Earth Coupling and Natural Stack Ventilation in a Temperate Inland Climate

A Performance Appraisal of the Johannesburg Eco-City Community Centre's Zero-energy Strategies

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(Fig. 1); The community hall seen from the north west corner.

Abstract

After testing three possible construction methods of the same design under different yet typical operating situations, the building as designed has performed consistently better than the other cases throughout all tests. Under normal situations one could still question the economics of underground construction for such benefits, yet in this case, the internal economics and politics of the project lent other favourable qualities to this normally expensive style of building; (large quantities of cement were donated for construction, and unskilled labour intensive methods and local outsourcing were favoured to provide employment in an impoverished area).

The combination of these outside factors and the performance demonstrated here make a strong case for the replication of similar building styles where similar outside determinants may exist. In other situations, it may not be the best choice economically as many of the comfort benefits could be achieved through other, less costly means.

Introduction

South Africa is a country of stark contrast. Extreme wealth and extreme poverty live side-by-side in the economic capital city of Johannesburg. One of these poorest areas is the focus of this research, where a poverty alleviation initiative is attempting to provide an alternative example of a development model. The project is an eco-village, where local economic development (LED) is combined with alternative housing and agricultural solutions. The intention is to encourage similar development and reduce the need for transport to employment, shops and amenities. All this is done in a way that reduces the community's expenditure on energy, food, and transport, thus freeing up the scarce income available for the improvement of quality of life for the inhabitants. If successful, this model could influence the policy makers' decisions on future development models, and improve the living conditions of millions of people living on or below the poverty line.

(Fig. 2); A typical view of the Ivory Park area.

Johannesburg EcoCity (JEC) is a local economic programme focussing on environmentally friendly technologies to address poverty alleviation. The JEC initiative is developing an eco-village in Ivory Park, a low-income informal settlement on the outskirts of Johannesburg where poverty still reigns supreme.

Eco-villages are environmentally friendly and sustainable settlements. An eco-village is often characterized by an integrated approach to environmental, social and economic concerns. Eco-villages strive for a better quality of life. They aim to supply their own water, treat their own waste water, often supply their own electricity, collect their own refuse, often build and maintain their own roads and parks and yet still pay their rates to council. They can be net providers of services, not users.

(Fig. 3); The Eco-village "business quarter"; half completed.

An eco-village can take care of many of the residents' social, economic, food and transport needs. Some ideas that are used in the Ivory Park eco-village include:

- Provision of communal facilities, (Crèche, Hall, Gardens)
- Provision of cultural facilities, (Poet's corner, traditional village)
- Provision of infrastructure for Local Economic Development, (Offices, Crafts, Light Industrial)
- Shared facilities, (energy, ablutions, secretarial, etc.)
- Water harvesting, conservation and recycling
- Waste recycling
- Food production on site
- Solar power is used in place of fossil fuels such as oil, coal and paraffin for heating and lighting
- Buildings are built using various technological approaches to energy and resource conservation
- All development is carried out by local unskilled labour

Background

This research focuses on the community hall building that has been built in the Ivory Park eco-village. The research paper attempts to asses the effectiveness of the zero-energy strategies employed in the building. The community centre building of this eco-village has been designed as an underground building with natural ventilation. The building is situated in the "business quarter" of the eco-village. The building consists of a single large space 100m^2, four smaller habitable rooms of about 12m^2 each, and a storeroom of 6.5m^2. It is used for community meetings, training, and exhibitions. The building is often filled to capacity with people.

The eco-village project relies completely on donor funding. Many donations are in the form of materials for construction, and this obviously influences the choice of materials to be used dramatically. An example of this is Lafarge's donation of 6000 bags of cement. This meant that heavy masonry and concrete buildings had to be considered. This in turn has lead to certain zero-energy strategies;

namely the concept of a heavy underground building that is thermally coupled to the stable earth temperatures. This has been elaborated with concrete underground pipes delivering fresh supply air into the building at stable temperatures year round. This air supply system is driven by stack ventilation through the "lantern" that protrudes through the earth-covered roof of the hall.

Geography

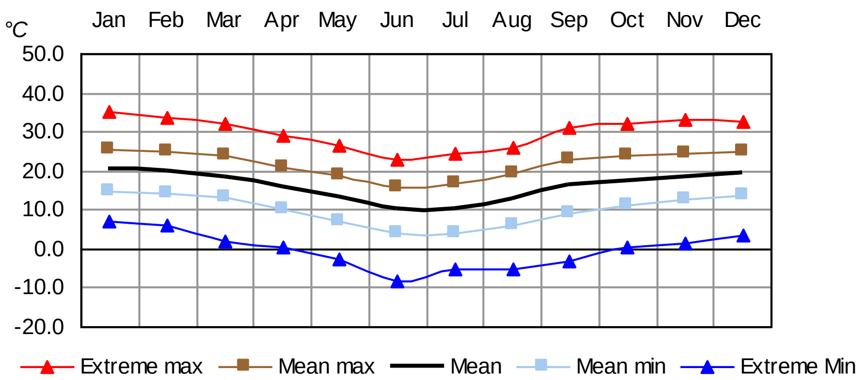
The local area is built up in a dense pattern, with 40% of inhabitants living in tin shacks, most in small brick dwellings, and a few more established brick dwellings scattered between. Most roads are dirt, with only major routes being tarred. Few houses are serviced with electricity, telephone, water or sewerage drainage connections. The main form of energy is the coal fire – "umbhawulas" that cause terrible pollution and many respiratory diseases.

The site slopes down slightly to the north, (the sunny side). The ground is poorly drained and clayey in nature.

Climate

The local climate on the Highveld can be considered temperate. Johannesburg is located at latitude 26^{o} south. Temperatures vary between average maximums and minimums of 25^{o}C and 4^{o}C respectfully. Large diurnal swings between 10^{o}C and 13^{o}C are experienced.

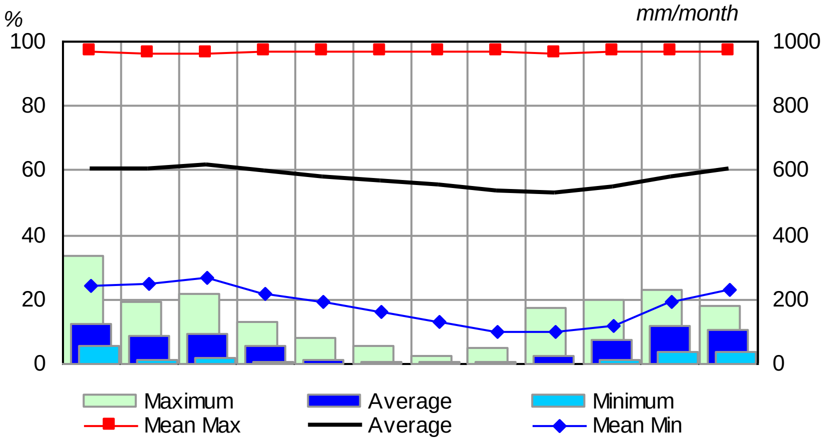
Temperature graph for Johannesburg



(Fig. 4)

The area experiences distinct rainy and dry seasons. Humidity is usually a moderate 60%, with temporary increases during the short but significant summer rain storms, and dry periods in winter.

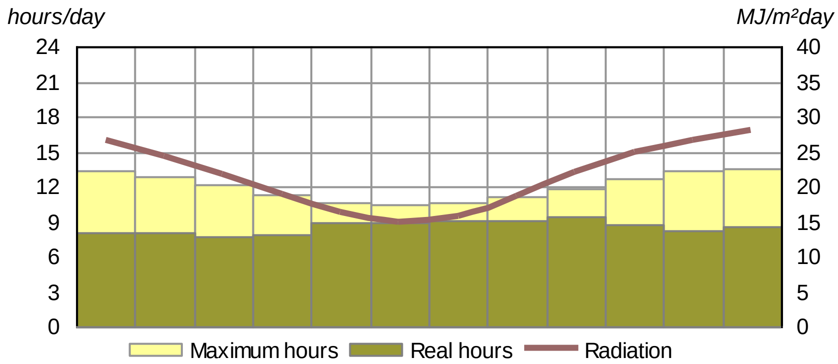
Relative Humidity and Rainfall for Johannesburg



(Fig. 5)

The area is at an altitude of almost 1700m, and radiation can be severe.

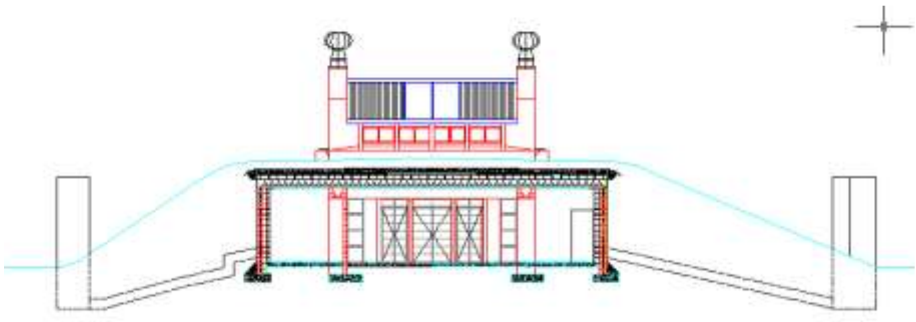
Solar Radiation and Sunshine hours for Johannesburg



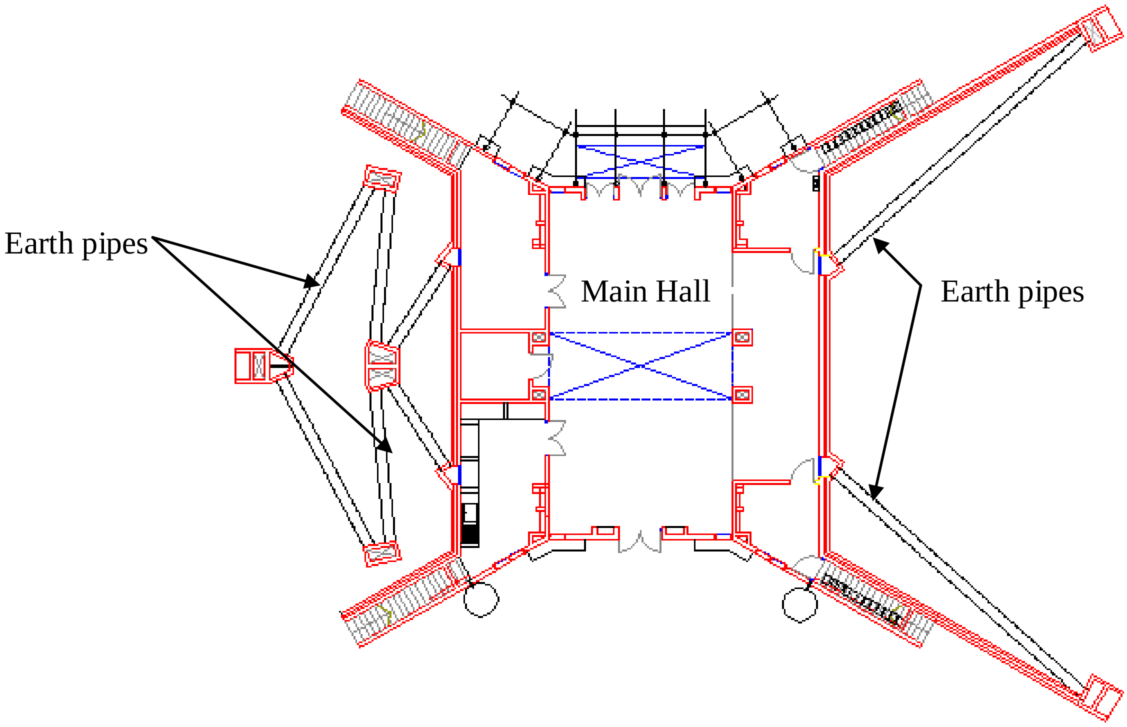
(Fig. 6)

Architecture

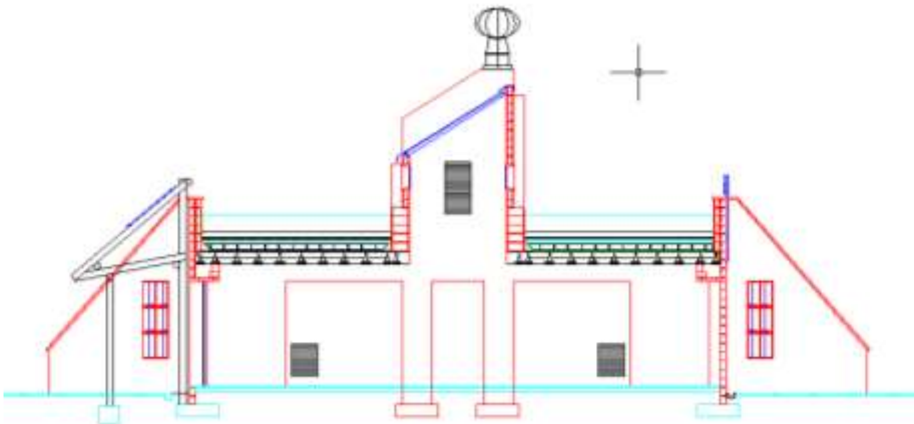
The community centre building was conceived as an underground heavy concrete structure. It is built of hollow concrete blocks that were filled in-situ with soilcrete. A pre-cast beam and block system with integrated in-situ concrete slab was used for the roof. Solar access was given on the northern and southern aspects only. The "lantern", with north and south facing windows rises above the centre of the hall to provide further daylighting and an opportunity for natural stack ventilation, assisted with wind powered turbines. Once built, the building was buried with soil, with great depths achieved on the eastern and western sides, and only a 150mm layer on the roof. The roof was further insulated with polystyrene below the earth layer. The roof and embankments are to be planted. A sophisticated sub-soil drainage system was incorporated on all the underground aspects. Ventilation pipes run at depth through the earth mounds and supply fresh air to the internal spaces.



(Fig. 7); Long section through the community hall.



(Fig. 8); Plan of the community hall.



(Fig. 9); Cross section of the community hall.

(Fig. 10); South east view of the community hall.

(Fig. 11); North east view of the community hall.

(Fig. 12); View up into the lantern from inside the main hall space.

Problem

The purpose of this study is to determine the effectiveness of the zero-energy strategies employed in this design:

- Is the earth coupling effective?
- Is the natural exhaust strategy effective?
- How does the design compare to more traditional construction methods?
- What improvements could be made to the completed design?

In order to complete this assessment, three comparative studies are made:

- Design case; The existing building as designed including the earth coupling and earth delivering tempered air
- Baseline case; The same layout with a simple steel roof, and no earth coupling or earth pipes delivering tempered air
- Baseline 2 case; The same layout with an insulated steel roof, and no earth coupling or earth pipes delivering tempered air

These three scenarios are modelled with identical simulated usage patterns and ventilation air flows. The extremities of two seasons are simulated for each model; represented by the model's performance on the summer and winter solstices. The space being studied is the main hall space, as this is the primary space of the building.

In this way the earth coupling is isolated and compared to a non-coupled design made of traditional materials of different levels of sophistication.

The summer ventilation strategy is also isolated to be assessed by simulating the models both with and without natural stack ventilation at the summer solstice. The models assume that the adjustable louvers are closed during winter and therefore there is no ventilation in winter. Natural infiltration is estimated at 1 ACH for all design cases.

The following cases have therefore been studied:

	Baseline; Steel roof	Baseline 2; Insulated steel roof	Design; Earth roof and walls
Winter solstice, no ventilation	X	X	X
Summer solstice, no ventilation	X	X	X
Summer solstice, with ventilation	X	X	X
Summer solstice, with special event		X	X
Summer solstice with extra ventilation		X	

(Fig. 13); Schedule of studies made.

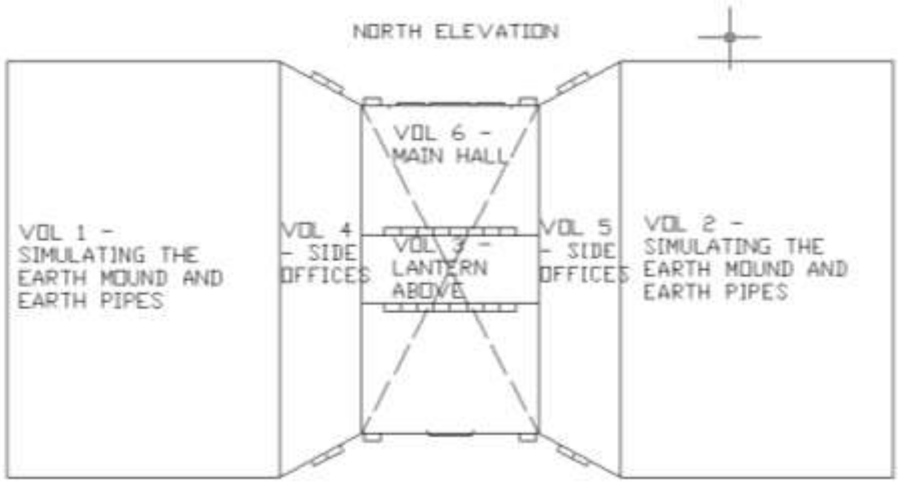
Method

Geometric model

The building is evaluated on a theoretical basis, using computer thermal simulation. The software used is DEROB-LTH, (Dynamic Energy Response Of Buildings)[i].

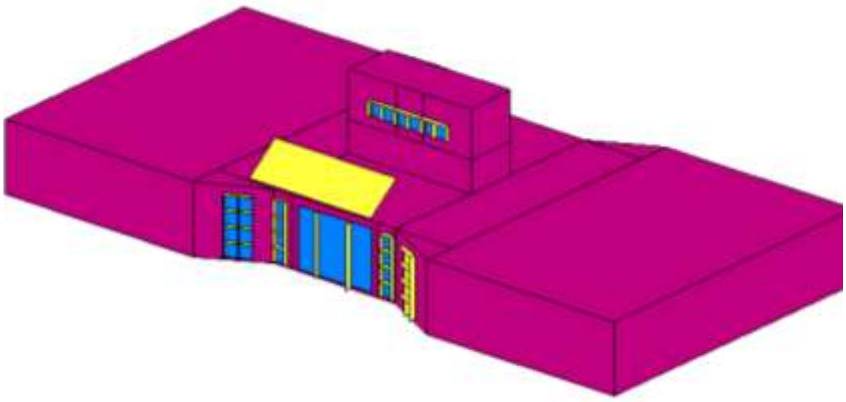
This software first involves building a geometric model of the building. In order to simulate the three case studies, three geometric models were built.

Due to limitations within the software, certain internal volumes and external shading devices have to be omitted. However, these are the same for all cases, and are not expected to affect the comparative study of the main hall. Following is a simplified plan of the geometric model built for the design case.



(Fig. 14); Schematic diagram of geometric model

Following is the geometric model of the design case model; (the earth coupled building). That is to say the thermal modelling version of the actual built design, including the earth mound, earth pipes, earth roof, and sun shading.



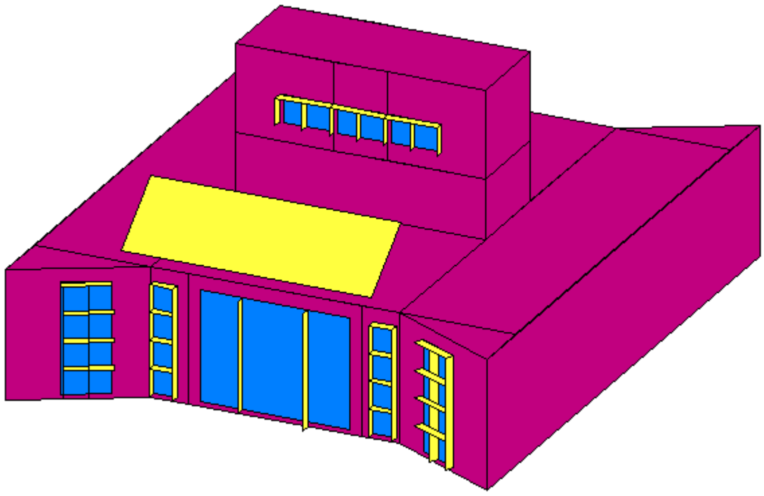
(Fig. 15); 3D view of the earth coupled building thermal model.

In this model, the buried earth cooling pipes are modelled as two large volumes either side of the actual building. These volumes have adiabatic walls, floor and roof to the outside air, and are connected thermally to the adjoining walls of the building. In order to simulate the thermal effect of the buried pipes and earth mound, these volumes have been set to maintain an internal temperature equal to the annual average external air temperature of 17^{o}C.

The two baseline models (steel roof and insulated steel roof) are conceived as not being buried, and with no earth pipes supplying fresh air. The external wall construction used on the north and south faces of the actual building is now used for the east and west walls as well.

The first baseline model is constructed with only a steel roof, (as is very common in this area), and the second baseline model has 50mm of mineral wool insulation and a plasterboard ceiling.

Both geometric models for the baselines look like this, and include the sun shading devices:



(Fig. 16); 3D view of the two steel roof cases' thermal model.

Materials

The following thermal characteristics of materials were used in the thermal modelling.

Material	Conductivity (W/mK)	Specific Heat (Wh/kgK)	Density (kg/m^3)
Concrete	1.7	.24	2300
Reinf. concrete	1.28	.26	2100
Cement mortar	.93	.29	1800
Gypsum	.22	.23	900
Mineral wool	.04	.24	50
Air Space at 21 C	.024	.280	1.201
Soilcrete	.85	.24	1900
Polystyrene	.036	.47	73
Earth	.39	.24	1300
Adiabatic	.024	.279	15
Hollow block 150	1.36	.25	1200

Steel	55	.13	7800
Hardboard	.2	.406	900
Hollow block 300	.968	.25	1100

(Fig. 17); Materials table.

Building Elements

Following is a description of the buildings elements made up of different thicknesses of different materials used in the thermal models.

Element name	Material name	Material thickness (mm)
Adiabatic		
	Adiabatic	1000
Earth-wall		
	Reinf. concrete	100
	Concrete	100
	Soilcrete	130
Exterior wall		
	Cement mortar	15
	Hollow block 150	150
Earth roof		
	Earth	150
	Cement mortar	75
	Polystyrene	100
	Concrete	100
	Hollow block 300	300
Steel roof		
	Steel	2
Interior wall		
	Soilcrete	90
	Concrete	50
Interior door		
	Hardboard	6
	Air space at 21^{o}C	32
	Hardboard	6
Floor		
	Earth	500
	Concrete	100
	Cement mortar	50
Lantern wall		
	Soilcrete	400
	Concrete	50
Lantern adiabatic		
	Concrete	25
	Polytsyrene	300
	Concrete	25
Steel roof insulated		
	Steel	2
	Mineral wool	70
	Gypsum	12

(Fig. 18); Elements table.

Glazing

The following glazing materials were used in the model.

Glass type	Emittance (front) %	Emittance (back) %	Transmittance %	Reflectance %
clear_4	83.7	83.7	83	7
NOGLASS	1	1	97	1

(Fig. 19); Glazing table.

The “NOGLASS” type is used to create two volumes in the model out of one in reality, i.e.where no glazing actually exists; it is one of the techniques commonly used to circumvent the limitations within DEROB-LTH.

Internal Heat Loads

In all cases (except the special case) the internal heat loads are based on the building operating as normal, with 30 people (3000W) in the main hall between 8.00am and 5.00pm, and 3 people (300W) in the smaller rooms for the same period. As the building is not electrified, there are no other applied internal loads to be considered.

In the special case the internal heat load is based on a summertime special occasion being hosted in the building over two days. Here there are 100 people gathered in the main hall, (10000W), and 10 people in the smaller offices, (1000W) for the same hours. This case is modelled slightly differently due to the internal workings of DEROB-LTH; 5 days are simulated, with the special event occurring on the second and third days. Ventilation rates in all cases are increased to 400l/s during the event to simulate the natural acceleration of the lantern stack ventilation in such circumstances.

Ventilation & Infiltration

Infiltration is set at 1 ACH in all the models. In summer the additional ventilation effect of the lantern is calculated and simulated for each model.

In the design case, the ventilation includes temperature control achieved by the earth pipes. As previously stated, this is fixed at 17^{o}C. This is the annual average external air temperature, and it is assumed that the earth will have reached this stable temperature by the average pipe depth of 3m. It is further assumed that the 17m length of the buried concrete pipes is sufficient to allow enough thermal exchange between the earth and the fresh supply air to stabilise the air temperature to that of the earth; 17^{o}C. This would be an interesting study to undertake at a later stage, although it cannot fall within the scope of this investigation at this time.

In the two baseline models, external air enters at its hourly temperature.

The ventilation rate due to the stack effect caused by the lantern is considered in all cases, and is calculated using the British Standards method [ii] in the following manner:

$$Q = C_d A \left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{1/2}} \right] \left(\frac{\Delta T_g H}{T} \right)$$

where:
C_d is the discharge coefficient for the wind turbines on the top of the chimneys; calculated at 1.4 (see Appendix)[iii].
ε = A1/A2
A = A1 + A2
A1 = area of higher louver grille
A2 = area of lower louver grille
ΔT_g = temperature differential between the two louver grilles
T = average between the two temperatures (always positive and in Kelvin)

The lower temperature is taken as a fixed 17^{o}C, and the upper temperature is taken as the average of the day's temperature during daylight hours. This is 22.3^{o}C for the summer solstice, resulting in a total ventilation rate of 208 l/s.

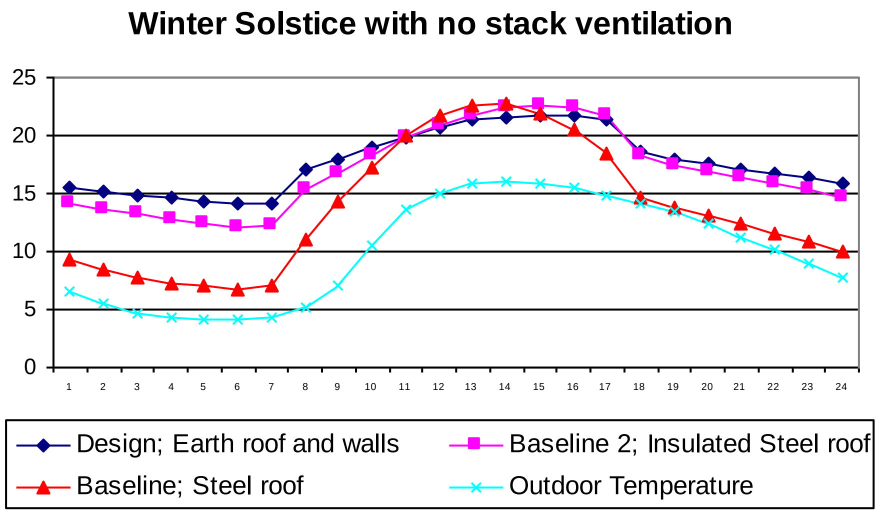
The actual ventilation rate would depend on the difference between the air temperature inside the lantern, (which would vary during the day, and certainly be higher than the outdoor temperatures for much of the time), and the incoming air at 17^{o}C. Therefore this estimation of the ventilation rate is very conservative, and the actual rates would most likely increase significantly beyond this amount during the day. For example, the highest simulated air temperature in the lantern in this scenario was 27^{o}C, while ventilated at 208 l/s; this would in fact produce a ventilation rate of 387 l/s, and not the estimated 208 l/s used in the simulation.

Furthermore, the two baseline cases benefit from the ventilation rate modelled for the design case. This is because the stack ventilation rate used in all cases is based on a temperature difference between 22.3^{o}C and 17^{o}C; while in reality, this stack effect ventilation would be considerably less in the two baseline cases, where the air supply temperature is actually outdoor temperature; well above the 17^{o}C used for the design case. However it is necessary to make these compromises to avoid a circular reference calculation, and it is reasonable to assume that the occupants would open the doors and increase the natural ventilation should it become too warm.

Results

The results for the simulations are shown below, these are the average operative temperatures in the main hall in each case, and they include air temperature and surface radiation from all walls, floors and roof. Humidity is not considered in DEROB-LTH's calculations of operative temperature. All case studies are plotted on the same graph for each climatic and operating method for easy comparison.

The winter solstice scenario assumes that the adjustable louvers are closed in all cases, and therefore there is no allowance for forced ventilation other than the infiltration of 1 ACH.

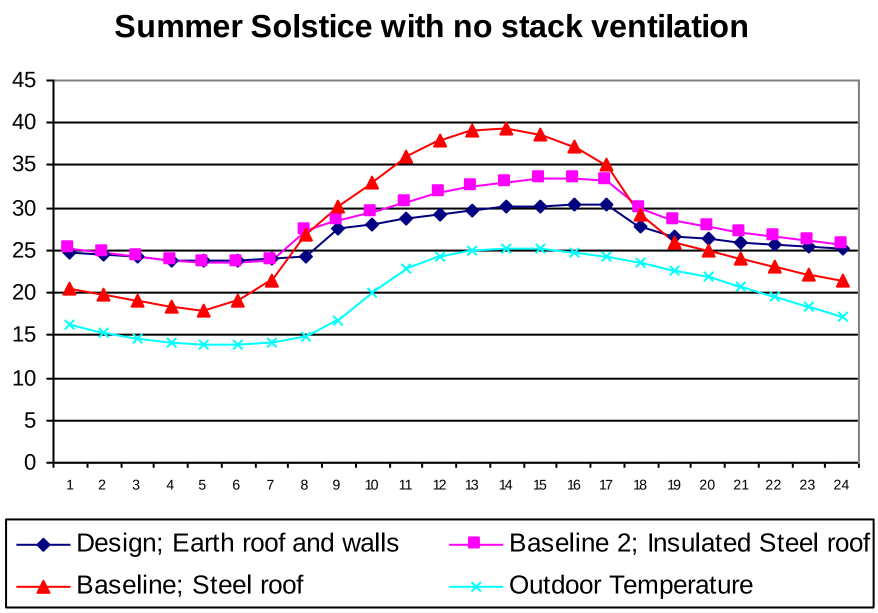


(Fig 20)

In this result, the baseline study (steel roof) loses and gains heat very rapidly, with little thermal inertia visible. It begins the day at 7°C, and rises to a maximum of 23°C operative temperature. This corresponds with experience of rooms with no insulation under a steel roof.

Baseline 2 (insulated steel roof) performs significantly better, retaining some heat each night from the day before. It oscillates between minimum and maximum operative temperatures of 12°C and 23°C respectively. The beneficial effects of insulated ceilings are well known, and this result seems to correlate with that experience.

The design case (earth coupled) performs the best however, retaining the most heat from the day before, and rising to a lower maximum temperature. It oscillates between minimum and maximum operative temperatures of 14°C and 22°C respectively.



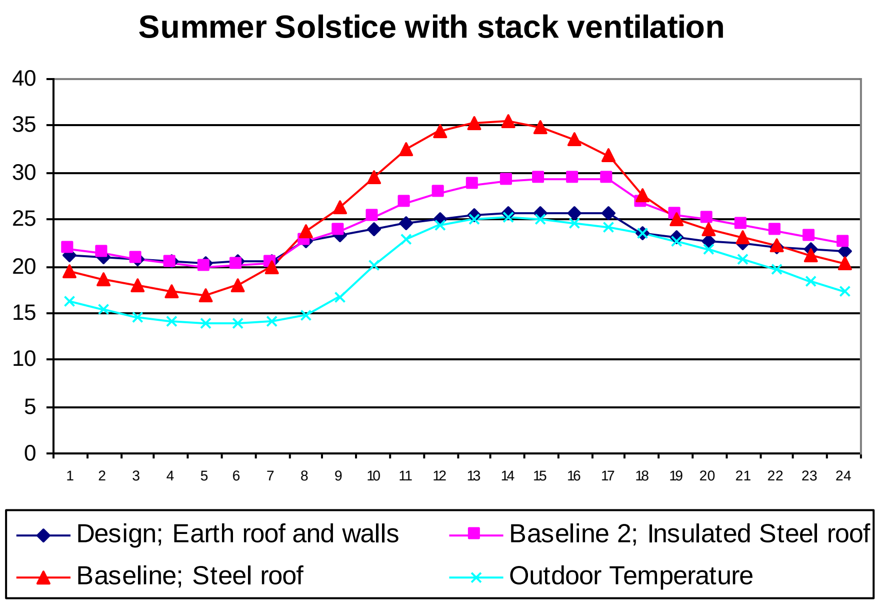
(Fig 21)

This summer simulation excludes the ventilation achieved by the stack effect through the lantern. This is so the effectiveness of the ventilation strategy can be independently assessed.

Again the baseline case (steel roof) performs poorly as expected, with internal operative temperatures reaching almost 40°C, and dropping to 17°C in the morning. This is largely due to the radiant heat from the un-insulated steel roof that reaches a surface temperature of 50°C during the day.

Baseline 2, (insulated steel roof) performs well during the night, but temperatures reach 33°C during the day.

The design case again performs the best, with good night-time temperatures, and the maximum daytime operative temperature limited to 30°C.



(Fig 22)

Finally the natural stack ventilation rate of 208 l/s is introduced. Half of this air is fed directly into the main hall (Volume 6), and half is delivered via the one set of side offices (volume 4).

In the two baseline cases, this air is delivered at external air temperature. In the design case it is delivered at a constant temperature of 17°C throughout the day, due to the cooling achieved in the earth pipes during their 17m length at an average depth of 3m.

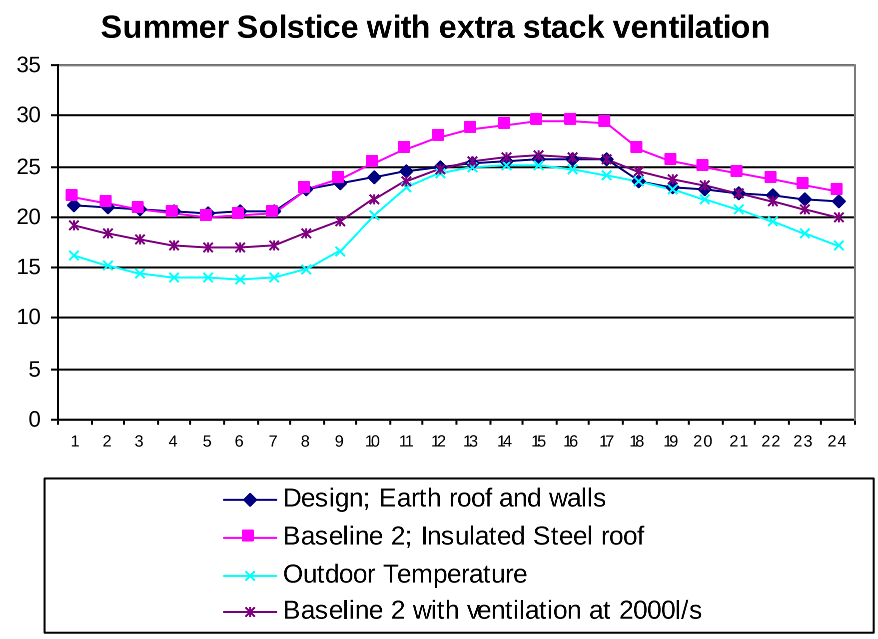
All three cases improve performance with the introduction of ventilation.

The baseline case (steel roof) reaches the same low, but the maximum temperature is reduced to 36°C. Interestingly, the steel roof surface temperature remains at 50°C, (as in the unventilated scenario), but the effect of the ventilation reduces the operative temperature by 4°C.

Baseline two (insulated steel roof) drops lower than before to 20^{o}C, and rises less to 30^{o}C.

But most noticeably, there is a marked improvement in performance of the design case compared to the two baseline cases; it operates between 21^{o}C and 26^{o}C. This is not surprising with the assumptions made about air being delivered at a stable temperature of 17^{o}C.

By comparing the unventilated and ventilated performances of the design case, we can see that the stack effect and earth pipes combine to reduce the operative temperature by 4^{o}C at the hottest time of the day. It is worth noting that this reduction, although the same amount, (4^{o}C) as in the baseline (steel roof) case above, it is more difficult to achieve, because the temperatures are generally lower, (i.e. it is a greater effect when measured on a percentage basis; 13% vs. 10%; a net increase of 30% in cooling effect by the earth pipes).

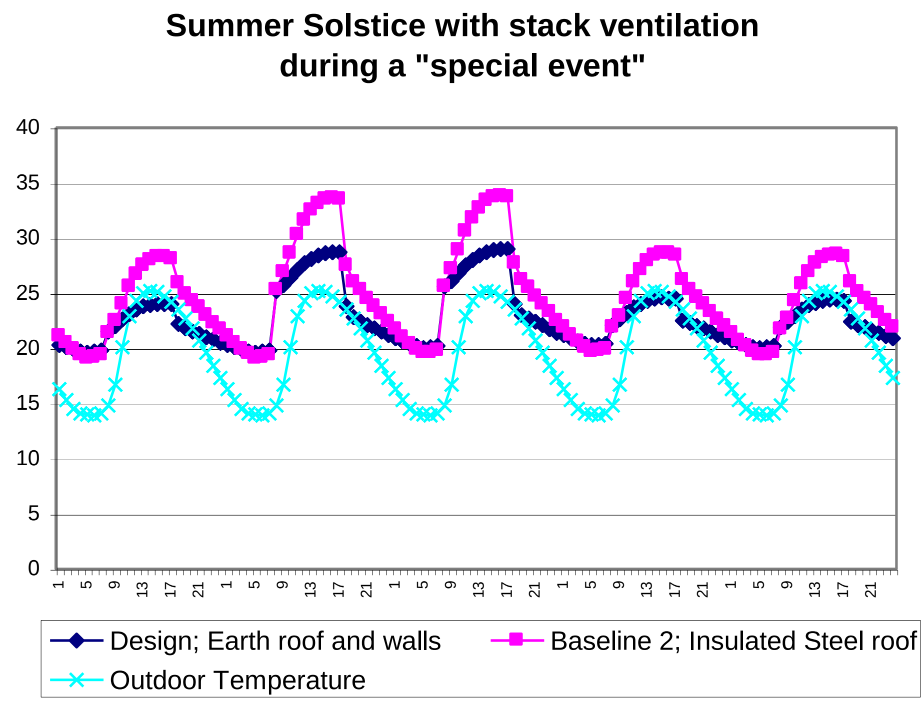


(Fig 23)

This result determines the ventilation rate required by the baseline 2, (insulated steel roof) case in order to achieve the same results as the design case. A ventilation rate of 2000 l/s achieved the same maximum temperature of 26^{o}C, however the lowest temperature was much lower at 17^{o}C compared to 21^{o}C in the design case.   Of course it would be possible to close off the ventilation at night, but due to limitations within DEROB-LTH, this cannot be easily modelled.

Using an average wind speed of 3.6m/s from due north, the required opening on both the north and south facades would be 14m^{2}. This is approximately the total façade area of the main hall facing north/south. Obviously, this result is highly dependant on the wind, which in this area is not reliable enough to guarantee good performance at the required time. But more importantly, the northern façade is sheltered to the north by another existing two-storey building

14m away from the facade. A completely open facade to the north and south would therefore not necessarily provide the required ventilation rate to match the performance of the design case.



(Fig 24)

Shown above are the results for a five-day period including the simulated 2-day special event, (with 100 people in the main hall (volume 6) and 10 people in the smaller offices). Only the baseline 2 (insulated steel roof) and design cases are simulated, because it is clear that baseline 1 (steel roof) is not a viable solution. The ventilation rate is 400 l/s for both cases. Infiltration remains at 1ACH.

These results show the baseline 2 (insulated steel roof) rising to a maximum operative temperature of 34^{o}C during the event, while the design case only reaches 28^{o}C. The minimum temperature for both cases is about the same at 20^{o}C.

In reality of course, the ventilation will vary according to the varying temperature created in the lantern (volume 3). In other words, the system is self regulating, because as the heat builds up, the ventilation rate will increase, quite possibly to above the 400 l/s estimated for this study, and hence the building may well perform better than described here.

Interestingly, with good ventilation all night neither case retains much of the heat from the day before. Of course baseline 2 has an advantage here in that it is drawing in outside air during the night at 14^{o}C, while the design case is still pulling in air through the earth pipes at 17^{o}C.

Conclusions

Summer operations:

Baseline 1 – The steel roof.

This option does not perform at all well in any of the simulations. The volume gains too much heat in the day and loses too much at night. Although a common construction method in the area, it does not control its internal climate sufficiently to be considered a good design alternative.

Baseline 2 – The insulated steel roof.

This option generates quite a large amount of competition to the design case as a much more cost effective construction method. However the building's performance, although quite good under average circumstances, becomes too uncomfortable (34^{o}C) under heavy load conditions, as simulated by the special event with 100 people in the main hall for two 8-hour days.

As the building is a community hall, it is often used for large gatherings, this requirement is therefore quite significant in assessing the construction alternatives.

Design case – the earth coupled building with earth pipes and stack ventilation.

The building as designed performs the best of the three case studies; especially when put under heavy internal heat loads. The maximum summer operating temperature in any circumstance modelled is 28^{o}C, and this would only be for special events. Normal operating temperature maximum is 26^{o}C. This would be considered acceptable under the circumstances of this building.

Winter operations:

Baseline 1 – the steel roof.

Again this case study behaves very poorly as expected, and should not be considered a viable alternative.

Baseline 2 – the insulated steel roof.

This option again competes quite well with the design case; its main disadvantage is the minimum operative temperature of 12^{o}C in the morning.

Design case - the earth coupled building with earth pipes and stack ventilation.

The design case again performs the best of the three modelled, with its minimum temperature reaching 14^{o}C in the morning. Here it could be possible to improve the design case's performance by ventilating with the earth pipes at night, and thus bringing in air at 17^{o}C, (warmer than 14^{o}C). Again, due to limitations within DEROB-LTH's ventilation input style, this cannot be modelled.

Due to the simplification of the building in the modelling process, it is possible that some of effects of the internal thermal mass that is exposed to solar gain is not being accurately reflected. Therefore, it is possible that the design case, (that relies quite heavily on its thermal mass) is not actually showing the full benefits of this device.

It seems that all three cases would benefit from more possibility of solar heat gain in the winter months. Currently the northern façade is almost entirely glazed, although the glazed area could be increased by $2.9m^2$ within the current layout. Alternatively stretching the layout along the east-west axis could increase the northern façade; unfortunately this would lead to structural difficulties in supporting the earth roof with the increased spans.

Generally

The study has shown that earth coupling both to the space and particularly the air supply has beneficial effects, especially in summer and with high internal heat loads. However the cost effectiveness of this approach is not necessarily justified in all cases. The competition in internal thermal performance shown by the insulated steel roof option; a significantly cheaper alternative under normal circumstances, is significant. However the other factors involved in this particular circumstance, (the donated cement and the need to provide work for many unskilled labourers), have meant that it was appropriate in this context.

The study highlights the need for specific solutions to individual circumstances, and the need to consider many factors, including procurement and construction factors in choosing an appropriate method of zero-energy thermal control.

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Appendix 1

C_d – Discharge coefficient of windmaster 300mm tornado was calculated using the ASHRAE method:

$Q = A.C_d.W$ or $C_d = \frac{Q}{A.W}$

Where:
Q is the ventilation rate
A is the area of opening
W is the wind speed

The product information given by Windmaster for the Tornado 300mm was:

1489m^3/h of air removed in a wind speed of 15km/h at a height of 5m. The turbines in the model are at a similar height, and therefore the discharge coefficient was calculated thus:

$$C_d = \frac{0.4136}{0.0706 \times 4.1667} = 1.4$$

Endnotes

[i] DEROB-LTH Operation manual by the Department of Energy and Building Design, LTH , Lund university, Sweden 2003.
[ii] Natural Ventilation in Buildings; A design handbook.
[iii] Windmaster Ventilation (Pty) Ltd. "Tornado 300mm" product information.