Bibliographic Search on the Potential of Earth Tubes

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1 Introduction

Earth tubes are long metallic, plastic or concrete pipes that are laid underground and are connected to the air intake of buildings, particularly houses. Their purpose is to provide some pre-conditioning of the air – either pre-heating in the winter or pre-cooling in the summer. These systems received some attention in the late 70s and early 80s but they did not end up enjoying wide acceptance, either because of lack of performance or because of other associated problems such as poor air quality (mold and bacterial growth in the tubes).
The current push towards a wider use of green technologies has generated a resurgence of interest in the concept of earth tubes. The aim of this document is to review the current state of the art regarding earth tubes, using a literature search in scientific journals and the Internet.

For the reader in a hurry, Section 3.2 provides a short list of a few significant publications particularly worth reading.

2 Earth tubes

2.1 Terminology

Various technical terms are used to refer to earth tubes:

- Earth tubes
- Buried pipes
- Earth channels
- Air-to-soil heat exchanger
- Underground air pipe
- Earth-to-air heat exchanger (EAHX)
- Subsoil heat exchanger
- Earth-air tunnel system
- Ground tube heat exchanger
- Hypocaust (Hollmuller and Lachal, 2001)
- Ground coupled heat exchanger

These terms all refer to the same kind of device: a pipe or series of pipes buried underground, and through which ventilation air is circulated. ‘Earth-to-air heat exchanger’ is probably the most technically accurate terminology, although ‘earth tubes’ also enjoys wide use.

The systems can either be ‘closed-loop’ (i.e. recirculating the air from the building through the earth tubes), or ‘open-loop’ (i.e. drawing outside air through the pipes to ventilate the house). The first kind seems to have fallen out of favour, probably because it is insufficient to provide heating to the building by itself, and because it does not help meet the building’s fresh air requirements.

2.2 Design considerations

Design parameters that are well documented in the literature are:

1. Tube material

   This is actually of little importance from a thermal point of view, as the conductivity of the soil surrounding the pipe is the limiting factor. PVC or concrete have been used. The material has to be strong enough to withstand crushing when the pipe is buried. Corrugation (as in corrugated PVC) gives a stronger structural strength but should be avoided as it traps water in the pipes. The pipes should not be perforated so that water does not seep through.

2. Length

   Length can typically range from 10 to 100 m. Longer tubes correspond to more effective systems, but the required fan power and the cost also increase.

3. Diameter

   Smaller diameters are preferred from a thermal point of view, but they also correspond (at equal flowrate) to higher friction losses, so it becomes a balance between increasing heat transfer and lowering fan power. Typical diameters are 10 cm to 30 cm but can be as large as 1 m for commercial buildings.

4. Spacing

   Spacing should be large enough that tubes are thermally independent, typically at least 1 m apart. Tubes can also be placed in a radial pattern.

5. Number of tubes

   The number of tubes is dictated by air flow requirements, the length of the tubes and the required thermal performance.

6. Soil type

   Wet soil is preferable to dry soil because of better thermal conductivity; peat and dry sand should be avoided. Some authors suggest surrounding the pipes with compacted clay to ensure good thermal contact between the pipes and the earth.

7. Depth

   Deeper positioning of the tubes ensures better performance. Typical depths are 1.5 to 3 m. The tubes can be positioned under the building or in the ground outside the building foundation.

8. Flow rate

   Lower flow rates are beneficial to achieve higher or lower temperatures, and also because they correspond to lower fan power. However, a compromise has to be made between pipe diameter, desired thermal performance, and flow rate.

9. Controls

   The system should be bypassed when the outside temperature is typically between 15 and 22 °C (one can also take the earth temperature into account to decide when to turn the system off). Windows need to be closed for the system to contribute properly to the heating or air conditioning of the building.

2.3 Economics

The economics of earth tubes are controversial. The economics are reported to be positive for cooling applications, because in some climates earth tubes enable the user to dispense with a dedicated air-conditioning system. The economics are not as good for heating applications because earth tubes by themselves are not sufficient to significantly heat a building and therefore a heating system is still required. In other words, the small heating gain does not justify the additional cost of the earth tubes. However, if earth tubes are used for cooling in the summer, an added benefit is to use them for preheating ventilation air in the winter, either directly or by preheating the inlet air of a heat recovery ventilator (HRV).

2.4 Potential problems

The main problem that is mentioned in the literature is moisture control, either because of condensation or because of water seepage. Moisture may lead to mold and bacteria growth, although the problem is not reported in recent installations. The problems can be mitigated by:

- carefully laying out the pipes with a 2-3% slope so that any water condensation or water seepage collects at the lowest point, from which it can be pumped out;
- using intake filters to prevent the entry of spores, insects, etc into the system;
- providing access to the pipes for easy cleaning;
- using an anti-microbial coating on the pipes.

Another potential problem is radon seepage from the soil. Care is required, particularly during planning and installation, so that no radon penetrates the house through the earth tube system.

2.5 Climate

Many earth tube systems are designed for cooling, either in Western Europe (Germany, Switzerland) or in warmer places such as India, particularly for greenhouse applications. Earth tube systems are reported to be gaining acceptance in some Northern European countries, particularly Sweden and Finland, although little documentation was found to support that claim.

2.6 Actual system performance

System performance is often not well documented. In the particular case of simulation or design tools, validation of the models with data collected over significant periods (e.g., at least a year) is generally lacking. Even when monitoring data is provided, studies are often incomplete. For example some papers report that lower temperatures are achieved if the airflow is reduced, but that doesn't address the issues of how much *energy* can be displaced. Similarly, many papers do not provide a comprehensive summary of the energy required to move the air through the pipes. Long-term thermal imbalance in the soil around the pipes is rarely addressed.

Earth tubes clearly dampen significantly the diurnal temperature cycle. Some of the papers with monitoring results report that earth tubes can provide between 30% and 100% of cooling needs, and only a small fraction of heating needs. In heating mode, they also report that earth tubes help prevent freezing on the intake of heat recovery ventilators. Coefficients of Performance (COPs) around 30 are often reported; they are calculated by dividing the energy transfer from the earth tubes by the *incremental* fan power required to push the air through them (that is: a fan would be required to ventilate the house anyway; the power required to do so is not taken into account. What is taken into account is the *extra* fan power required because of the earth tubes).

2.7 Commercial products

At least one company provides a piping system specifically designed for earth tubes, although it is not clear whether that product is distributed in Canada. The company is Rehau and the product is called Awadukt Thermo. More information is available at:
http://www.rehau.co.uk/building.solutions/civil.engineering/ground.heat...geothermal.energy/awadukt.thermo.shtml
The product seems well designed with attention to such details as the use of filters on the air intake and the use of an anti-microbial pipe inner layer.

2.8 Design tools

A number of computer modeling tools are commercially available or can be downloaded for free. The TRNSYS model by Hollmuller and Lachal seems reasonably well developed. Tools developed for International Energy Agency (IEA) Annex 28 may also be useful. Apparently Rehau also proposes a design tool for their products.

3 Bibliographic search

3.1 Overview

The bibliographic search was conducted using a number of sources, including scientific journals, Internet, and personal contacts. The search could be somewhat endless and has been limited by the number of hours available. Over 40 publications have been read; a commented list can be found in section 3.3. Not all papers deserve extended attention, though: a list of recommended reading can be found in section 3.2, and readers with limited time available can restrict themselves to that list to learn the essentials of earth tube systems.

3.2 Recommended reading

The following publications are recommended:

- IEA Annex 28 (2001b). The focus of this document is mostly cooling, but it also provides a good introduction to the construction, design, and use of earth tubes.
- IEA Annex 28 (2001d). This document provides a real example of the use of earth tubes.
- Rehau (2007a). This is a commercially available earth tube system.
- Midwest Plan Service (1990). This document provides useful information for the design of earth tube systems, although in an agricultural context.
- Hollmuller P (2003). This is a short presentation about the potential of earth tubes. An extended version of this can be found in Hollmuller and Lachal (2001).
- IEA (2003). Although this publication lacks specifics as to the performance of the system, it presents an interesting application of earth tubes for the pre-heating and cooling of a house.

3.3 Annotated Bibliography (in alphabetical order)

With the exception of two marked with (*), all the publications listed here are available in PDF format in the companion CD-ROM.

1. Abrams DW (1986) *Low-Energy Cooling – a guide to the practical application of passive cooling and cooling energy conservation measures*. Van Nostrand Reinhold Company Inc., NY, ISBN 0-442-20951-7.

   Chapter 13, *Earth Cooling*, features a section on earth-cooling tubes. This chapter is an interesting introduction to earth tubes but is somewhat dated.

2. AdvancedBuildings.org (2007) Underground air supply. Available from http://www.advancedbuildings.org/main_t_vent_underground.htm

   The document provides a short, two-page introduction to earth tubes, with a couple of interesting pictures of a piping installation and an air intake.

3. Al-Ajmi F, Loveday DL and Hanby VI (2006) The cooling potential of earth-air heat exchangers for domestic buildings in a desert climate. Building and Environment 41, 23-244.

The paper presents a numerical study of earth tubes, with limited validation. Application to a desert climate (a house in Kuwait) is discussed and a reduction of 30% of the cooling load is deemed achievable with earth tubes.

4. Argiriou A, Lykoudis S, Balaras C and Asimakopoulos D (2004) Experimental study of a earth-to-air heat exchanger coupled to a photovoltaic system. Trans ASME, 128, 620-625.

   The authors study a system coupling an earth-to-air heat exchanger with a photovoltaic system, to make use of the good match between cooling needs and availability of solar radiation (used to generate photovoltaic electricity to power the fan). Measured average temperature drop between inlet and outlet of the heat exchanger ranges from 1.4°C in September to 4.7°C in June, during which it can reach values as high as 9.8°C. The authors observe that the system performance is maintained throughout the season, despite the fact that ground temperature increases by about 10°C in the vicinity of the tubes during that period. The authors also report a COP of 12 for the system.

5. Bojic M, Papadakis G and Kyristis S (1999) Energy from a two-pipe, earth-to-air heat exchanger. Energy 24, 519-523.

   This is a weak paper from which not much can be concluded.

6. Breesch H, Bossaer B and Janssens A (2005) Passive cooling in a low-energy office building. Solar Energy 79, 682-696.

   This article is based on a system from Belgium, which is used both for preheating in the winter (coupled with a heat recovery ventilation (HRV) system) and cooling in the summer (air conditioning). The authors also compare the use of earth heat exchanger systems to that of natural night ventilation and conclude that the latter is more effective.

7. Cook, J (Ed.) (1989) *Passive Cooling*. MIT Press, ISBN 0-262-03147-7.

   - Chapter 5, *Earth Coupling*, written by K. Labs, contains a section on Earth-Air Heat Exchangers (section 5.10, pp. 318-322).
   - Chapter 6, *Passive Cooling Systems*, written by G. Clark, contains a section on Earth Contact Cooling Systems (section 6.7, pp. 434-448; more particularly, section 6.7.3, *Isolated Earth Coupling*, deals with earth cooling tubes).

   This material is somewhat dated, especially considering the results in IEA Annex 28.

8. De Paepe M and Janssen M (2003) Thermo-hydraulic design of earth-air heat exchangers. Energy and Buildings 35, 389-397.

   This theoretical paper is concerned with formulating a design method which can be used to determine the characteristic dimensions of the earth-air heat exchanger in such a way that optimal thermal effectiveness is reached with acceptable pressure loss. The parameters of interest are tube length, tube diameter, and number of parallel tubes. Smaller tube diameters give better thermal performance but also larger pressure drops. The authors have developed graphs for determining the optimal design, given the ventilation requirements.

9. Deglin D, Van Caenegem L and Dehon P (1999) Subsoil Heat Exchangers for the Air Conditioning of Livestock Buildings. J. Agric. Engng Res. 73, 179-188.

   This is a theoretical model, with a particular application to livestock buildings; validation using an experimental setup is detailed. Corrugated, non-perforated plastic pipes were used. Validation was done with one year of data for a system including 18 m long, corrugated PVC pipes with 3 different diameters (250, 315 and 400 mm), buried at three different depths (1.50, 2.25 and 3.00 m). The authors conclude that (1) soils saturated in water are better from a thermal point of view, (2) greater depths are preferable since they provide higher temperatures in winter and lower temperatures in summer, (3) smaller pipes are more thermally efficient, i.e. they result in a higher heat exchange per unit volume of air; however they cause greater pressure losses and require larger installations (4) lower fan speeds lead to higher efficiencies, and (5) 70% of the heat transfer occurs within the first 10 m of the pipe.

10. Dibowski G (2003) L-EWTSim program. Available for download from: http://www.ag-solar.de/en/service/d_sim.asp

    The author offers freely downloadable software (in German) for the design/sizing of earth/air heat exchanger systems. The web site also gives access to the corresponding technical report (also in German).

11. Eicker U, Seeberger M H and Vorschulze C (2006) Limits and potentials of office building climatisation with ambient air. Energy and Buildings 38, 574-581.

    This paper presents monitoring results for three years for a European office building featuring passive cooling techniques, including an earth-to-air heat exchanger. The authors conclude that excellent COPs are achieved (of the order of 30), but that earth tubes alone meet only a limited portion (20%) of the daily cooling load.

12. Gauthier C, Lacroix M and Bernier H (1997) Numerical simulation of soil heat exchanger-storage systems for greenhouses. Solar Energy 60,6, 333-346.

    The authors present a fully transient three-dimensional heat transfer model of heat pipes. The model can handle multiple pipes, non-homogeneous soil properties, transient boundary conditions, and evaporation and condensation in the pipes. The model is validated against data from an earth tube system installed in a commercial greenhouse in Canada (unfortunately, only 3 days of data is used, probably because the model is very computationally expensive). The paper concludes with a parametric study to quantify the effect of various system variables.

13. Hollmuller P (2003) Thumb rules for the design of earth channels. Available for download from http://software.cstb.fr/articles/17.pdf

    The author provides several examples of earth tube systems currently in operation. He concludes that earth tubes are not advisable solely for preheating, particularly because heat recovery ventilators (HRVs) are more effective and because they don't circumvent using an auxiliary heater. Earth tubes can, however, be useful to avoid ice on a heat exchanger on the exhaust air side. Earth tubes do have good potential for cooling: they help reduce diurnal temperature peaks, they increase building inertia using soil, and they represent an investment competitive with air conditioning which they may be able to replace completely.

14. Hollmuller P and Lachal B (2001) Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects. Energy and Buildings 33, 509-518.

    This paper examines the heating and cooling potential of earth tubes, both from a technical and from an economic point of view. The paper focuses on Central Europe, and pays attention to the issues of sensible and latent heat exchange and heat diffusion into the soil. A model is developed and compared to one year of monitored data from various systems. The paper also mentions the problem of uncontrolled infiltration, e.g. from water droplets from the greenhouse entering the earth tube. The authors compare the performance of a heat recovery ventilator to that of an earth tubes system and find that the former clearly outperforms the latter. Infiltration and subsequent evaporation reduces the energy gains in the winter by roughly 50%. It does have a positive effect in the summer, though, as evaporative cooling further lowers the temperature of the air delivered to the space (the authors estimate that this increases the cooling potential by 25%). Economics are not favourable for heating, as the authors find that the system cannot compete with traditional fuels. The cooling mode is more economically viable, especially since the installation of earth tubes may permit dispensing with air conditioning in the climate studied. Finally, the authors mention that a closed-loop water-based ground heat exchanger, coupled with a water/air heat exchanger, may be a better solution, in particular since they avoid the sanitary problems related to the presence of stagnant water.

15. Hollmuller P and Lachal B (2005) Buried pipe systems with sensible and latent heat exchange: validation of numerical simulation against analytical solution and long-term monitoring. Proc. 9th Conference of International Building Performance Simulation Association, pp. 411-418, August 15-18 2005, Ecole Polytechnique de Montréal. Available for download from: http://www.unige.ch/cuepe/html/biblio/pdf/BuriedPipes_IBPSA_2005.pdf

    This paper presents a fairly complete model for the simulation of earth tubes. The model can be incorporated within the TRNSYS computer simulation environment and includes modeling of both sensible and latent heat. Model predictions are compared

to analytical solutions and to monitored results for two buildings: a commercial building in Germany, and a greenhouse in Switzerland. The paper claims that simulation results compare well to monitored data, however no numbers are provided. The paper also mentions that water infiltration seems to be a problem in both systems considered.

16. *IEA (2003) Solar Energy Houses: Strategies, Technologies, Examples, 2^{nd} Edition. James & James, London.

    Chapter 2.6 discusses ground-coupled heat exchangers, and in particular the German Rottweil House which has an earth tube system. The system is used both for pre-heating the fresh air supply in the winter, and for cooling in the summer. Chapter 3.10 discusses the construction, operation and monitoring of the system. The system works together with a plate heat recovery ventilator. The earth tubes are used to preheat the incoming air only when the outdoor temperature falls below 8 °C; and to cool the air only when its temperature exceeds 25 °C. The publication unfortunately does not provide monitoring data, save to say that the house has achieved its space heating energy requirements.

17. IEA Annex 28 (2001a) Low Energy Cooling: Technology selection and early design guidance.

    This is a scanned version of the entire IEA report on low energy cooling technologies. For a better-quality scan of the chapter devoted to earth tubes, see IEA Annex 28 2001b.

18. IEA Annex 28 (2001b) Low Energy Cooling: Technology selection and early design guidance, Chapter F – Ground Coupled Systems.

    This is simply a better quality scanned version of Chapter F of IEA Annex 28 (2001a). The focus is obviously cooling, but some of the information presented in the document is also applicable to heating. The chapter has charts and tables for system sizing, and presents information about existing systems.

19. IEA Annex 28 (2001c) Low Energy Cooling: Programme for the simulation of air-earth heat exchangers.

    The authors describe a program developed under IEA Annex 28 for the evaluation of the cooling potential of earth tubes. The program seems somewhat simplistic and of limited interest.

20. IEA Annex 28 (2001d) Low Energy Cooling: Case studies of low energy cooling technologies. Chapter 15, Ground cooling (air).

    The authors describe the use of earth tubes for cooling an office building in Switzerland. The system provides about a third of the cooling load, and is also used in the winter for preheating ventilation air. The article also contains interesting descriptions of the main features of the system.

21. Jacovides C P and Mihalakakou G (1995) An underground pipe system as an energy source for cooling/heating purposes. Renewable Energy 6,8, 893-900.

    The authors describe a TRNSYS model for the simulation of earth tube systems (TRNSYS is a computer modeling tool). The authors don't discuss the general potential of earth tubes for cooling or heating. The model includes latent heat transfer phenomena between the air and the pipe, and models the moisture content of the air circulating in the pipe and moisture migration through the soil with a temperature and moisture gradient. In the case studied (which is mostly applicable to greenhouses), the earth-to-air heat exchanger is buried under the foundation of the building. Ground temperature is therefore a superposition of the soil temperature field due to surface ground temperature and the temperature field due to the pipes themselves. Limited validation of the model was provided, as the time period was short (two summer months) and relative humidity was not measured.

22. Kumar R, Ramesh S and Kaushik SC (2003) Performance evaluation and energy conservation potential of earth-air-tunnel system coupled with non-air-conditioned buildings. Building and Environment 38, 807-813.

    This is a mostly theoretical paper dealing with modeling earth tubes for agricultural applications in India. The model includes humidity variations of circulating air, natural thermal stratification of the ground, latent and sensible heat transfer, ground surface conditions, etc. The model addresses both heating and cooling. Very limited validation (120 h) is provided. With the local climatic conditions used in the paper, cooling potential is estimated at 19 kW on average for the system considered (80 m long, 0.53 m^2 cross section), and heating potential is estimated around 4 kW.

23. Kwang Ho Lee and Richard K. Strand (2006) Implementation of an earth tube system into EnergyPlus program. *Proceedings of SimBuild 2006*, MIT, Cambridge, Mass., August 2-4, 2006. Available for download from http://simulationresearch.lbl.gov/dirpubs/SB06/kwangho.pdf

    The paper documents the development and integration of an earth tube model into the EnergyPlus building performance modeling code, and focuses on the effects of pipe radius, length, air flow rate and pipe depth. It also includes a model for soil temperature calculation. A parametric study concludes that, in agreement with common sense, a deeply placed and longer earth tube with a lower air velocity and smaller radius should result in better performance. It should be noted, however, that the model does not include possible latent heat exchange (condensation) with the air blown through the pipes. The model predicts that a building air conditioned only with earth tubes experiences only a modest temperature decrease.

24. Mihalakakou G (2003) On the heating potential of a single buried pipe using deterministic and intelligent techniques. Renewable Energy 28,6, 917-927.

This author shows how a neural network algorithm can be trained (using results from simulation) to calculate the outlet temperature of an earth tube. This paper has limited applicability.

25. Mihalakakou G, Lewis J O and Santamouris M (1996a) The influence of different ground covers on the heating potential of earth-to-air heat exchangers. Renewable Energy, 7,1, 33-46.

This is a theoretical paper, but it uses experimental ground temperature measurements. It bears some similarity with Mihalakakou et al. (1996b). The author looks at the heating potential of earth tubes under bare soil and under grass; data is provided at depths of 0.3, 0.6 and 1.2 m. Soil under grass is found to have a lower average temperature, but also a smaller annual temperature variation than bare soil. The authors conclude that the use of bare soil surface can increase the system's heating capacity.

26. Mihalakakou G, Lewis J O and Santamouris M (1996b) On the heating potential of buried pipes techniques – application in Ireland. Energy and Buildings 24, 19-25.

The authors provide simulation data for an earth tube system in Dublin, Ireland, and study the influence of pipe length, pipe radius, air flow velocity, and soil depth. The data shown in the article indicates that with a system featuring a 30 m long, 125 mm diameter tube buried 1.2 m underground, with air velocities of 8 m/s, one can expect a maximum rise of air temperature between 2.1 and 7.9°C, depending upon the time of year. These values increase roughly by 1°C for each additional meter in depth, and by 0.5 to 0.9°C for each additional 20 m in length. Lower velocities increase the temperature rise, and so do smaller diameters. However the paper does not address the global energy performance of the system, which should include the energy used to power the fans. Also, it doesn't either provide a summary of energy gains on a monthly basis.

27. Mihalakakou G, Santamouris M and Asimakopoulos D (1994) Modelling the thermal performance of earth-to-air heat exchangers. Solar Energy 53, 301-305.

This authors present a TRNSYS model for earth-to-air heat exchangers. It is an earlier version of a very similar paper by Jacovides and Mihalakakou (1995).

28. *Midwest Plan Service (MWPS) (1990) Heating, Cooling and Tempering Air for Livestock Housing. Available from Midwest Plan Service, publication MWPS-34, www.mwps.org.

This publication contains a whole section on earth tubes: chapter 5 discusses system sizing and provides useful installation tips. The focus is livestock housing so it may not be directly applicable to residences, however some of the concepts are very similar and can easily be transposed using different ventilation rates, etc.

29. Pfafferott J (2003) Evaluation of earth-to-air heat exchangers with a standardized method to calculate energy efficiency. Energy and Buildings 35, 971-983.

The author presents monitoring data for three German systems, all used for both cooling and heating. All three are monitored. The author stresses the need for appropriate controls for earth-to-air heat exchangers (EAHX), to avoid cooling cold air or heating warm air. The author derives four parameters to characterize the performance of the systems. One of them is the Coefficient of Performance, which the authors define for such systems as the energy gain divided by the mechanical dissipation energy (in other words, they don't take into account the whole ventilation energy, on the assumption that some of it exists anyway if the building is mechanically ventilated; only the increment in ventilation energy, that is imputable to the EAHX, should be taken into account). They obtain COPs between 29 and 380. The authors remark that the advantages of an EAHX are negligible in heating mode if a heat recovery ventilator is present; the only advantage is to avoid the danger of freezing of the heat recovery ventilator. In cooling systems, the authors conclude that systems with pipe lengths up to 100 m and pipe diameters around 250 mm are suitable.

30. Rehau (2007a) Awadukt Thermo sales brochure. Available for download from http://www.rehau.co.uk/building.solutions/civil.engineering/ground.heat...geothermal.energy/awadukt.thermo.shtml

This brochure presents a commercially-available earth tube system.

31. Rehau (2007b) Rehau geothermal systems. Available for download from http://www.rehau.co.uk/building.solutions/civil.engineering/ground.heat...geothermal.energy/awadukt.thermo.shtml

A section of this brochure discusses earth tubes systems developed by the company.

32. Sawhney R L, Buddhi D and Thanu N M (1999) An experimental study of summer performance of a recirculation type underground airpipe air conditioning system. Building and Environment 34, 189-196.

This is an experimental paper but with only limited data. The author describes a recirculation underground system made with concrete pipes. The system is used to air-condition a building in a tropical climate. The pipes form a closed circuit. Metal wire mesh is used to prevent insects and foreign matter from entering. The system is designed to work both for cooling and heating. Only one month of monitoring (May) was done. Air from the house is cooled by around 1.5°C as it passes through the system. Temperature of air delivered by the system is fairly stable (around 27°C, which is the ground temperature for the location). Relative humidity is somewhat higher (5%) than that of a non-conditioned room; that is, moisture is added as it is circulated through the tubes. Given that a 3 HP blower is used to circulate the air, the COP was found to be only 3.35.

33. Sharan G and Jethva K (2006) Cropping in Arid Area Greenhouse. Downloadable from http://www.iimahd.ernet.in/publications/data/2006-12-03_gsharan.pdf

The authors present an application of earth tubes to heat and cool a greenhouse in the North-West part of India, in an arid climate. The paper is mostly experimental and reports that the system is able to heat the greenhouse during cold nights and keep it significantly cooler during hot days.

34. Shukla A, Tiwari G N and Sodha M S (2006) Parametric and experimental study on thermal performance of an earth–air heat exchanger. Int. J. Energy Res. 30, 365-379.

The content of this paper significantly overlaps with the content of the paper by Tiwari et al. (2006).

35. Staahl F (2002) Preheating of Supply Air through an Earth Tube System – Energy Demand and Moisture Consequences. Building Physics 2002 – 6th Nordic Symposium. Available for download from: http://www.ivt.ntnu.no/bat/bm/buildphys/proceedings/67_Staahl.pdf

The focus of this paper is the quality of the air coming out of earth tubes, particularly related to the moisture content. The author notes that the material of the earth-tube wall is of great importance since it determines the moisture transfer: for example concrete will let the moisture through, plastic will not. For that reason the relative humidity predicted by the author for a concrete tube is 100% year round. For a plastic tube it reaches 100% only in summer in a Nordic climate. Over half the year the relative humidity is above 80%, which is conducive to mold growth. The paper also mentions mold growth in two of three Swedish schools equipped with earth tubes. On the energy side, the author predicts (through simulations) that an earth tube will typically deliver 1,200 kWh/yr to a house in the Swedish climate, or about 10% of the heating needs.

36. Thomsen K E, Schultz J M and Poel B (2005) Measured performance of 12 demonstration projects – IEA Task 13 "advanced solar low energy buildings". Energy and Buildings 37, 111-119.

The authors describe (among other things) the Ultra House in Rottweil, Germany, which features earth tubes. Unfortunately the paper is of little usefulness as the monitoring results for the earth tube system are not reported.

37. Tiwari G N, Akhtar M A, Shukla A and Khan M E (2006) Annual thermal performance of greenhouse with an earth–air heat exchanger: An experimental

validation. Renewable Energy 31, 2432-2446.

The authors present an experimental validation of a simple earth tube model using experimental data for a greenhouse located in New Dehli, India. Temperature increases of 4 °C in the winter and decreases up to 8 °C in the summer are observed. The earth tube system is more efficient in the summer than in the winter. Despite its simplicity, the model seems to be in good agreement with experimental data.

38. US Department of Energy – Energy Efficiency and Renewable Energy (2007) EERE Consumer's Guide: Earth Cooling Tubes. Available from: http://www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/mytopic=12460

This is a two-page primer about earth tubes, which provides a quick overview of the parameters at play but does not go too deep into detail.

39. Vargas J V C, Ordonez J C, Zamfirescu C, Campos M C and Bejan A (2005) Optimal Ground Tube Length for Cooling of Electronics Shelters. Heat Transfer Engineering, 26,10, 8-20.

This theoretical paper deals mostly with calculation methods for earth tubes. It provides an optimal tube length that will maximize heat exchange for a given pumping power.

40. Voss K, Reinhart C, Löhnert G and Wagner A (2000) Towards lean buildings - examples and experience from a German demonstration program for energy efficiency and solar energy use in commercial buildings. Downloadable from: http://www.solarbau.de/monitor/doku/proj00/dokuproj/eurosun-monitor.pdf

The authors provide a description and initial evaluation of a number of commercial large-scale green buildings situated across Germany. Some of them feature earth-to-air heat exchangers for the pre-cooling of the buildings' air supply. The article includes pictures of a very impressive 1 m diameter, 100 m long earth pipe.

41. Wikipedia (2007) Earth cooling tubes. Available from: http://en.wikipedia.org/wiki/Earth_cooling_tubes

This is a very short but also very incomplete introduction to earth cooling tubes.