

Earth-tubes for Building Heating and Cooling in Drylands

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Abstract: Building heating and cooling strategies for dryland communities should consider the needs of modern cities as well as traditional agriculturalists. Successful heating and cooling approaches must therefore be economically viable in both urban and rural settings as well as environmentally safe and sustainable. One low energy alternative for conditioning building space is to pass ambient air through earth tubes, which are long buried tubes also known as earth to air heat exchangers, through the relatively stable environment of the subsurface before being delivered and/or circulated through living space. The difference between the temperature of the outside air and that of the ground results in a cooling or heating effect on the transported air depending on the time of the day and/or year. In the past few decades the use of earth tubes has evolved from preliminary numerical, analytical and experimental investigations to commercial adoption. This paper presents an overview of the fundamentals of earth tube design and installation. Several published dryland applications are reviewed and the potential to cool or to heat buildings in a hot and in a cold dry region are discussed. This low-tech low-energy technology can be a viable strategy for the improvement of health and life in dry and arid climates in remote rural settings, as well as a technology that can significantly decrease the energy demand to condition space in rapidly growing urban centers.

Key words: Earth tubes, earth-to-air heat exchangers, ground air heat exchange, sustainable buildings.

One low energy alternative for air conditioning building space is to pass ambient air through earth tubes, which are long buried tubes also known as, earth-to-air heat exchangers, through the relatively stable environment of the subsurface before being delivered and/or circulated through living space. The difference between the temperature of the outside air and that of the ground results in a cooling or heating effect on the transported air depending on the time of the day and/or year. In the past few decades the use of earth tubes has evolved from preliminary numerical, analytical and experimental investigations to commercial adoption.

This paper presents an overview of the current status of earth tube design and installation and is organized as follows. First a short background on the world's drylands is presented with a discussion on the potential of expanding this technology specifically to dry regions. Secondly, important design parameters are introduced through a review of several analytical, numerical and experimental studies, followed by a discussion of practical considerations related to this technology. The paper then summarizes results from several

published demonstration projects, examines a few recent commercial installations, and concludes with a discussion of the potential of earth tubes to condition a school or community center size building in two different dry regions, Jaipur, India and Tashkent, Uzbekistan. We conclude that this low-tech low-energy technology can be a viable strategy for the improvement of health and life in dry and arid climates in remote rural settings, as well as a technology that can significantly decrease the energy demand to condition space in rapidly growing urban centers.

Drylands: Background and the Potential of Earth Tubes

Drylands cover about 40% of the Earth's land surface and occur in broad bands centered approximately over the 30° north and the 30° south latitude. At these latitudes large atmospheric air cells absorb moisture from the Earth's surface and fail to give up rain. Drylands cover over 53 million square kilometers, of which, 12% is characterized as arid, 45% as semi-arid and 25% as dry sub-humid (www.wri.org/publication/content/8236).

Drylands are inhabited by approximately 2.3 billion people worldwide with the majority living

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in semi-arid and dry sub-humid zones. Regionally, Asia has the largest population living in drylands, both in terms of numbers and per cent: over 1.4 billion people or 42% of the regions' population (www.wri.org/publication/content/8237). Africa has nearly the same per cent of people living in drylands, 41%, and South America has 30% of its people living in drylands.

Dobie (2001) estimates that approximately 900 million (39%) of the world's drylands population live in cities. Such significant population numbers challenge the heating, ventilating and air-conditioning (HVAC) community to examine sustainable solutions for building comfort. To ensure the overall vitality of drylands communities both urban and rural, alternative building management strategies must consider the needs of modern cities as well as traditional agriculturalists. Successful heating and cooling approaches must therefore be economically viable as well as environmentally safe and sustainable.

Twelve countries in the world are 90-100% dryland¹. The challenge for these countries will be to manage their resources in an equitable way to encourage prosperity in all sectors of their society. Drylands support mega cities (ex. New Delhi, Mexico City) as well as large numbers of people, pastoralists and farmers, whose livelihoods rely directly on the traditional rearing of livestock and the growing of agricultural products well adapted to low rainfall ecosystems (ex. Eritrea, Mali, India, Nigeria, Kenya, Cameroon). Space conditioning solutions must thus be adaptable to many different types of building structures in a wide range of communities.

Most of the world's dry regions occur in the subtropical belts associated with the hot low latitude deserts². These areas have a primary need for building cooling, but also require some seasonal heating. Cold high-latitude and cold high-altitude dry regions associated with the world's cold deserts³ experience both hot and bitter cold temperatures and require both building heating and cooling strategies. In addition, dry regions often have a large daily wide range in temperature because cloudless skies and low levels of moisture in the

air offer little barrier to incoming solar radiation during the day (heating up) and these same conditions allow significant nighttime re-radiation (cooling down).

The earth tube is a low energy system that can replace or lower the demands on conventional heating or cooling systems by exchanging heat with the subsurface ground. The stable-subsurface neutral zone found 5-400 m below the earth's surface has a constant temperature that is a phase-shifted and amplitude-damped representation of the mean ambient temperature. The temperature of the ground between the surface to the depth of the neutral zone experiences diurnal fluctuations (one cycle per day) within a meter of the surface and annual fluctuations (one cycle per year) penetrate deeper. The temperature level and depth of the surface variations is determined by meteorological influences, the thermal and hydraulic ground parameters, and by the nature of the ground surface land use. The temperature of the ground at a depth of about 4-5 m in sub-tropical regions is generally in the human comfort range (27-29°C) and for most of the cold dry regions, this ground temperature is lower (10-16°C).

Earth tubes or earth-air heat exchangers are long tubes buried in the near-stable region (1.5 m to 4 m). The difference between the temperature of the outside air and that of the ground results in a cooling or heating effect on the transported air depending on the time of the day or year. Earth tubes are effective at moderating large daily temperature amplitude swings (ex. hot days and cold nights), a condition often found in dryland regions. In addition, earth tubes provide a low-tech alternative for moderating significant seasonal temperature extremes. The potential for earth tube building air conditioning will be presented in the last section of this paper for two dryland areas, Jaipur, India, and Tashkent, Uzbekistan. Jaipur, India, is located in a hot low latitude subtropical region and Tashkent, Uzbekistan, is located in a cold high latitude region. Both locations have densely populated rural communities as well as growing urban centers.

- 1 Botswana, Burkina Faso, Turkmenistan, Iraq, Moldova, Uzbekistan, Kazakhstan, Armenia, Syria, Gambia, Senegal, Afghanistan, Tunisia, Kuwait, Morocco, Namibia, Iran (World Resources Institute (WRI)).
- 2 Listed from east to west: Simpson, Great Victoria, Gibson, Great Sandy, Thar, Arabian, Somali-Chalbi, Sahara, Kalahari, Monte, Chihuahuan, Sonoran, and Mojave.
- 3 Listed from east to west: Gobi, Takla Makan, Iranian, Turkestan, Namib, Patagonian, Atacama-Sechura, and the Great Basin.

An earth tube cannot be operated via free convection (due to the friction resistance of the air moving through the buried pipes) and requires the installation of a fan. Earth tubes can be coupled with conventional heating or cooling systems to reduce overall power requirements, or the system can be installed on its own to provide a low energy building conditioning approach. By utilizing decentralized electricity production (solar panels or small scale wind turbines and battery banks) they can also be used in remote locations. Earth-air heat exchangers are mostly free of objections from the ecological point of view. As long as the system components have been properly selected and routinely inspected, earth tubes are a low energy uncomplicated mechanical system that can address quality-of-life issues by moderating temperature extremes.

Fundamentals of Earth Tube Design and Installation

Design factors for earth tubes can be divided into free and fixed parameters. Fixed parameters are defined by location and purpose and cannot be changed, or changed to a minor extent. Location, weather, ground and backfill material, ground water content, and the building heating/cooling load are all examples of fixed parameters.

It is essential to know the ground parameters before design planning of an earth tube system. Soil thermal properties, such as thermal conductivity, specific heat capacity and thermal diffusivity, are associated with the transfer of heat through the soil. Thermal conductivity is important because it is a measure of the ground's ability to conduct heat. Thermal diffusivity describes the rate at which heat flows through the ground, a gauge of how fast the ground reacts to temperature changes, and the specific heat capacity is a measure of the amount of heat per unit mass required to change the temperature of the soil. These three properties are related to each other through the soils bulk density. Soil moisture variations have a measurable effect on thermal conductivity, thus in dry regions that have seasonal rains, the water content of the soil can change substantially depending on the time of year.

Free parameters are selectable by the design engineer. Flow rate, tube length, tube diameter, tube material, installation depth, and tube layout are all examples of free parameters. Many of these parameters are related to each other and computer simulation software codes have been written to

find the best balance between air speed, dwell time, pressure loss, the heat transfer area and the heat transfer coefficient. For example, a building may specify the required air exchanges per hour, which would influence the desired flow rate. Commonly available pipe diameters would then be considered that could deliver the required flow rate, however, the pipe diameter also influences the system pressure losses and the heat transfer, which would in turn influence the efficiency and the performance factors.

Several dynamic computer simulation programs that consider the transient nature of the surface conditions and predict the extent of the ground reaction and system performance have been developed and published in the literature. These approaches are based on various solutions to the non-steady multidimensional thermal conduction equation. In general, the numerical simulations coupled with experimental verifications have shown that earth-air heat exchangers dampen ambient fluctuations, and that long tube length, low velocities and large depths all contribute to desirable air temperature at the tube exit. This paper will not cover all the studies and papers written about earth tube design, installation or performance, but will rather summarize the results of academic research and discuss how these results have been modified into industry's best practices.

Tube and Ground Temperature Gradients

Kumar *et al.* (2003) presented a transient numerical model (validated with experimental measurements taken from dry regions in India), that included the ground temperature gradient, surface conditions, moisture content and design aspects of an earth-to-air tunnel. Their research recommends low airflows (1.2 kg s^{-1}), long tube lengths (80 m) and an optimal radius (0.52 m), where the heat transfer area is balanced by the heat transfer coefficient for the most favorable performance. Similar results were reported by Sharan (2008) and Sharan and Jadhav (2003) who also presented a mathematical model validated with experimental results and confirmed that increasing pipe length and reducing the air velocity would lead to system improvement.

One interesting result from Kumar *et al.* (2003) study reports that inlet soil temperature fluctuations decrease exponentially within 12 m from the entry point and the soil is not affected by fluctuations in inlet temperatures after 24 m. This data

corroborates that the tube/ground inlet transition region is important and cannot be neglected in the design of earth tube systems. Insights into the inlet zone of influence help establish appropriate effective lengths for sizing earth-air heat exchangers. The inlet ground/tube zone seems to be of a similar size as the well known thermal and hydrodynamic entrance regions from pipe flow theory.

Ground temperatures decrease or increase peripherally around this inlet section of the earth-air tube system depending if the air temperature is less than or greater than the subsurface temperature. If both heating and cooling operations are required the resultant heat loss/gain should be balanced without any permanent long-term temperature changes in the ground. The temperature field around an earth tube is limited locally and once the earth-air heat exchanger is shut down, the natural temperature of the field should be restored. At installation depths of 2 m or more it is assumed that the earth tube temperature field has no influence on the root zone, however, for installation depths of less than 2 m it is necessary to check if local heating or cooling activities have any effect on plant growth.

Baxter (1992, 1994) measured lateral and longitudinal gradients of soil and airflow temperatures for two years in the central region of the USA, to examine the inlet variations and the long term trends. Lateral temperature gradients were measured with the greatest thermal lateral gradient at the inlet and vertical portion of the earth tube as would be expected. He reported that longitudinal gradients existed throughout the entire length of his system and thus the heat transfer rates between the air and the soil, varied along the entire length of the tube. His longitudinal measurements during the heating season, however suggested that when ambient air temperatures fell below freezing, a freezing front of soil moisture occurred along the length of the tube. This latent heat exchange in the soil resulted in lower outlet air temperatures than expected. The length of the freezing front was measured up to one half of his 64 m earth tube. In his air cooling experiments he also noted that during periods of high humidity condensation occurred within the tube, indicating that the summer energy exchange in the air stream was both sensible and latent.

This secondary thermal condition, where very cold air entering the tube, can freeze soil moisture has important ramifications in temperate earth tube

installations. As a result, installations in zones with large ambient temperature fluctuations, that have temperatures below freezing, are usually more effective in the cooling mode and for design purposes the heating mode calculations are limited to the required length to achieve 0°C and not the undisturbed far field ground temperature. In these conditions, earth tubes do not deliver air temperatures in the human comfort zone; however, when coupled with conventional heating schemes this air pre-heating can offer significant energy savings.

An early parametric model was presented by Mihalakakou *et al.* (1995, 1996) which looked at tube length, tube radius, velocity of the air inside the tube, and depth of buried pipe. Interestingly, they performed a sensitivity analysis on the effect of the soil moisture on the system thermal performance and reported that changing the soil moisture level did not make a significant change in outlet air temperatures. Their investigation used multi-year ambient air and soil climatic measurements from Ireland, an area of constant moisture, as inputs to their model. In Savory's landmark text on land management, Savory (1999) introduced the idea of land brittleness and demonstrated that non-brittle (constant moisture) lands and brittle lands (characterized by a dry and rainy season) behaved very differently. Even though Savory's observations were based on surface ecosystems, it would be prudent for earth tube system designers to examine more thoroughly the effect of soil moisture on earth tube performance in brittle lands, before a conclusion that soil moisture is insignificant on system performance is made.

Tube Placement Considerations

Tube placement has been examined by several groups. Tube depth and tube arrangement impacts both the system installation costs as well as the system performance. Baxter (1992, 1994) recorded that at a depth of 1.8 m, the measured annual amplitudes in the undisturbed soil temperatures varied by over 11°C (from 19.9°C in late summer to 8.9°C in late winter). Sharan and Jadhav (2002) developed an analytical expression for temperature variation with depth, which predicted that at 3.0 m there were no diurnal fluctuations and the amplitude of the seasonal fluctuations reduced to about 4°C. They verified their results with measured ground temperatures in the Ahmedabad region, a subtropical dry region in north-west India. Kumar *et al.* (2007) also presented a mathematical model

to predict subsurface temperature profiles. Their equation predicted that all fluctuations in the ground temperature were negligible at a 4.0 m depth.

An interesting market assessment was presented by Hanby *et al.* (2005) who coupled a parametric model with an optimization study that minimized the external energy consumption of the whole system and the payback time. They considered the cost of tube installation including the excavation of a trench and backfilling as well as the annual maintenance costs. Their results showed that savings increase with depth of tube (to maximize cooling potential). Their model, based on conditions in Kuwait, which has an annual mean air temperature of 26°C, reported reasonable payback periods of about 7 years for a 57 m system buried at 5.5 m to offset conventional cooling technologies in Kuwait, where domestic air conditioning accounts for 75% of electrical power consumption.

Pipe layouts depend on the property size and topography. Grid, ring and serpentine layouts are possible. For small buildings one tube at a minimum distance from the building wall is usually laid around the structures perimeter. The ring is the simplest design and by using foundation excavation most cost effective. The serpentine is ideal for systems requiring a longer pipe length. For larger buildings the most common layout is a grid. Tube grids are laid horizontally with the spacing determined by the width of mutual influence and care must be taken to locate the inlet and outlet manifolds to ensure balanced flow through the branches. Several studies have discussed the design of multi-tube systems.

Vargas *et al.* (2005) introduced an optimization principle, which presents a non-dimensional tube length in a closed analytical form as a function of several dimensionless parameters (ex. dimensionless pumping power, heat transfer units, dimensionless flow rate). In their study they arranged the tubes in a horizontal layer bundle, so that any particular tube segment was neighboring two other tubes. Two features of the geometry were analyzed, the number of branches working in parallel and the length of one branch. They suggested that the most advantageous situation is reached when a large number of short tubes are used. This result is contrary to single tube studies and current industry practice. It was unclear why they chose to study a bundle arrangement, which does not seem to be particularly favorable for heat transfer; nonetheless, their

non-dimensionless variables provide alternative groupings that may provide additional insights.

Yoon *et al.* (2009) also discussed a design procedure for multiple pipes in a close arrangement taking into account thermal interference between the tubes and proposed an estimation method for multi-tube systems. In this study, multiple tubes were laid in a close arrangement and monitored for two years in a four story building in Japan. They present a correction factor for the decrease in heat transfer rate due to interference between tubes.

The design of earth tube multi-grid systems requires the use of a multi-dimensional simulation program. The annual mean ground surface temperature, the amplitude of the annual soil surface temperature variation and the phase constant of the soil surface are increasingly being calculated by utility programs in commercially available software. Appropriate meteorological data for a particular location is necessary to obtain both an annual view and a consideration of extreme situations.

Lee and Strand (2008) implemented the heat transfer and soil algorithms into EnergyPlus (http://apps1.eere.energy.gov/buildings/energy_plus/), a US Department of Energy managed set of energy calculations that can be used in whole building energy simulation programs. Their parametric numerical analysis examined the potential performance at four locations in the USA, two of which were in dry zones. They reported that pipe length, pipe depth and airflow rate were the primary variables in system performance and that tube radius was a secondary variable. They found that pipe length was different due to different soil conditions, but after 70 m the performance leveled off at the four locations that they considered. They also suggested a depth of 4 to 5.5 m at which the temperature fluctuations ceased. They concluded that for latitudes found in the USA, earth tubes are useful for cooling load reductions, and depending on the particular location, may have the capacity to replace conventional air conditioning. They also concluded that earth tubes can preheat fresh air in the heating mode, but do not deliver resultant air in the comfort zone and would thus need to be coupled with a heating system.

The Division of Building Physics and Solar Energy at the University of Siegen in Germany offers a reasonably priced, easy to use, downloadable

earth heat exchanger software package, Graphische Auslegung von ErdwärmeAustauschern (GAEA) that can be used by earth tube designers (<http://nesa1.uni-siegen.de/>). This calculation tool written and documented by Benkert *et al.* (1997), and Benkert and Heidt (1999, 2000), has been verified with large scale commercial projects in Europe and North America. The software can be used to examine different tube depths and layouts, for any given weather file. It is easy enough to use in an undergraduate course and sophisticated enough to use for professional design work.

Tube depth, length, radius and flow rate are not the only considerations in the design and installation of earth tube systems. Equally important are the environmental air safety issues, and the economic costs.

Air Purity Concerns

In Europe, transported air is regarded as a foodstuff and treated with corresponding care (VDI 4640, 2004). The outside air intake is equipped with an air filter and must be located at a height above the ground surface to avoid ground contamination and must be situated far from possible sources of contamination. The intake location height must also be adjusted in locations with elevated ground surface temperatures, which can occur in areas with high radiation absorption surface conditions like deserts. In North America, ASHRAE 62.2 provides further detailed guidance for the location, construction and filtration of outside air intakes. The intake column must be situated for convenient filter access. High efficiency filters can remove dust and allergens improving the buildings' air quality. The frequency of filter replacement depends on the airflow volume and the environmental conditions.

The pipe material which carries the air must be non-toxic and non-corroding, not attract dust, have a long service life, be non-hygroscopic and airtight, must not emit any hazardous substances, and must not provide a nutritive medium for micro-organisms. The interior walls should be smooth and allow for thorough cleaning. Metallic pipes would not normally be considered due to corrosion. Solid thick-walled pipes are selected with sufficient structural stiffness to withstand surface loads. Pipes with inadequate longitudinal rigidity are not recommended for ground-air heat exchange systems because they may sag and allow puddles

to form at low points. Polymer pipes such as plastic rigid polyvinyl chloride (PVC), polyethylene and polypropylene have all been used successfully as earth tubes. They are good for most applications up to 500 mm diameters. Polymer pipes have the capability for solvent connections, gasket connections and bolted flanges. The connection strategy would be selected based on price, availability and local concerns for radon intrusion. An anti-microbial treatment, such as an anti-microbial paint coating, is recommended. Concrete and fibrous concrete pipes are especially suitable for larger diameters and may be a better value than plastic pipes; however caution should be exercised as related to the porosity of the concrete and the concern for microbial growth. Fiberglass pipe/duct may be a good choice for cost, strength and smoothness. Material selection also needs to consider ease of assembly, the ability to allow for a flexible pipe layout and the availability of a wide range of fittings to meet the project parameters. Each earth tube installation is sized considering the building use and occupancy schedule.

For long term installations, the earth tube system must be designed in such a way that the entire earth-air exchanger can be inspected and cleaned. The frequency of inspection and cleaning is in accordance with local conditions to ensure hygienically safe operation. A visual inspection is often performed with a small camera. A disinfectant⁴ and water fill and flush technique are a low cost cleaning approach (VDI 4640, 2004), however cleaning agents must be disposed of properly to exclude any ground water contamination.

The entire earth-air heat exchanger system must incorporate a condensate collection strategy. If the air falls below the dew point temperature at the pipe walls, dehumidification of the air results and this moisture must be collected. Condensate collection can be easily achieved by installing the tubes at a slight downward gradient (1-2%) towards drainage at the system's lowest point. For European and North American building codes, the condensation water may be discharged into the building's waste water system via a sump pump. In arid regions of the world where condensation is less of a problem, a condensation trap draining into the ground may be permissible; however, condensation water in an earth-air heat exchanger is classed in the same way as surface water and is thus subject to local water legislation.

4 Hospital-grade quaternary disinfectant cleaner registered with the local environmental agency.

Other Practical Considerations

Backfilling the earth tubes requires the proper compaction of the soils in layers or stages. Proper compaction of the soil is important to ensure that the pipe is structurally supported and does not affect the condensate draining. Additionally, if the pipes are to be under a road or parking area, proper depth and compaction are essential for the pipe stiffness to withstand any surface loading. These subterranean loads/stresses dissipate rapidly, but must be considered. Backfilling material can be enriched by adding suitable materials to create the desired thermal properties, but adding building rubble or coarse material that can create voids would have a negative effect on the system performance and should be avoided.

At the end of its useful life, earth-air heat exchanger tubing would be cleaned, closed off and left permanently in the ground. Both cement and PVC are considered non-hazardous materials, but they are not biodegradable. The U.S. Green Building Council (USGBC) has issued a statement on the use of PVC for drains, waste and vent pipes (USGBC 2007) where they conclude that PVC is not the worst option from an environmental end-of-life perspective for pipes. The report states that in terms of end-of-life toxicity, burning PVC is much more hazardous to human health and the environment than leaving it in a landfill. PVC primarily harms human health through occupational exposure during its manufacture. If using PVC use is of concern, other alternatives could be considered, however there are no alternatives that are completely impact free.

It is not possible to control the humidity of the air leaving an earth-air heat exchanger. Precise humidity control would require an auxiliary system. The air outlet temperature flowing through the earth-air exchanger also cannot be regulated. It can be mixed with a controllable air supply or connected to a conventional heat or cooling system for precise controls. Using outside air directly is desirable in off-season situations where only air exchange is required and the ambient air itself does not need any further conditioning.

Earth Tube Economic Factors

Total costs include the capital, installation, operation, maintenance and end of life expenses. Capital costs are determined by the excavation and material costs. Installation costs include setting up the site, the ground excavation, the delivery and placement of the tubes, and backfilling. It

is most economical to install the system as part of the normal construction process that would utilize the available technical equipment. Operational costs consist of the electrical energy costs for driving the mechanical ventilation system. Maintenance costs take account of filter replacement and the working time for cleaning the system. A forty-year service life can usually be set for concrete or plastic tubes.

In general, the installation and operation of earth-air heat exchangers only makes sense when the benefits are greater than the costs. However, the value proposition is more nuanced than strictly adding up the material, installation and operational costs and comparing that to heating and cooling in some other fashion. For instance, in rural areas the value in increased human health and comfort or in increased agricultural yields must be considered. In urban areas where there is a culture or commitment to renewable energy or carbon reductions, there is a non-monetary value to implementing low energy strategies. A triple bottom line approach which examines the benefits to people and the planet captures an expanded spectrum of values and criteria for evaluating these systems.

Another important consideration is the proper selection of a high efficiency fan to draw the ventilation air through the pipes. Because the pipes are of relatively large diameter with slow airflow rates, the resulting pressure drop is not large. Therefore the fan wattage input energy can be very small compared to the energy harvested from the earth yielding favorable coefficients of performance. In addition, seasonal and annual performance factors that examine the cumulative output over the operating period provide realistic evaluation criteria.

Installation Examples from the Literature

Several full scale demonstration projects have been published in the literature. Sawhney *et al.* (1999) reported the performance of an earth-air heat exchanger tube in the cooling of an eight-room guesthouse during the hot season in North-west India. The results showed a strong damping of the ambient extremes of 24-42°C and the resultant average temperature and relative humidity (28°C and 52% RH) was near the human comfort zone.

Also in an arid area of North-west India, Sharan *et al.* (2001) reported the results of the environmental control of a zoo dwelling. The earth tube buried

at a 2 m depth cooled the ambient air about 8°C in summer and warmed the ambient about 10°C in winter. The authors speculated that it may be a useful technology for dairy cattle, animal husbandry and other farm buildings. In a later study Sharan (2008) concluded that earth-air heat exchangers are capable of meeting the heating requirements and some of the cooling requirements in subtropical drylands. Dhia (1995) reported using an earth-tube buried at 2.5 m in Iraq for conditioning air in a poultry house and Sodha *et al.* (1985) used an earth tube system to condition a hospital complex.

Other rural applications include a growing-finishing swine building in Canada, which was ventilated with an earth tube (Lemay *et al.*, 1994; Lemay and Marquis, 1995). When the ambient temperatures fell below freezing, the earth tube was only able to heat the air slightly above freezing, suggesting that a freezing zone was forming in the ground. Their results and those of Millette and Galanis (1995) concluded that heating through an earth tube system would not be sufficient for the climatic conditions in Quebec.

A recent economic analysis was presented by Chel and Tiwar (2010) who examined the integration of an earth tube and a standalone photovoltaic (PV) system for space heating/cooling of an adobe house in New Delhi. They calculated the energy payback time and unit cost of electricity for two different PV systems. Their key point was to examine designs suitable for areas where a decentralized PV power source can compete with conventional diesel fired generators. Their system generated sufficient electricity to meet the power requirements of the research adobe home and the temperature data at the tube exit was stable, reliable and comfortable. A thorough life cycle cost analysis including the capital costs (including the procurement of the land, the materials and the installation costs), cost for the electricity with different capital investments at different interest rates, plus a discussion on the mitigation of CO₂ emissions and the corresponding carbon credit potential of the system during its lifespan and the total annual energy conserved as compared with conventional system was presented. Their three-year demonstration study concluded that the earth air heat exchanger is economical as well as an environment-friendly option for thermal comfort for areas where grid extensions are difficult. With an energy payback time calculated to be 9-11 years depending on the PV system, the earth

tube PV combination may also be viable for rapidly growing urban suburbs.

Commercial Installations of Earth Tubes

In the US and Europe earth tube installations are becoming important contributors to new energy efficiency building baselines. In the US, the 2010 Energy Standard for Buildings Except Low-Rise Residential Buildings (<http://www.ashrae.org/education/page/1834>) has raised the overall minimum efficiency for light commercial buildings by 30%. An earth tube installation can provide up to 50% of the renewable requirement. Earth tubes, classified as energy use from an 'on-site renewable' can be used for new building labeling programs that can educate the general public, building owners and tenants on the potential and actual energy use of buildings. In addition, international energy conservation codes and standards such as the International Green Construction Code (<http://www.iccsafe.org/cs/igcc/pages/default.aspx>) released in 2009, and the 2012 International Energy Conservation Code (http://reca-codes.org/pages/current_code.html) which will specify a 30% energy reduction from 2006 levels, are being adopted globally.

Earth tubes can play a significant part of the Architecture 2030 pledge for buildings to be carbon neutral by 2030 (<http://www.architecture2030.org/>). The first certified Passivhaus in North America (an ultra low energy building) is the Biohaus Environmental Living Center in Bemidji, Minnesota. The structure uses 85% less energy than a comparable US structure. The summer temperatures in Minnesota are hot and humid, and the winter temperatures are very cold. The earth tube system provides all the system cooling in the summer, and in the winter preheats the air from -29°C to -4°C. Figures 1 and 2 show the grid pipe layout and the air inlet tower for this installation.

There have been multiple successful installations for schools and community centers in the UK with flow rates between 700-36,000 m³ h⁻¹. Figure 3 shows an example 700 m³ h⁻¹ flow rate grid layout for the Nairn Academy in Scotland.

Finally, an increasing number of small installations with low flow rates (174 m³ h⁻¹) have been designed and installed. Figure 4 shows a serpentine installation for a house at the University of Nottingham in the UK.

REFERENCE PROJECTS

BIOHAUS ENVIRONMENTAL LIVING CENTER IN BEMIDJI, MN

PROJECT DESCRIPTION

First ever certified Passivhaus in North America:

- Uses 85% less energy than comparable U.S. structures
- In summer, system works as air conditioner, for example, cooling an ambient temperature of 85°F (29°C) to an output temperature of 67°F (19°C)
- In winter, an ambient temperature of -20°F (-29°C) is pre-warmed to an output temperature of 25°F (-4°C)



Grid Pipe Layout

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Air Inlet Tower

Fig. 1. Grid pipe layout for Environmental Center in Minnesota

Fig. 2. Air inlet tower near Environmental Center in Minnesota

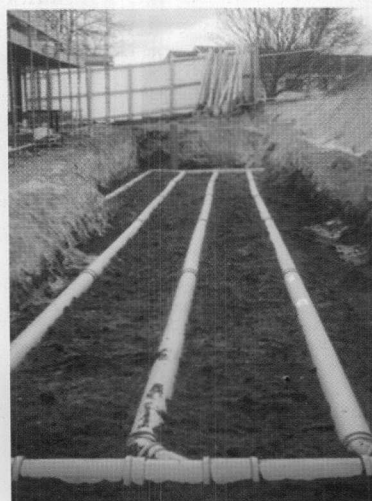
The next steps will need an assessment of customer perceptions of the systems and an advocacy campaign to achieve more widespread acceptance. There will also be a need for more professionals to design and install the systems and adapt them to local situations around the

globe. Many of the aforementioned installations have been designed using the GAEE software available from the Group for Building Physics & Solar Energy in the Department of Physics at the University of Siegen. In the following section of this paper, the GAEE software is used to examine

GROUND-AIR HEAT EXCHANGER

Nairn Academy, Scotland

- Flow rate: 700 m³/h (400 CFM)
- Header pipe DN 250
- 3 x 30m AWADUKT Thermo runs of DN 200
- Extension to existing school



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Fig. 3. Earth tube grid layout for school in Scotland.

CASE STUDIES

GROUND-AIR HEAT EXCHANGER

BASF House, University of Nottingham

- Air flow rate = $174 \text{ m}^3/\text{h}$
- AWADUKT Thermo 200/250 OD
- 34m of 200 OD in meander pattern
- 1 air inlet – 2 air outlets



Fig. 4. Serpentine installation for a small building.

the potential for earth tubes in two dry regions, one in the hot dry subtropical latitudes, and one in a cold dry high latitude area.

Earth Tube Examples in Dry Regions

In the following examples for both Jaipur, India, and Tashkent, Uzbekistan, the assumed building is a small rural clinic, school house or community meeting room. The assumed building size is roughly $33 \times 33 \text{ m}$ and 3 m tall. This yields a building volume of $3,398 \text{ m}^3$. The actual ventilation rate determination needs to consider a number of factors such as building use and occupancy; however a ventilation rate of 0.3 air changes per hour is reasonable. For this assumed building volume, this translates to an air flow rate of $1019 \text{ m}^3 \text{ h}^{-1}$.

Considering the need for relatively slow air velocities in order to maximize the time in which

the air is in contact with the earth, three pipes with a diameter of 200 mm and a length of approximately 60 m were selected yielding per pipe an air velocity of approximately 3.0 m sec^{-1} . Figure 5 shows a realistic pipe grid layout. The pipes are assumed to be municipal water and sewer PVC pipes that have been treated with an antimicrobial coating.

The pipes would be laid at a 2% condensate slope. A pipe depth of 2 m was chosen to minimize the excavation costs while obtaining sufficient depth to harvest the geothermal energy. A deeper trench would yield better thermal results, but at increased excavation costs. The pipe depth suggested in some of the academic studies mentioned earlier in this paper of 4.0 to 5.5 m is rarely used in practice. An excavation trench of 5 m would have serious safety issues and the

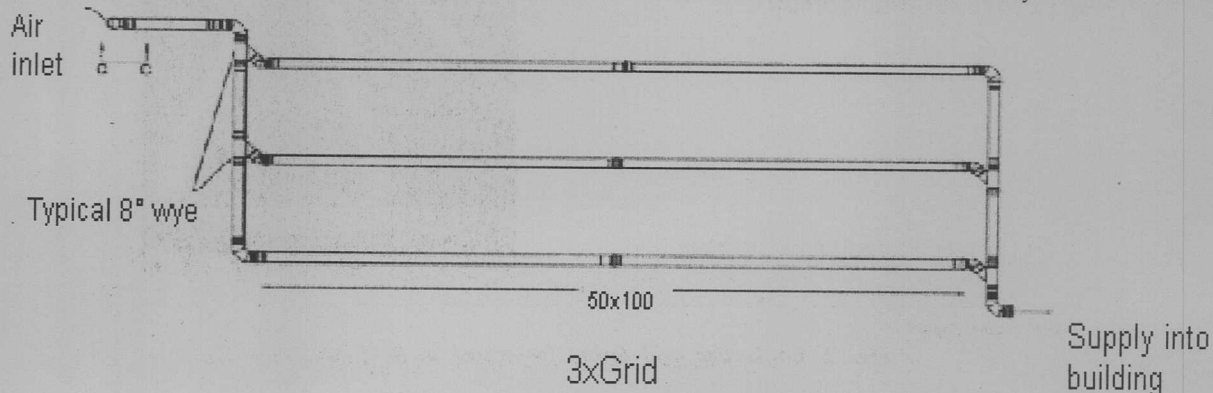


Fig. 5. Three pipe grid layout.

Table 1. Summary earth tube data

Number of pipes:	3
Length of pipes:	60.97 m
Pipe diameter:	202 mm
Depth of pipes:	2 m
Distance between pipes:	1 m
Distance to building:	20 m
Type of soil:	Loamy
Density:	1800 kg m ⁻³
Heat capacity:	1.34 kJ/(kg-K)
Thermal conductivity:	1.49 W/(m-K)
Ventilation flow:	1019 m ³ h ⁻¹
Individual tube air velocity:	3.0 m sec ⁻¹
System operation:	Continuous
Total pressure drop in pipe:	93 Pa
Estimated fan wattage:	65 Watt

increase in thermal performance usually would not warrant the additional cost or risk. The soil parameters, density, heat capacity and thermal conductivity were selected for loamy soil. Dry sandy soils would perform slightly less favorably. Table 1 presents a summary of the selected design parameters.

Using the GAEA software and the weather files for Jaipur, India and Tashkent, Uzbekistan,

from the US Department of Energy⁵ the predicted thermal outputs are presented in Table 2.

The results show that both locations would have significant potential for earth tube cooling, 7339 kWh yr⁻¹ and 7103 kWh yr⁻¹ in Jaipur and Tashkent, respectively. However, the heating gains are much greater in the Uzbekistan location, 7463 kWh yr⁻¹, as compared to 2717 kWh yr⁻¹ in the north-west India location. This is due to the larger range of yearly ambient temperatures. Note that the hottest hour of the year is similar in the two locations, 42.9 and 40.1°C, but the coldest hour of the year is quite different, 3.7 and -11.0°C. Also note that the below zero temperatures in the Uzbekistan example may cause a freezing zone in the soil. Nonetheless, pre-conditioning the air to slightly above freezing temperatures would reduce conventional heating significantly.

Plotting the hourly ambient air temperatures with the predicted earth tube outlet temperatures over a yearly cycle is shown graphically in Figure 6 for Jaipur, India, and Figure 7 for Tashkent, Uzbekistan. For both locations the earth tube system moderates both daily and seasonal extremes.

When designing an earth tube system, it is important to look at the heating and cooling phenomenon of the air moving through the earth tubes. Figure 8 plots the temperature variation

Table 2. Predicted outputs for Jaipur, India and Tashkent, Uzbekistan

Project Output Data: Jaipur, India	
Heat gains	2717.7 kWh yr ⁻¹
Heat loss	7339.0 kWh yr ⁻¹
Total energy supplied/offset	10056.7 kWh yr ⁻¹
Ambient air on hottest hour of year	42.9°C
Earth Tube supply on hottest hour of year	32.1°C
Ambient air on coldest hour of year	3.7°C
Earth Tube supply on coldest hour of year	13.3°C
Project Output Data: Tashkent, Uzbekistan	
Heat gains	7463.5 kWh yr ⁻¹
Heat loss	7103.8 kWh yr ⁻¹
Total energy supplied/offset	14567.3 kWh yr ⁻¹
Ambient air on hottest hour of year	40.1°C
Earth Tube supply on hottest hour of year	27.0°C
Ambient air on coldest hour of year	-11.0°C
Earth Tube supply on coldest hour of year	1.8°C

5 http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=IND/cname=India

http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=UZB/cname=Uzbekistan

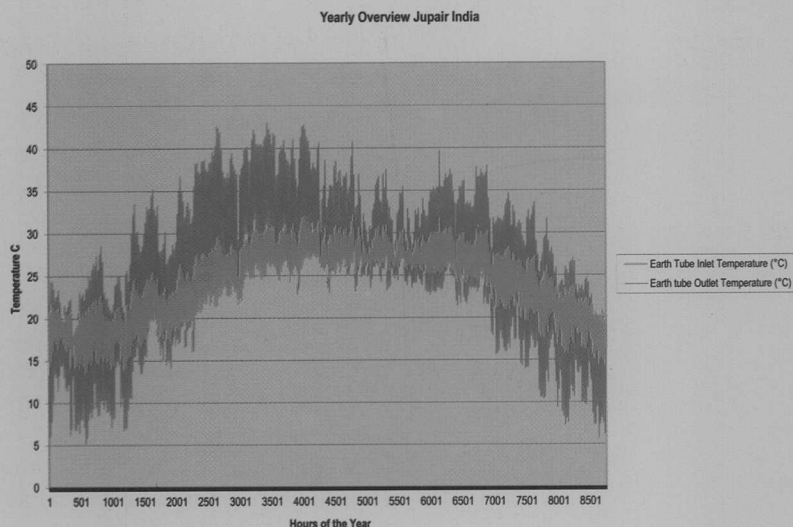


Fig. 6. Jaipur, India, yearly overview.

as the air proceeds down the 60 m pipe length for one typical cooling and one typical heating case from the Jaipur, India. The plot demonstrates how the rate of heat transfer decreases along the length of the tube. Lengthening the tube will cause the air temperature in the tube to approach the soil temperature at the tube wall, but at a decreased rate. These visual plots can assist the designer in optimizing the pipe length. Also note that the far field soil temperature at the prescribed depth is noticeably different than the predicted temperature at the pipe wall.

Another interesting way to look at the output data is to average the hourly changes in ambient air and delivery temperatures as presented in Figure 9. This plot provides a good illustration of the temperature relationships over the year and indicates the energy harvesting potential between the ambient air and the earth. For Jaipur, India, the season of cooling is significantly more pronounced than the winter heating capability. Also, for this particular location and climate the overall yearly ambient air temperature is a bit unusual in that it is not a defined sinusoidal shape.

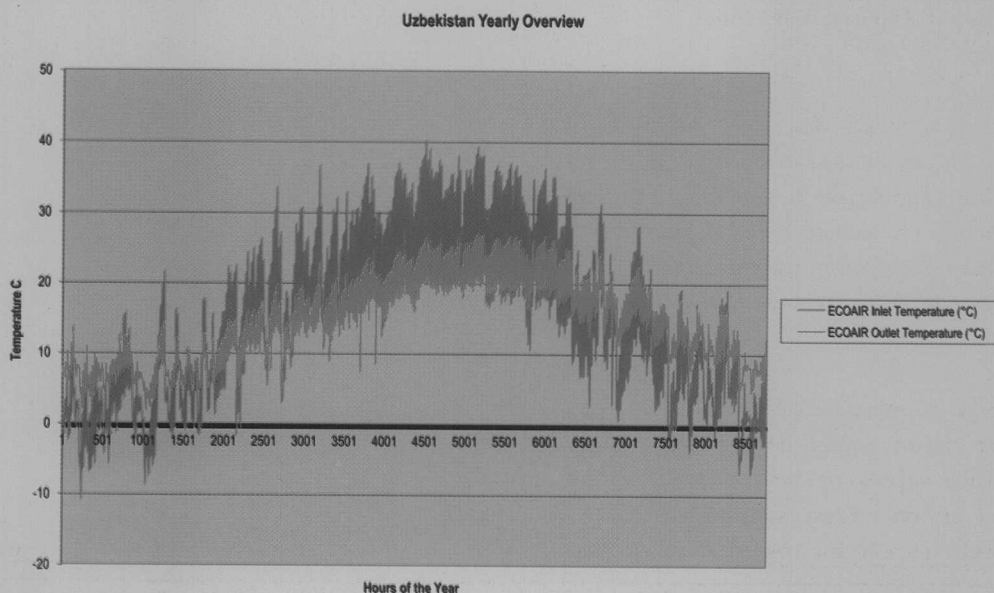


Fig. 7. Tashkent, Uzbekistan, yearly overview.

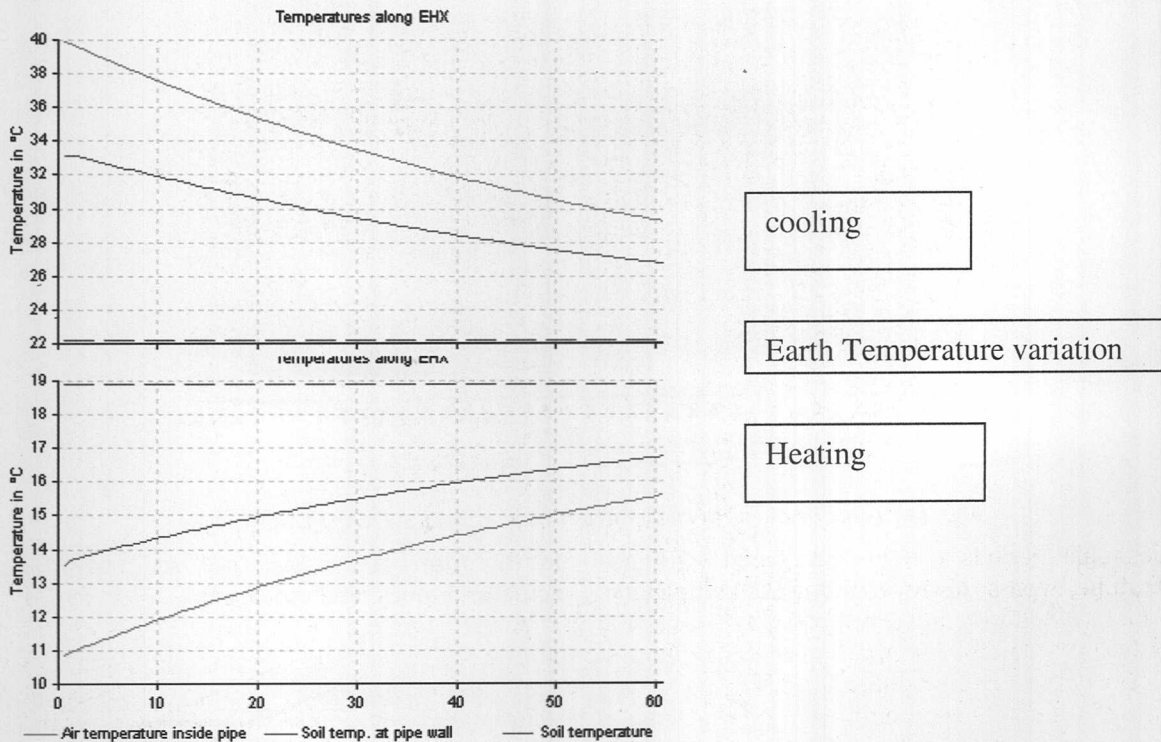


Fig. 8. Heat transfer trends for Jaipur, India.

Note that for the months of September and October (highlighted with the shaded oval) the average ambient air and sub-earth temperatures are nearly identical and as a result there is reduced opportunity for energy harvesting. However, an in depth look at the data points for October presented in Figure 10, indicate that there is still cooling opportunities during the peak heat hours

of the day. In hours of the day when there is not a dramatic difference between the ambient air and the soil temperature, there may occur undesirable heating or cooling. For this situation, an earth tube installation should have the option to use the ambient air directly because it is at the desired comfort level. With the addition of air and ground temperature sensors, these

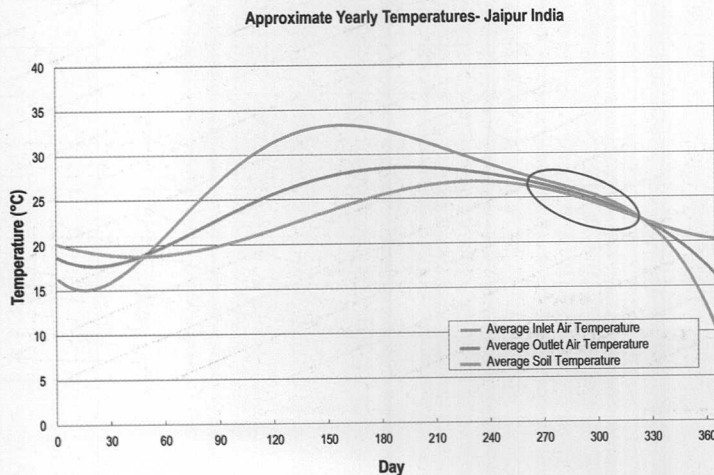


Fig. 9. Averaged temperature for Jaipur, India.

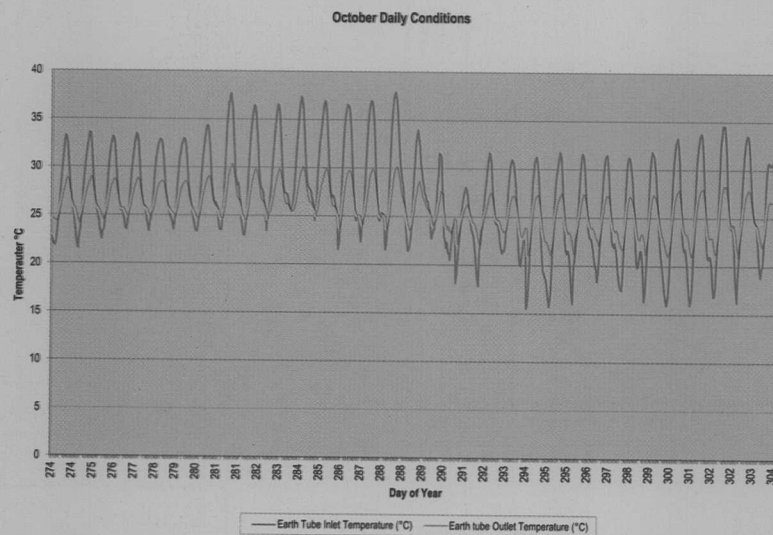


Fig. 10. Temperature moderation in a month of reduced energy harvesting.

undesirable periods can be eliminated with an earth tube bypass; however this adds complexity

in the form of sensors, 24V AC transformers, actuator valves and so forth.

PSYCHROMETRIC CHART

Normal Temperature
SI Units

82 METERS

BAROMETRIC PRESSURE 100.344 kPa

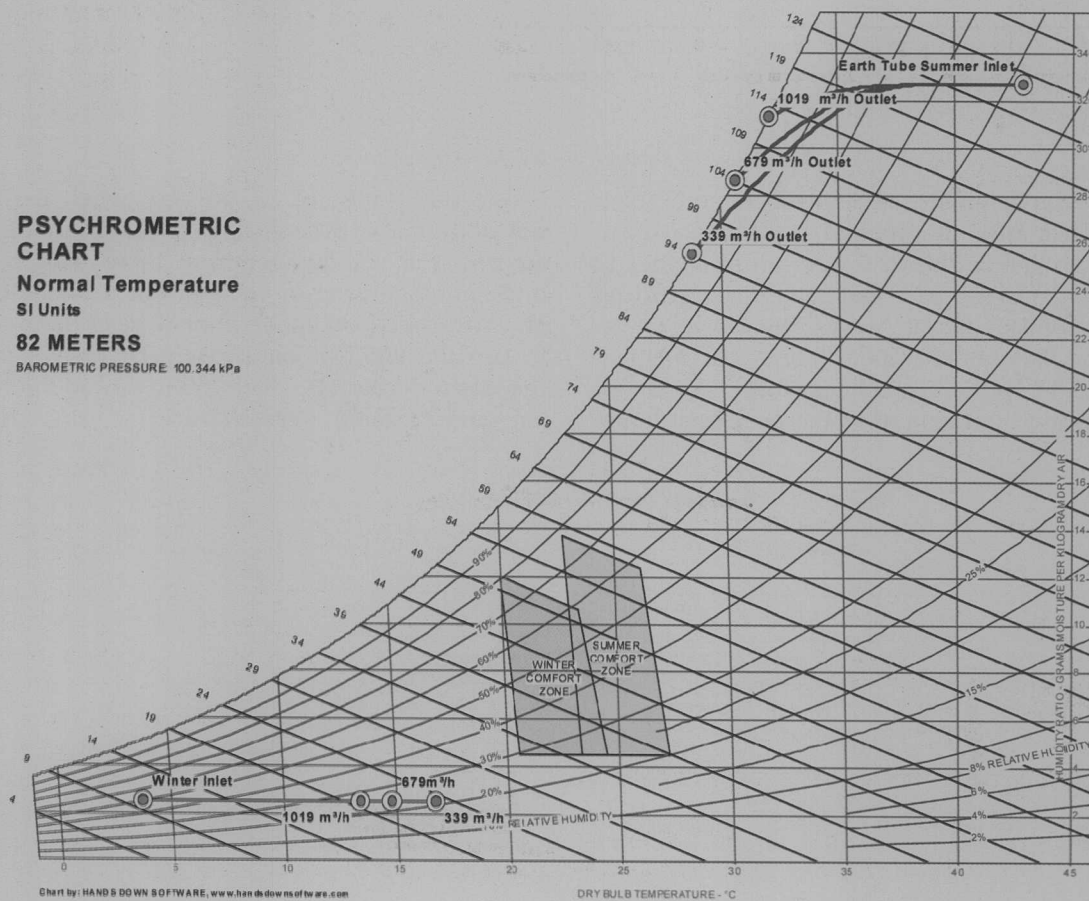


Fig. 11. Psychrometric chart for maximum and minimum conditions in Jaipur, India.

Table 3. Condensate requirements for a hot and humid day in Jaipur, India

Air flow rate	Cooling energy provided	Dehumidification (assuming 55% RH ambient air)
1019 m ³ h ⁻¹	6.154 kWh	3.2 kg h ⁻¹
679 m ³ h ⁻¹	6.027 kWh	4.3 kg h ⁻¹
339 m ³ h ⁻¹	4.109 kWh	3.4 kg h ⁻¹

In order to gain a better understanding of the capabilities of this earth tube design for this location, the predicted capabilities are shown on a psychrometric diagram in Figure 11. The operating points shown are taken on the hottest and coldest hours of the year. In this example, the GAEA software was re-calculated at two additional air flow rates, 679 and 339 m³ h⁻¹. It is assumed that the system may operate in a "demand ventilation" mode. Specifically, the ventilation rate may be altered by a variable speed fan that is operating either manually or via sensors based on building schedule, occupancy sensors and CO₂ sensors. On the hottest hour of the year, as per the weather file, the ambient air temperature is 42.9°C. Looking over the possible humidity values that could occur in this region during the hot season, a relative humidity value of 55%⁶ was assumed to investigate the need for a condensate strategy. The earth tubes cool the air to a delivered temperature of 32.1°C, and under these

Table 4. Maximum Heating Potential at Different Flow Rates for Jaipur, India

Air flow rate	Maximum heating energy provided
1019 m ³ h ⁻¹	3.3 kWh
679 m ³ h ⁻¹	3.8 kWh
339 m ³ h ⁻¹	4.5 kWh

circumstances, the air moving along the pipe reaches dew point. This air in contact with the pipe walls will begin to dehumidify; latent energy removal is now occurring. Per the psychrometric analysis the process behaves similar to passing air over a cooling coil. At the various mass flow rates indicated, water removal in the range of 4 kg h⁻¹ occurs. Table 3 presents the cooling capability and water removal at the calculated flow rates. This calculated dehumidification illustrates the need for pipe installation along a

slope and helps the designer size a condensate removal strategy.

It is interesting to note that even for a dry region, the cooling operation is both sensible plus latent.

Looking at the heating potential for this example, the data suggests that the earth tube is heating the air in a "sensible heating" mode only with no humidification. Table 4 presents the maximum heating potential for the coldest hour of the year from the weather file for Jaipur, India. A higher maximum heating output is achieved at lower air flow rates because of the greater temperature change achieved in the earth tube as a result of slower mass flow rates of the air and therefore longer residence time for the air in the earth tube.

Final Thoughts

The idea of earth tubes or earth-to-air heat exchange is not new. Enough research has been done to show that these systems can be combined with regional building construction practices to provide non-conventional strategies to cool or heat building. Earth tubes improve the comfort of occupants by moderating temperature extremes. The technology presents an opportunity to engineer building ventilation, usually a significant part of a buildings energy footprint, in the most energy efficient manner. The technology has been used successfully in Europe and North America for a variety of building sizes. The authors believe that this technology could be easily adapted to many dryland regions, both urban and rural.

Adoption of earth tubes in rural areas where electricity may not exist, is potentially a method of improving human life and health conditions. Coupling low energy earth tubes with a decentralized power system could be a transformative technology. Polymer pipes or some other suitable pipe as previously discussed can be utilized. Appropriate caution, however must be taken to add a suitable antimicrobial coating to ensure cleanliness. Such a low-tech approach to the improvement of human welfare should be supported by both governmental and non-governmental organizations. International human health and aid programs could prepare the necessary technical instruction and installation details for the desired locations. Locally, village leaders could coordinate the manpower for installation.

6 http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=UZB/cname=Uzbekistan

Summary

One low energy alternative for conditioning building space is to pass ambient air through earth tubes, which are long buried tubes also known as, earth-to-air heat exchangers, through the relatively stable environment of the subsurface before being delivered and/or circulated through living space. The difference between the temperature of the outside air and that of the ground results in a cooling or heating effect on the transported air depending on the time of the day and/or year. In the past few decades the use of earth tubes has evolved from preliminary numerical, analytical and experimental investigations to commercial adoption.

This paper presented an overview of the current status of earth tube design and installation. Important design parameters were introduced through a review of several analytical, numerical and experimental studies, followed by a discussion of practical considerations related to this technology. The paper then summarized results from several published demonstration projects, examined a few recent commercial installations, and concluded with a discussion of the potential of earth tubes to condition a school or community center size building in two different dry regions, Jaipur, India and Tashkent, Uzbekistan. The authors conclude that this low-tech low-energy technology can be a viable strategy for the improvement of health and life in dry and arid climates in remote rural settings, as well as a technology that can significantly decrease the energy demand to condition space in rapidly growing urban centers.

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