openable area. These settings result in a less fluctuating air temperature inside the earth tube outlet, as shown in Figure 10.

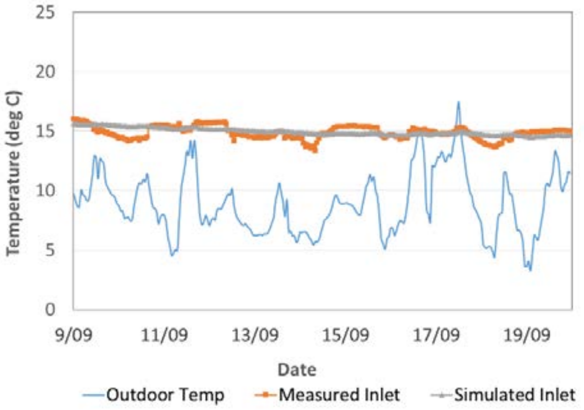

Figure 10: Measured and simulated temperatures in the earth tube outlet during 9-19 September

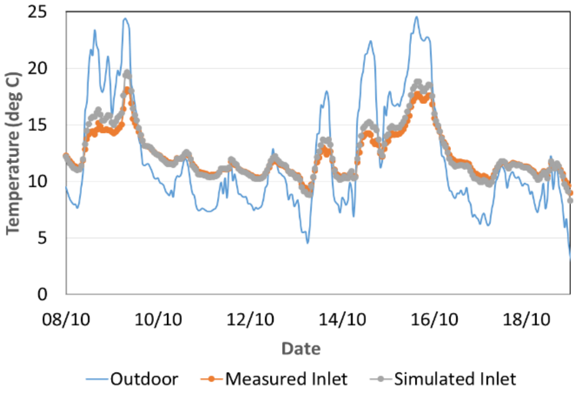

Figure 11: Measured and simulated temperatures in the earth tube inlet during 8-18 October

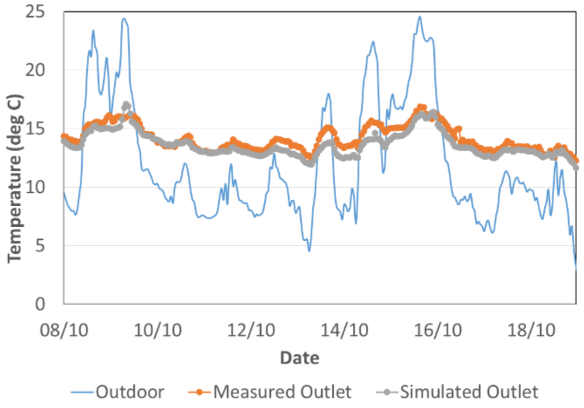

Figure 12: Measured and simulated temperatures in the earth tube outlet during 8-18 October

In October, during the majority of the time, the earth tube outlets were left opened. These were modelled in the Macroflo module as having 40% of openable area. Figures 11 and 12 show the comparison between the measured and simulated indoor temperature inside the earth tube inlets and outlets. Overall, the CV(RMSE) between the predicted and measured indoor temperatures in the living space, greenhouse, earth tube inlet and earth tube outlet is 8.61%, 9.65%, 2.94% and 3.96%, respectively.

Based on the above comparisons and as the CV(RMSE) between the predicted and measured temperatures of various spaces were within the acceptable range, the model is considered a good representation of the actual building. This calibrated model was then used for further investigation; however, it is worth noting a number of issues learned during the calibration processes.

Lessons learned from model calibration

Slope of pipes

Initially the earth tubes were assumed to be level instead of sloping down towards the north of the building. While this did not have much impact in terms of the indoor temperatures (in the living space and greenhouse) when the earth tube outlets were closed, it was found that the simulated airflow inside the earth tubes was much lower than the measured airflow. Even with the earth tube outlets being opened, the airflow inside the earth tube was still low.

The model was then fixed by changing the earth tubes to be sloping downward from the house, as in the real situation. By creating a difference in heights between the air inlets and outlets, the simulated airflow started to become closer to the measured airflow as this increased height difference enhances the stack effect.

Ground temperature

As the earth tubes are buried in the ground, it is critical that the coupling to the ground is simulated properly. In ApacheSim, this was done by assigning the adjacent external condition of the pipe surfaces to the corresponding soil temperature. Daily and monthly soil temperature profiles for different parts of the ground (i.e. outside to the north of the building, under the greenhouse, and under the living space) were created, and each part of the earth tubes was assigned to have adjacent external surfaces to correspond to these soil temperature profiles. This has resulted in a simulation model that closely reflects the actual building.

Predicting the impact of earth tubes in summer

Using the calibrated model above, the impact of earth tubes was further investigated for the summer period. Note that since summer monitored data were not available, this investigation was purely based on simulation for Adelaide, a nearby city. Also, due to space limitation, only results from the warmest period in summer in this location are reported (i.e. early to mid-February are presented here).

To investigate the impact of earth tubes and how effective they would be in cooling the building, several cases were explored, as follows:

1. Case 1: Earth tube inlets and outlets were closed and all other openings were also closed. In Figure 13 this is indicated as ‘All closed’.
2. Case 2: Earth tube inlets and outlets were opened, but all other openings were closed or ‘Only ET opened’.
3. Case 3: Earth tubes were opened, doors between the living space and green house opened, skylights were closed, or ‘ET and doors opened, skylights closed’.
4. Case 4: Earth tube inlets and outlets were opened, and so were the doors between the living space and greenhouse and the skylights were opened. This is indicated as ‘All opened’.
5. Case 5: Earth tubes were closed but all other openings were opened, or ‘ET closed, others opened’.

When the doors and windows above the doors between the living space and the green house were opened, it was assumed that the opening area was only 40% of the total doors area, and when the skylights were opened, only 40% of the total skylight area was opened, to reflect that in reality, they were not totally opened.

The results show that the living space would experience the warmest indoor temperature when the earth tubes and all other openings were shut (Case 1). As the building has a considerable amount of thermal mass and the north-facing façade of the greenhouse is not shaded, the collected heat would warm up the entire living space without letting it escape. Bringing in fresh cooled air from the earth tubes would slightly lower the temperatures in the living space, however without having any outlet, the living space would remain warm (Case 2).

Opening the doors and windows above the doors between the living space and greenhouse noticeably lowered the living space temperatures as the cooled air from the earth tubes was able to remove the heat from the living space to the greenhouse; however, without allowing the heat in the greenhouse to escape, the heat from the greenhouse mixes with the air in the living space (Case 3). The effectiveness of the earth tubes to bring in fresh air depends on letting out all the warm air from the living space and the greenhouse, as shown in Case 4. In this case, the skylights in the greenhouse were opened, allowing the warm air to escape out thus lowering the temperatures in the living space by around 5º K during the day and 8º K at night.

In Case 5, the windows, doors and skylights were opened but the earth tubes were closed. This was to test the case for typical houses where earth tubes were not installed. The result showed that even though this arrangement helped to release the heat from the living space, the temperatures in the living space were higher than with the earth tubes in use. Without the earth tubes the air flow through the window above the door between living and greenhouse in a typical day was 38.3 L/sec but with the earth tubes operating this air flow increases to 46.6 L/sec. This demonstrates the effectiveness of earth tubes in providing improved ventilation and lowering the temperatures compared with just natural ventilation.

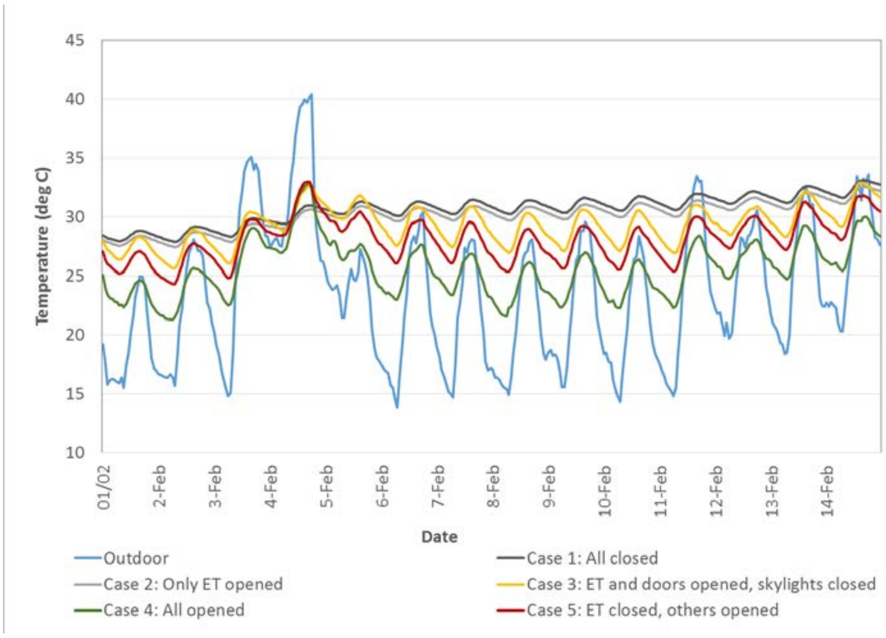

Figure 13: Testing the five cases in 2 summer weeks in Adelaide, South Australia

In other words, it is clear that using earth tubes in the summer will help to passively cool the building; however, such strategy will only work effectively if there are sufficient high level openings to let the warm air out, inducing a stack effect to draw cool air through the earth tubes, thus continuing to cool the internal space of the building.

Predicting the impact of using earth tubes in another climate

With the model calibrated to measured data at sufficient accuracy to represent the real building, as presented in the low CV(RMSE,) it can be used with some confidence to explore other possibilities. In this case, we explored the use of earth tubes (for the same Earthship building design) in Taos, New Mexico, where the Earthship was invented. Taos is located in a Warm Summer Continental Climate (Dfb). It has a warm summer and a very cold winter with the average high of 29.2ºC in July and average low of -11.8ºC occurring in January (US Climate Data 2016).

To model the building in this location the monthly ground temperatures for various positions were also calculated based on the ground temperature modelling approach discussed above, i.e. outside adjacent to the earth tubes, under the greenhouse around the earth tubes and under the greenhouse floor, under the living room around the earth tubes and under the living room floor, and adjacent to the living room walls. Daily, weekly and yearly ground temperature profiles were created in the IESVE model from these data. See Table 2.

Note also that the building orientation in Taos was turned 180 degrees so that the greenhouse would face the equator (i.e. south) in order to receive passive solar heating in winter. A number of scenarios were tested and they include:

1. Summer with earth tubes, doors and windows above doors between living room and greenhouse opened (opening area 100%, 40%, 10%), denoted as S100, S40, S10.
2. Summer with earth tubes but all openings closed, denoted as S0.
3. Winter with earth tubes, doors and windows above doors between living room and green house opened (opening area 100%, 40%, 10%), denoted as W100, W40, W10.
4. Winter with earth tubes, but all openings closed, denoted as W0.

Note that when the openings and earth tubes were indicated as opened, they were simulated as being opened all the time.

Table 2: Calculated ground temperatures for Taos, NM

Month	A	B	C	D	E	F
1	2.1	14.7	14.2	13.4	14.3	13.0
2	2.4	14.9	15.2	15.1	14.4	13.6
3	4.2	14.8	14.6	15.4	14.7	14.2
4	7.0	16.5	16.5	17.6	16.4	14.7
5	10.2	17.2	17.1	19.1	17.3	15.9
6	12.8	19.1	18.9	22.2	19.8	17.3
7	14.2	20.2	19.4	22.3	20.3	18.4
8	13.9	20.4	18.9	22.1	20.8	18.7
9	12.1	20.6	19.0	21.9	21.1	18.2
10	9.3	19.6	18.0	20.4	20.1	17.2
11	6.1	18.7	17.5	18.4	18.8	15.7
12	3.5	16.2	15.1	15.0	15.9	14.2

A = outside, 2.5m depth; B = under living room, -1m; C = under living room, -2m; D = under greenhouse, -1m; E = under greenhouse, -2m; F = berm, 1m from tyre wall, -2m.

Figures 14 to 16 show the predicted living room temperatures in the Taos location in July (summer) and January (winter). Figure 14 shows that the earth tubes would only be effective if the openings between the living room and greenhouse as well as the skylights in the greenhouse were opened (S10, S40 and S100). It is also important to note that the opening area does not need to be too large. In this study, openings as little as 10% of the total openable area (would result in the lowest living room temperatures during summer days (case S10). Opening the doors between the living room and greenhouse as well as the skylights for 40% of the total openable area or more would result in lower temperatures at nights as more internal heat would be released to the outside. What this means is, if lower night-time indoor temperatures are desired in summer, the occupants can easily open all the openings between the living room and greenhouse as well as the skylights until the desired condition is reached. However, during the day, it is not necessary to widely open these openings as doing so would result in bringing in too much warm air from the outside and from the greenhouse into the living space. Ideally just the windows above the doors would be opened (doors remain closed) to allow the stack effect to occur while isolating the warm greenhouse air from the cool living room air.

The most effective strategy for winter is the opposite of that for summer. In winter, opening the earth tubes' inlets and outlets as well as all other openings would result in the lowest indoor temperatures despite the fact that the air coming through the earth tubes was warmed by the ground (Figure 15). This is because the openings would let warm air escape and this is obviously not desired as the temperatures in the living room could be as low as -12.5ºC when the outdoor was -18.4ºC (Figure 16). The living room would be the warmest in winter when the earth tubes' outlets were closed (W0). This result is similar to previous monitored data in a built Earthship home in Taos (Freney, Soebarto & Williamson, 2013B).

Similar results were obtained when the earth tubes' outlets were left opened but with the doors and windows between the living room and greenhouse as well as the greenhouse' skylights being closed. However, if the doors and windows above the doors were opened during winter months, e.g. for 10% of the total openable area even though the greenhouse skylights were closed, the living room's temperatures would drop by around 7-10ºC (Figure 17).

Discussions and Conclusions

This study has investigated the use of earth tubes as a strategy for passive cooling and heating in an Earthship house. Figure 2 illustrates how the earth tubes will work – they require not only the inlet to bring in fresh air and the outlet to distribute the air to the internal space, but also external outlets for the warm air from the space to be exhausted to the outside in summer. These outlets, however, need to be closed in winter.

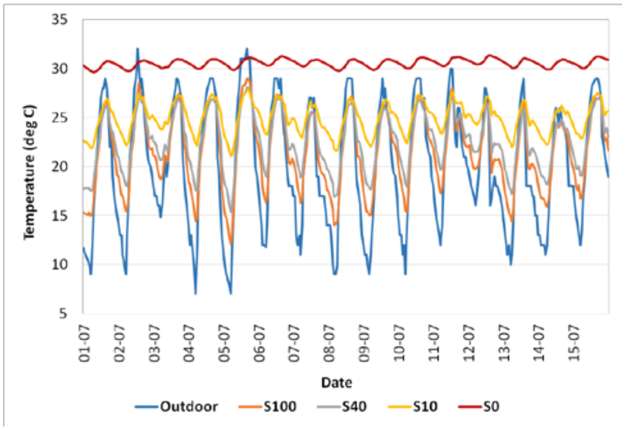

Figure 14: Predicted living room temperatures during two summer weeks in Taos, NM

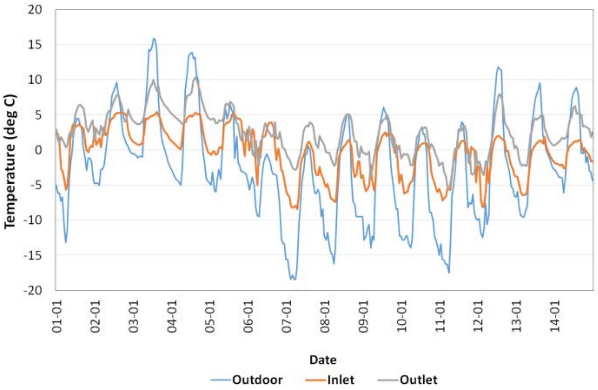

Figure 15: Predicted earth tube inlet and outlet temperatures during two winter weeks in Taos, NM

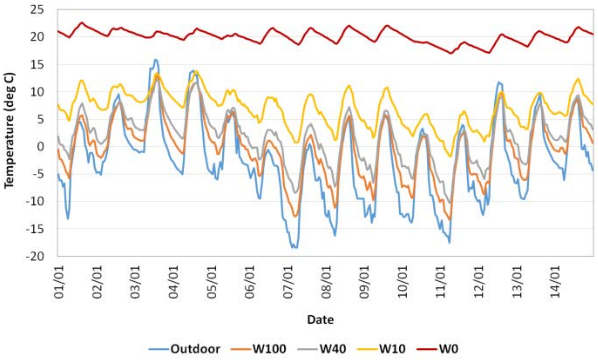

Figure 16: Predicted living room temperatures during two winter weeks in Taos, NM.

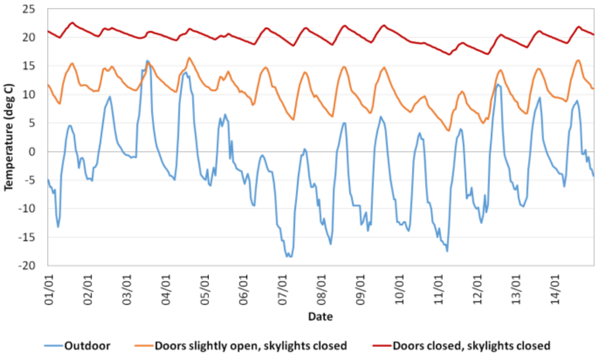

Figure 17: With doors and windows between the living room and greenhouse opened and closed.

This concept has been confirmed through a calibrated simulation model for the Earthship house in Ironbank, South Australia, and further tested in the same building design but located in Taos, New Mexico.

It was found that in order to accurately simulate the earth tubes and investigate their impacts, it is critical to calculate the temperatures of the ground adjacent to the earth tubes as well as of the ground under the floor and adjacent to the earth-bermed external walls. It is also critical to model the earth tubes as having several different zones to take into account different ground temperatures acting upon the earth tubes due to depth and proximity to different areas of the building.

The study has shown that the presence of openings between the living room and greenhouse as well as the presence of openable skylights in the greenhouse is crucial in ensuring the effectiveness of the earth tubes. To lower the temperatures in the living room during summer days, these openings need to be opened, even slightly, in order to create a stack effect to allow the warm air to rise and escape outward. It is shown that doing so can increase the airflow out through the greenhouse by 22%. Completely opening them while it is warm outside, however, is not recommended as it will bring in warm air from the outside during the day, as shown during the two hottest days in Figure 13. On the other hand, if lower indoor temperatures at night-time are desired, these openings can be opened fully.

During winter, maintaining indoor temperatures at a reasonable level, i.e. around 18ºC or above, can be achieved either by completely closing the earth tubes outlets or by opening the earth tubes but closing the doors and windows above the doors between the living room and greenhouse together with closing the skylights in the greenhouse. The former strategy clearly stops the air in the earth tubes from entering the living room, which even though it is warmer than the air entering the earth tubes, its temperature is still below the desired indoor temperature as the ground temperature is below 15ºC (see Table 2). The latter strategy does the same by preventing the air in the tubes from being sucked into the living room as there is practically no outlet for the air to escape. With either strategy, solar heat from the greenhouse, which radiates into the living room, is retained creating a much warmer indoor than outdoor. The result also shows that it is crucial to keep the doors and windows between the living room and greenhouse closed during winter because opening them, even as little as 10% of the total openable area, would result in lowering the living room temperatures by 7-10ºC. An exception to this is during sunny winter days when the greenhouse air temperature is greater than the living room temperature and mixing of the air between these two spaces is desirable. An advantage however of maintaining the air flow at all times is that fresh air is delivered to the living room which likely produces a healthier indoor quality.

In conclusion, the study shows that having earth tubes alone will not work. Other forms of openings are needed in summer to assist in creating a stack effect to draw the cool air through the earth tubes allowing the warm air to escape. In winter, even with the earth tubes' outlets being left opened, closing the other openings will prevent the stack effect from occurring, thus the heat radiating from the greenhouse can be retained resulting in indoor conditions that are much warmer than the outside. The study has also demonstrated that the most optimum strategy in using earth tubes can be tested via simulation which may help designers design better earth tube systems and educate Earthship occupants about how to 'sail' their 'ship' most effectively.

Acknowledgement

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