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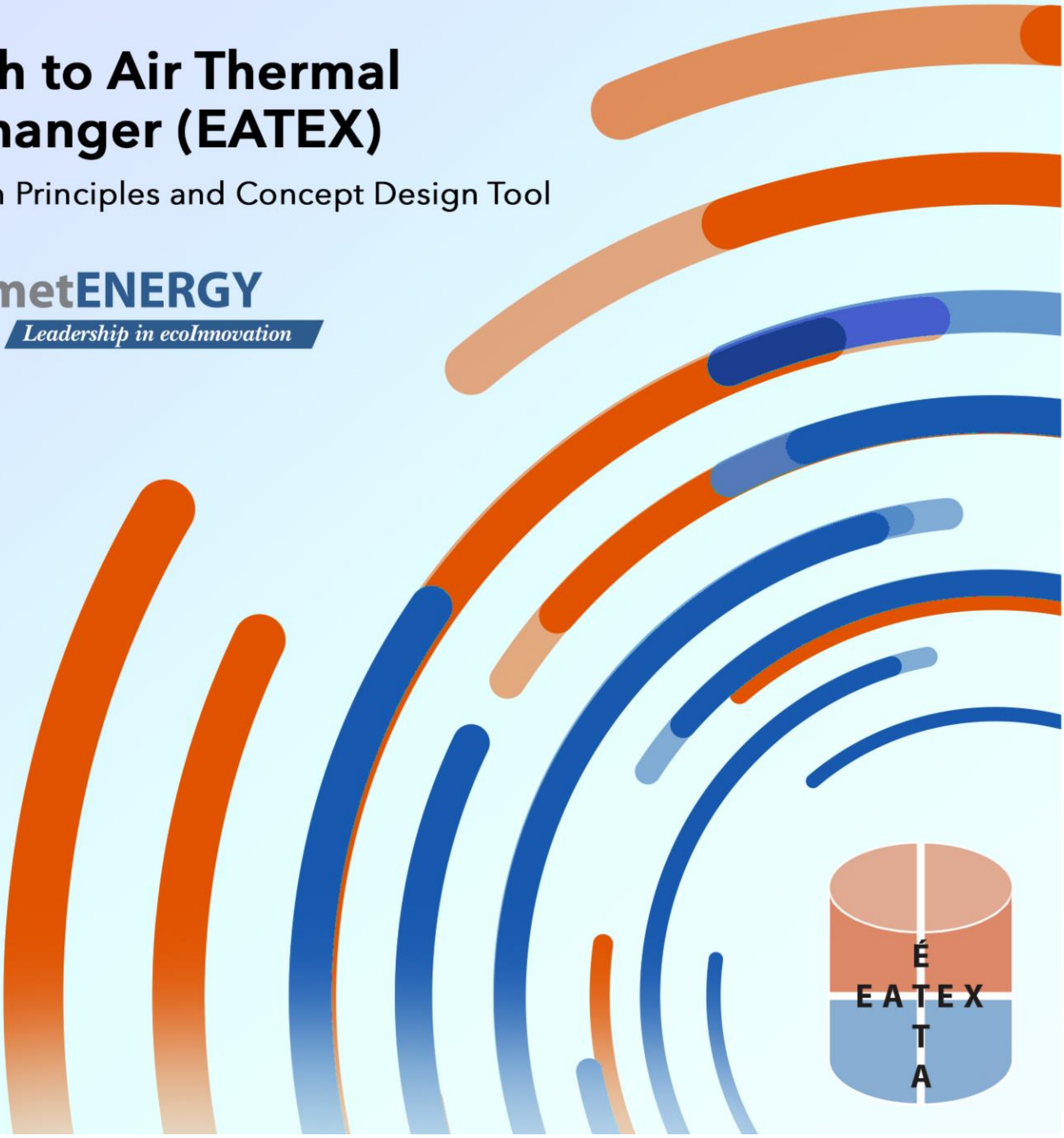
Earth to Air Thermal Exchanger (EATEX)

Design Principles and Concept Design Tool

CanmetENERGY
Leadership in ecoInnovation



Abstract

Earth to air thermal exchangers (EATEX) can provide a passive means of preheating and precooling ventilation and process air, thereby reducing reliance on electricity and fossil fuels. Their performance is governed by a series of interconnected variables such as tube material, length, diameter and layout; tube depth below grade; surface and deep soil conditions; ambient air temperatures and surface solar radiation; air flow, velocities, fan characteristics and operating schedules. The relationships between the soil, tube design, ambient air, and air velocity are quite complex. This document outlines the fundamental design principles and then applies these principles using complex energy simulation tools. The results of these complex sub-hourly simulations are then loaded into a tool that designers can use at the early design stage to assess the energy performance of design options for a series of Canadian climates.

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Disclaimer

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Contents

1.0 Introduction

Earth tube heat exchangers or earth to air thermal exchangers (EATEX) offer a passive approach to preheat (in winter) and precool (in summer) outdoor air (ventilation or process) by exchanging thermal energy to and from the surrounding earth.

There are a number of parameters that affect this exchange. These include: soil type, moisture and compaction; surface cover; earth tube size (diameter, thickness and length), earth tube material and layout; air velocity; and earth tube depth below the surface. In addition, hourly and seasonal variables such as temperature, solar radiation, rain, snow, and wind velocity at the surface will affect soil temperatures, which will impact the performance of an earth-to-air heat exchanger.

The design of the earth tube heat exchanger system must take into account these parameters in order to produce the temperature difference and heat transfer rate required of the system in a cost effective manner. These parameters will be described in this guide.

For the remainder of the guide, the earth tube heat exchanger or the earth-to-air heat exchanger will be referred to as an earth to air thermal exchanger (EATEX).

A companion early design tool was developed with this guide and a description of how the design parameters are applied in this design tool is also provided.

Prior to defining the parameters and design principles necessary for a high performing earth to air thermal exchanger, a brief explanation of why such a system should be considered in design projects and a rationale for an early design tool, is necessary.

An earth to air thermal exchanger (EATEX) is a relatively passive means of preheating and precooling ventilation and process air. Incorporating passive heating/cooling can add uncertainty in the design process; therefore the design community is somewhat hesitant to consider earth to air thermal exchangers (EATEX) in standard design projects. They seem to be considered in only specialty, niche type design projects. With the evolution towards net-zero energy buildings, passive measures to supplement – and in some cases, meet – space heating and cooling loads will require serious consideration. The IEA Annex 52 Task 40 (Solution Sets for Net Zero Energy Buildings) found that the prevalence of earth-based cooling/heating occurred in less than 20% of commercial buildings (Garde, Ayoub, Aelenei, Aelenei, & Scognamiglio, 2017). Feedback from 30 net-zero energy buildings within the Annex indicated performance uncertainty and a general lack of understanding of the technology were the main contributing factors in low adoption of earth to air thermal exchangers (EATEX) in net-zero energy buildings (Garde, Ayoub, Aelenei, Aelenei, & Scognamiglio, 2017).

This guide will provide design principles, result-oriented case studies, and a companion early design tool to ease some of the uncertainty in considering earth to air thermal exchangers (EATEX) in design projects.

2.0 Design Considerations

The following are the basic design considerations when designing earth to air thermal exchangers (EATEX):

- Application (intended use)
- Site conditions (location, soils)
- Earth tube diameter, depth, and length
- Earth tube materials
- Airflow and fan sizing
- Operation and controls
- Earth tube layout (single or multiple tubes, spacing, spiral design)
- Capital costs

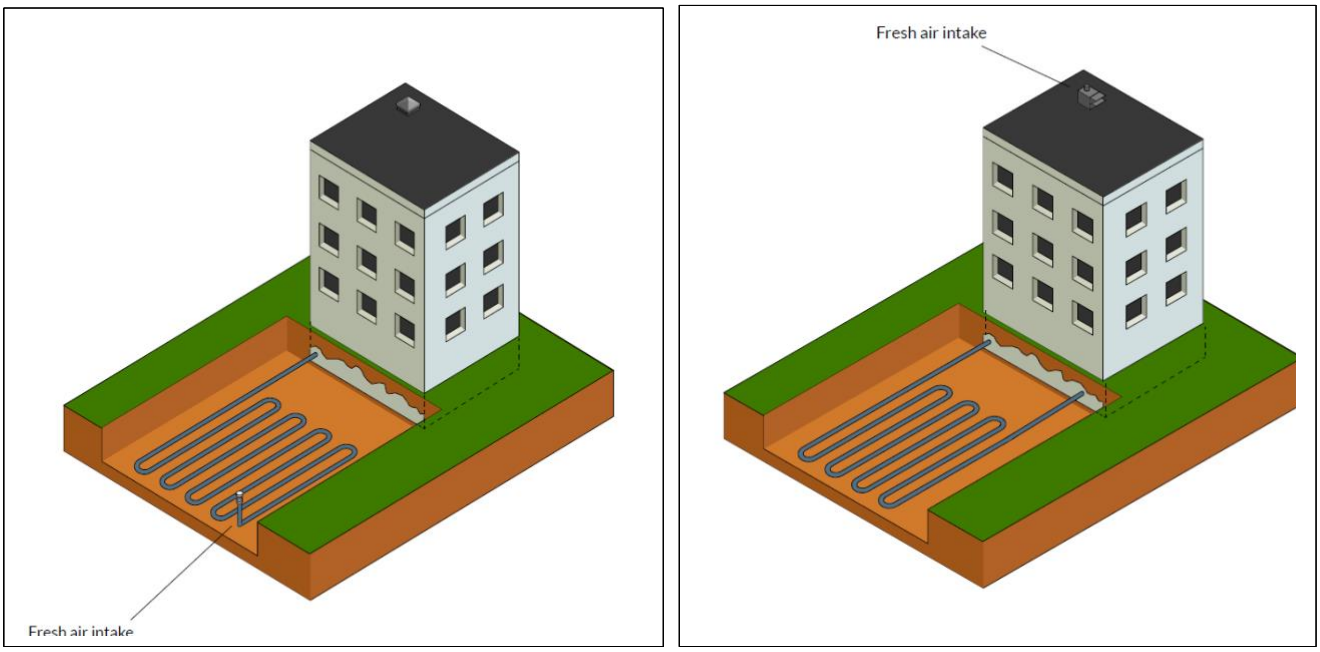
Each of these will be discussed in more detail and then demonstrated via the design tool.

2.1 Application

One must consider that in the majority of applications, an earth to air thermal exchanger (EATEX) is essentially a preheating or precooling system. In climatic locations or buildings with very low heating and cooling loads, an earth to air thermal exchanger (EATEX) may meet a significant portion of heating and cooling loads.

The first certified Passivhaus in North America – the Biohaus Environmental Learning Center in Bemidji, Minnesota – uses an earth to air thermal exchanger (EATEX) to meet its entire summer cooling load, and in the winter, to preheat air from -29˚C to -4˚C (George, 2010).

There are two types of earth to air thermal exchangers (EATEX): open loop and closed loop.



Open Loop

Closed Loop

Figure 1: Types of Earth to Air Thermal Exchangers (EATEX)

In an open loop system, outside air (ventilation or process) is drawn into buried tubes and then supplied to the conditioned space. Within the buried tubes, the supply air gains (or rejects) heat from (or to) the surrounding soil, thus providing a degree of ventilation air preheating or precooling. The earth tube is part of the supply air system. Building return air or exhaust air does not interact with the earth to air thermal exchanger (EATEX).

In a closed system, building air is recirculated through the buried pipe system to transfer building heat to the earth, thereby cooling the building.

In both types, the earth acts as a heat source or heat sink, exchanging heat from the warm medium to the cooler medium. The effectiveness of this transfer is governed by heat transfer principles of the air, soil, and earth tube, and the intended application of the earth tube system.

This guide focuses on open loop earth to air thermal exchangers (EATEX) to preheat and precool ventilation air.

2.2 Site Conditions and Earth Properties

In earth to air thermal exchanger (EATEX) systems, the soil is the heat source and sink. The soil temperature around the earth tube is dependent on its composition, compaction, depth, moisture, interactions with earth tubes and surface conditions, in addition to ambient conditions.

Far field soil temperatures at various depths have been measured and follow a sinusoidal variation with a yearly amplitude somewhat related to average air temperature (Kusuda & Achenbach, 1965). At a depth of greater than two metres (m), soil temperatures are fairly constant and similar to the annual mean air temperature (Peretti, Zarella, De Carli, & Zecchin, 2013). Figure 2 illustrates measured soil temperatures at different depths (0.025 m to 5 m below the surface) in relation to the ambient air dry bulb temperature.

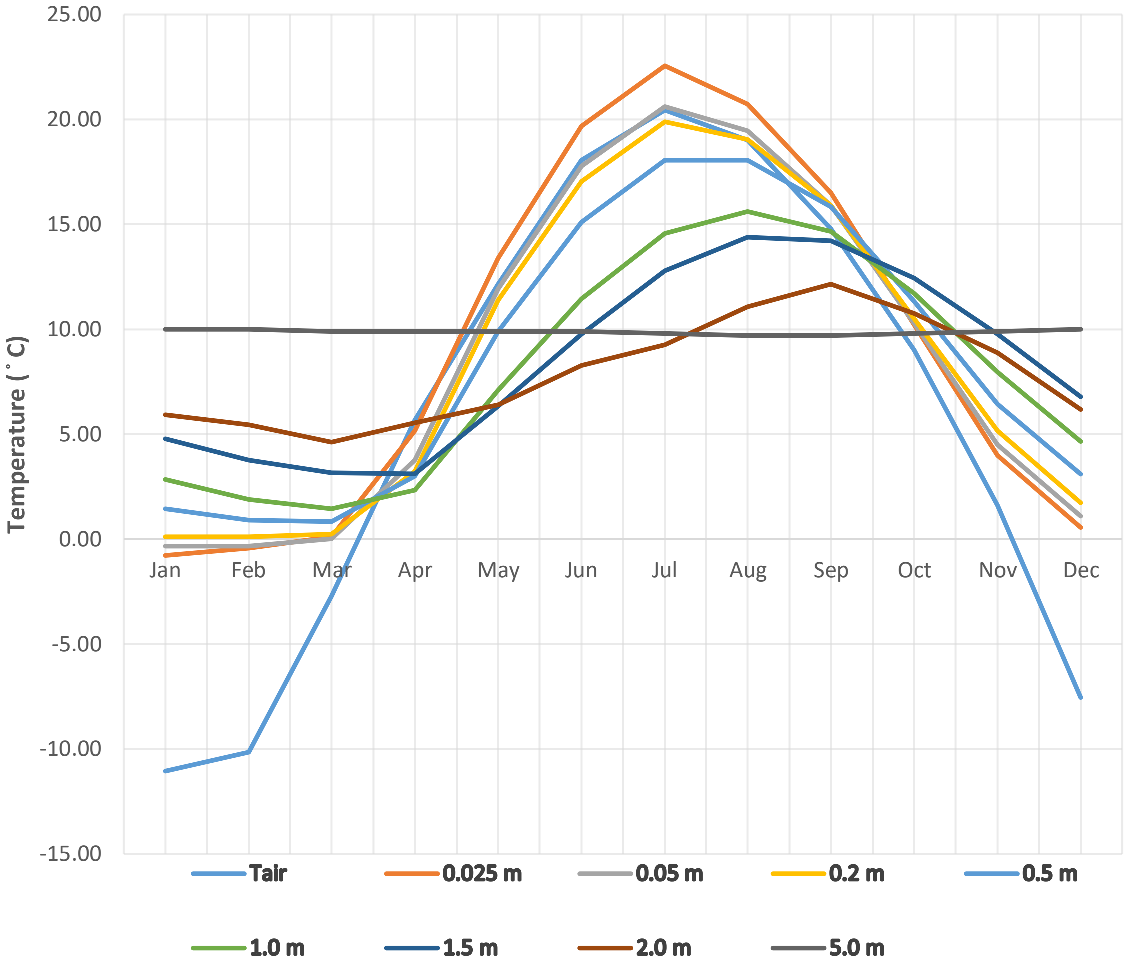


Figure 2: Measured Ottawa Monthly Average Soil Temperatures by Depth

Source: (Ouellet, 1975) (Williams, 1976)

The soil temperature at a given depth is but one parameter affecting heat transfer within an earth tube. Soil types (clays, loams, sands), properties (grain size, organic matter), moisture, compaction, and porosity determine the thermal resistivity, conductivity, diffusivity and effusivity variables affecting heat transfer (Birch, 1995; Farouki, 1986).

Thermal resistance is a measure of resistance or impedance of heat flow through a unit area, in a unit of time, under a temperature gradient; measured in (m^2-C)/W. Thermal conductance is the opposite of resistance and is a measure of heat flow through a unit area, in a unit of time, under a temperature gradient; measured in W/(m^2-C). Thermal diffusivity is the thermal conductivity divided by the density and specific heat capacity at constant pressure or thermal inertia. It measures the speed of heat transfer. Thermal effusivity is the heat storing and heat dissipating ability of soil particles, which affect conductivity and diffusivity.

The five major materials that constitute soil all have different conductivities, and based on their weighting, will determine the soil's resistivity and diffusivity. These are illustrated in Table 1.

Table 1

Major Soil Constituents

Soil Component	Thermal Conductivity W/(m-K)	Thermal Diffusivity cm^2/sec
quartz	3.0	0.043
other soil minerals	2.5	0.015
water at 25 °C	0.6	0.001
organic matter	0.25	0.00142
air at 20 °C at atmosphere	0.026	0.00021

Source: (Farouki, 1986)

The weighting of these main constituents will determine whether the soil is a loam, clay, sand, or peat type soil. The greater the conductivity, the greater the heat transfer ability; either from the soil to the earth tube or from the earth tube to the soil.

The moisture content of the soil impacts conductivity and diffusivity. As soil moisture increases, thermal conductivity increases (de Jong van Lier & Durigon, 2012), up to the point of saturation, where an increase in moisture content has little effect on overall soil conductivity. While soil moisture can increase heat transfer, other decisions related to depth, freezing potential, and compaction play an equally important role in soil heat transfer. Compacted soils with high-density materials (e.g. sands) will improve thermal conductivity (Peretti, Zarella, De Carli, & Zecchin, 2013). Cooling studies of compacted sands around an earth tube indicate that the heat transfer increased by 12% and 28% from loosely compacted sand to medium compacted sand and densely compacted sand, respectively (Elminshawy, Siddiqui, Qazi, & Addas, 2017).

The ASHRAE Applications Handbook (2015) provides typical thermal conductivities, diffusivities, moisture contents and densities for various soils (shown in Table 2).

The soil types, density, and moisture content are likely unknown at the early design stage. Therefore, these have been combined into a selection related to four general soil types: heavy saturated, heavy damp, heavy dry, and light dry; which are used in a number of simulation tools (Moncef & Kreider, 1996; Lee & Strand, 2008). Soil type selections for the concept tool are described in Section 3.

Table 2

Moisture Impact on Soil Conductivity and Diffusivity

Soil	Moisture	Density	Thermal Conductivity	Thermal Diffusivity
	Content	(kg/m^3)	W/(m-K)	m^2/sec
Heavy clay	15% water	1922	1.558	5.914E-07
	5%	1922	1.212	6.452E-07
Light clay	15% water	1281	0.865	4.624E-07
	5%	1281	0.692	4.839E-07
Heavy sand	15% water	1922	3.115	1.129E-07
	5%	1922	2.596	1.344E-06
Light sand	15% water	1281	1.558	8.065E-07
	5%	1281	1.385	9.677E-07

The backfill material will have an impact on the thermal conductivity of the soils, especially if it is different from the material that was originally removed. If the backfill is different, it is suggested to still use the backfill material as the soil conditions when using the design tool, as this material will be the primary contact with the earth tubes. From the above soil conductivity data, compacted heavy sand offers higher thermal conductivity. For detailed modelling and knowing the site conditions, it has been suggested to use multiple layers of soil conditions and temperatures, and complete a soil layer-by-layer analysis (Kaushal, 2017).

In addition to knowing the soil conditions at various depths, the surface conditions will also affect soil temperatures at various depths, but to a lesser extent beyond a depth of 3 m. Surface conditions – such as vegetation, snow cover, moisture, wind, humidity, and surface temperature – will all affect the surface soil temperature, conductivity, and diffusivity. Bare surface soils retain heat better than soils with a surface vegetative cover; therefore vegetative covered soil surfaces are better suited for cooling applications (Baten, Akter, Miah, Hassan, & Mobin, 2015). The vegetation acts as thermal fins, allowing solar radiation to dissipate more quickly and releasing some moisture from the surface (latent cooling). These effects have been incorporated in the various models (Moncef & Kreider, 1996).

2.3 Earth Tube Depth, Diameter and Length

2.3.1 Earth Tube Depth

As referenced above, soil temperatures are fairly constant at depths below 3 m. The type of soil, moisture content, and surface cover will influence the variation in temperature at various depths, but other factors will affect how deep the earth tube should be placed. These include underlying bedrock, drainage, and, most importantly, trenching and backfilling costs. Ideally, the depth should be at least 1.5 m below the surface to the top of the tube. Any depth below 3.5 m will result in minimal incremental improvements from a depth of 3.5 m. (Kaushal, 2017).

The closer the tube is to the surface, the greater the variation in monthly soil temperatures (see Figure 2). Surface soil temperatures will more closely track ambient conditions, therefore minimizing the amount of preheating (winter) and precooling (summer) potential. To minimize the monthly soil temperature variation, adding insulation above the tube at shallow depths is a possibility. Rigid insulation placed above the tube to act as a thermal separator from the influence of surface temperatures at the earth tube has been modelled. This approach can marginally improve the overall performance of the EATEX system and avoid the cost of deeper trenching. Figure 3 illustrates the modelled results of tubes with rigid insulation placed 5 cm below the surface and 1.4 m above a tube, compared to a tube without insulation installed at a depth of 3 m.

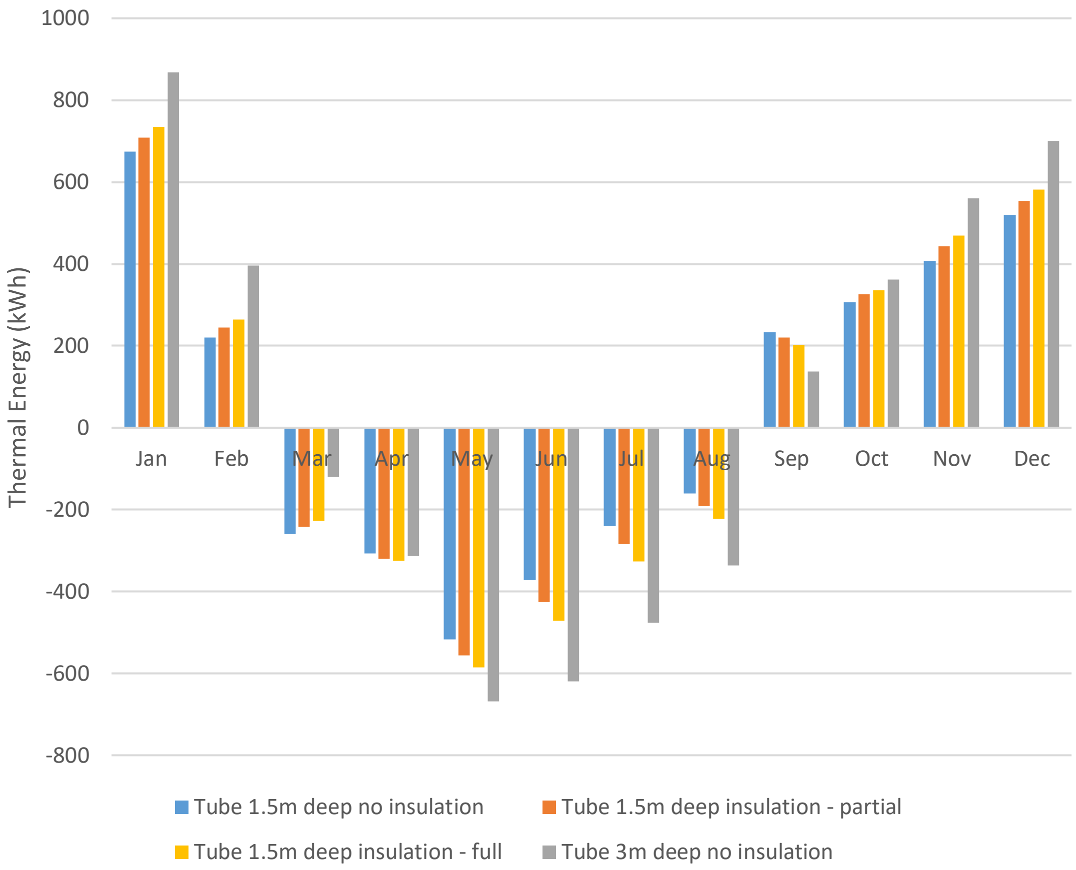


Figure 3: Effect of Insulation Placement above the Earth Tube

This single tube was 27 cm in diameter and 70 m in length, with an air velocity of 3 m^3/sec and located in Ottawa. Partial insulation consisted of 5 cm of extruded polystyrene (RSI 1.76 m^2-°C/W) at a width of 1.2 m, whereas full insulation was 2 m wide. The insulation covered the entire length of the tube. As Figure 3 illustrates, the tube installed at a depth of 3 m performed better than the tube installed at a depth of 1.5 m, even when insulation was added to reduce heat transmission to the colder surface in the winter and to avoid ground heating in the summer. The insulation did provide a small improvement (5-6% annually) compared to no insulation at a depth of 1.5 m. However, one cannot infer that further depth reductions are possible with additional insulation due to frost depth penetration in Ottawa.

The simulation results are based on the Transient Systems Simulation Program (TRNSYS) modelling using the Hollmuller/Lachal model (Hollmuller & Lachal, TRNSYS compatible moist air hypocaust model, 1998), which has been adapted for the creation of the simplified early design tool (Brideau, Lubun, & Tardif, 2018).

2.3.2 Earth Tube Diameter

The earth tube diameter will also affect the rate of heat transfer. To preheat or precool a given airflow, the designer can choose between a large diameter tube (larger than 1.0 m diameter), or multiple smaller diameter tubes (typically smaller than 0.6 m diameter). Given that smaller diameter tubes have a greater surface area to air volume ratio than larger diameter tubes, the potential heat transfer from the earth to the air stream should be greater in small tubes for the same cross sectional area of tubes. The larger diameter tubes will suffer from poor surface contact from the centre portion of the fresh air stream, therefore additional measures to create air turbulence to increase fresh air contact with the tube wall is required. This strategy increases static pressure in the system and may require different fan size decisions. A larger diameter pipe will have a greater heat transfer quantity if the length and flow volume are the same as the small diameter pipe. However, if you convert a 1 m diameter pipe into three 0.33 m diameter pipes and provide the same volumetric airflow, the three 0.33 m diameter tube configuration will deliver more heat transfer because the surface area for heat transfer almost doubles compared to a 1 m diameter tube. However, three trenches or one very wide trench are required which has cost implications, and additional fan energy would likely be required due to the additional static pressure.

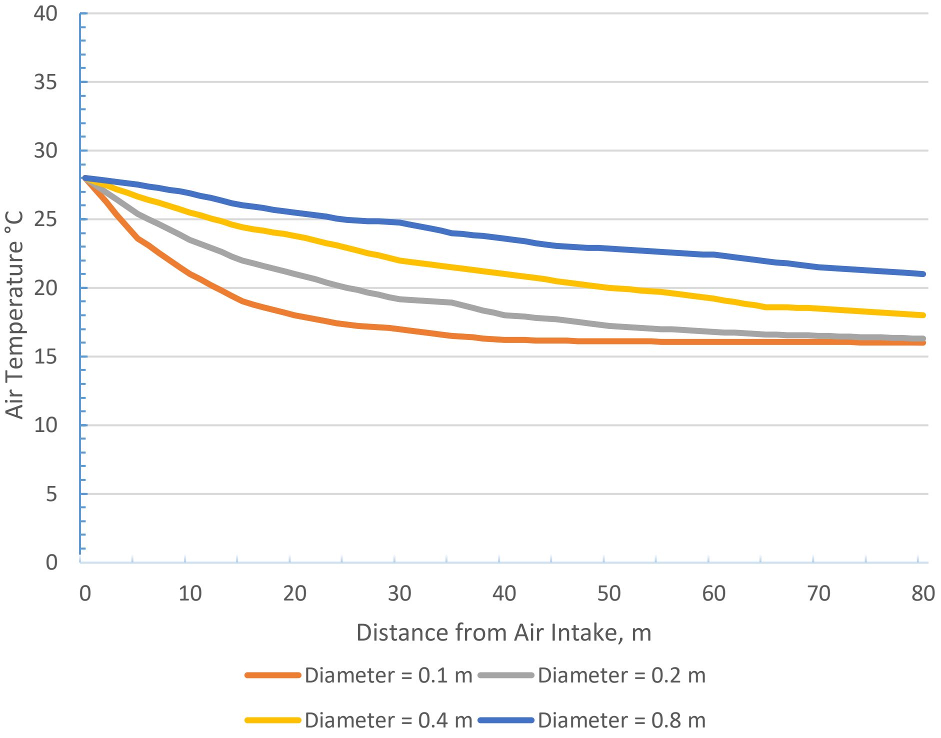


Figure 4: Effect of Tube Diameter on Temperature According to Length of Tube

Source: (Kelker, et al., 2016)

In Figure 4, the diameter of the earth tube varies from 0.1 m to 0.8 m and the tube air temperature is modelled from the intake to 80 metres from the intake, holding all other parameters (depth, air velocity) constant. Smaller tubes are shown to provide a larger temperature drop from the intake ambient temperature of 28 °C compared to the larger tubes. In this case, up to 10 °C in the first 30 m of length was modelled for the 0.1 m diameter tube. However, due to increased volumetric flow rates through the larger tubes, their total heat transfer rates were higher. The 0.8 m diameter tube (airflow – 1 m^3/s) provided 3.66 kW of cooling in the first 30 m compared with 0.195 kW for the 0.1 m diameter tube (airflow - 0.016 m^3/s).

The amount of cooling per unit flow rate is much higher in the 0.1 m diameter tube at 12 kW/ (m^3/s), compared to 3.66 kW/ (m^3/s) for the 0.8 m diameter tube.

The exact tube diameter selection needs to be correlated to the airflow requirement, in addition to space requirements. Too small a diameter tube for an airflow will increase pressure, fan requirements, and possibly noise. Too large a diameter tube for an airflow will result in reduced heat transfer due to lack of tube material surface contact.

Other measures would have to be added to induce air contact with the tube surface, such as turbulence vanes or air baffles. These would add additional costs, complexity, and increase the overall static pressure of the system. The design of additional systems to create turbulence needs to be considered in light of the addition of extra smaller diameter tubes, which would not require designing for turbulence to increase supply air contact with the earth tube.

The thickness of the earth tube will have a minor impact on the heat transfer rate, which is discussed in section 2.4.

2.3.3 Earth Tube Length

The length of the earth tube will influence heat transfer and performance for different tube diameters. Various studies have shown diminishing temperature impact when tube length is greater than 70 m (Vlad, Ionescu, Necula, & Badea, 2013) (Peretti, Zarella, De Carli, & Zecchin, 2013). Figure 4 indicates that the temperature reduction from 28 °C levels after 40 m in length for the 0.1 m and 0.2 m diameter tubes. Figure 5 shows the modelled cooling performance for different tube diameters as a function of tube length.

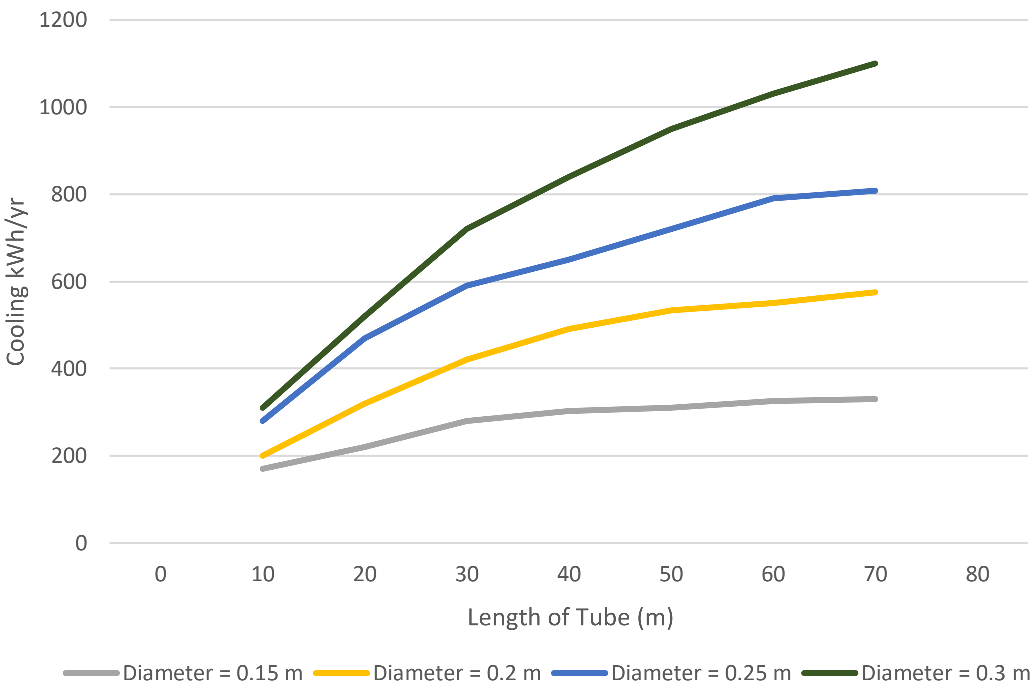


Figure 5: Effect of Tube Length and Diameter on Cooling Performance

Source: (Barnard & Jaunzens, 2001)

Tube lengths less than 10 m are not generally recommended, as there is insufficient heat transfer surface area to effectively preheat or precool ventilation air, even at low air velocities. Studies and measurements have indicated that 82-85% of the total increase (preheating) or decrease (precooling) in temperature of the air along the tube is achieved at a length of 34 m from the inlet for tubes with a diameter of 1 m or less (Darius, Misaran, Rahman, Ismail, & Amaludin, 2017).

2.4 Earth Tube Materials

The thermal conductance of the earth tube itself has an impact on heat transfer, but the performance is minimal amongst the different materials (Darius, Misaran, Rahman, Ismail, & Amaludin, 2017). Common tube materials include PVC, polyethylene, concrete, galvanized steel, and clay. Table 3 presents the thermal conductivity of earth tube materials and the conductance of manufactured materials.

Table 3

Earth Tube Material Thermal Conductivity and Conductance

Type of Pipe Material	**Thermal Conductivity W/(m-K)**
Polyvinyl chloride pipe	0.19
Polyethylene pipe (low density)	0.33
Polyethylene pipe (high density)	0.5
Polypropylene pipe	0.24
Concrete (sand and gravel or stone aggregates 150 lb/ft3)	1.44 – 2.9
Concrete (lightweight aggregates, 120 lb/ft3)	1 – 1.3
Carbon Steel	54
Aluminum	237
Type of Pipe Material	**Thermal Conductance W/(m^2- K)**
PVC: Schedule 40 (254 mm dia. 12 mm thick)	16
Polyethylene pipe (high density, 160 mm dia. 8 mm thick)	62.5
Galvanized steel: SCH 40 (3.5 mm thick 10 gauge)	15428
Concrete (63 mm thick reinforced 150 lb/ft3 density)	23 - 50
Clay (vitrified, 254 mm dia. 19 mm thick wall)	1.75 – 2.55
Aluminum (Schedule 40, 10 mm thick)	23700

Source: ASHRAE Handbook Fundamental 2009 (for conductivity data) Conductances are calculated.

The decision on tube materials should carefully consider thermal performance, resistance to bacteria growth, moisture content, material off-gasing (PVC), equally with handling and installed cost.

If polyethylene or galvanized steel is used, ribbed-type materials can accumulate condensation, even if the installation includes a slight slope to drain surface condensation. The material ribbing will hold moisture even if installed on a slope; therefore, the design must consider potential bacteria and mould growth if temperature conditions are favourable, or some means of mitigation (e.g. UV lamps) or drying must be implemented. In dry climates, or where installations involve process heating/cooling, ribbed materials would not pose a mould/bacteria concern. Also, ribbed polyethylene piping in large rolls do not require sealing of pipe joints and additional connections for bends, which can simplify installation.

Double-walled high-density polyethylene piping is common for culverts and involves a corrugated outer pipe bonded to a smaller, smooth inner pipe. These pipes are strong and allow water and air to move freely, thereby minimizing potential mould growth. However, an effective earth to air thermal exchanger (EATEX) works best when the earth tube material is in direct contact with the earth, and the air space between the outer corrugated pipe and the inner smooth pipe acts as an insulator, thereby reducing surface contact.

Polyethylene piping with drainage slots/holes should be avoided, especially in locations where radon gas may be present. Radon is a carcinogen formed in the natural degradation of uranium in the ground. It percolates through the soils and into cracks in foundations or other openings. Pipe drainage openings, connections will allow radon gas to enter the earth tube air.

A smooth inner surface pipe material with a gentle slope (2% min) can provide an effective means of removing condensate if it is present. The slope can be towards the building for condensate removal inside the building, or away from the building for condensate removal.

A layout involving a slope towards the building will require a drain or a pump to deal with the condensate. The draining of the condensate can be accomplished in the building basement if possible, at a floor drain or directly in a drain pipe, making sure to use an air trap or break and following all appropriate plumbing standards. It is recommended to use a trap with a water seal height of about twice the fan water column, with a minimum water seal height of 50 mm. The total trap height should be approximately twice the water seal height. A 26 mm inner diameter tube is generally sufficient for a condensate drain. In cases when a basement is not accessible, condensate removal is usually achieved outside of the building with a connection to a drainage pipe (e.g. storm water) or a drainage pit equipped with a condensate pump. Access to this pump must be maintained via a manhole. Additionally, make sure to maintain a seal around the earth tube to ensure that radon cannot enter the tubes, and ensure the manhole is completely sealed. It is recommended to set the condensate pump to the lowest possible depth below the earth tube (lower than 10 cm).

A layout involving tubes sloping away from the building would require a drainage pit (with or without a condensate pump) or connection to an existing drainage device.

If condensation occurs on the tube surface, some installations have opted for passing the preheated/precooled air through a ultra-violet light chamber to kill all mould or bacteria that could be present in the air as a result. Commercial EATEX manufacturers have also developed polypropylene pipes with an inner lining of silver particles as an antimicrobial liner (Moseley, n.d.). In most climates, there will inevitably be some condensation during humid conditions. If the natural wetting/drying cycle does not adequately evaporate moisture, the design must include an active condensation removal strategy.

Also, tube materials are subject to thermal expansion due to temperature changes. Thermal expansion of 0.2 mm/ (m-K) is common in high-density polyethylene piping, and PVC piping experiences a thermal expansion of 0.08 mm/m-K (Barnard & Jaunzens, 2001). Rubber seals are usually installed at collection headers to accommodate this axial movement, but also protect against ground water seepage. Long-term lateral movement is prevented by sealing the pipes together.

Non-rigid piping may be considered, as long as the installation does not permit pipe sagging, which could allow for water collection.

In addition to sealing at pipe connections, the length of the pipe material itself will influence the potential for leakage, water/radon gas entry, and air turbulence.

2.5 Airflow and Fan Sizing

The earth to air thermal exchanger (EATEX) design provides preheating and precooling of the airflow requirements of the space or building. A high air velocity will reduce temperature gradient, as the time of air contact with the earth tube wall will be shorter than a slower air velocity. The overall transfer of energy will increase with a high airflow, but the temperature impact will be lower.

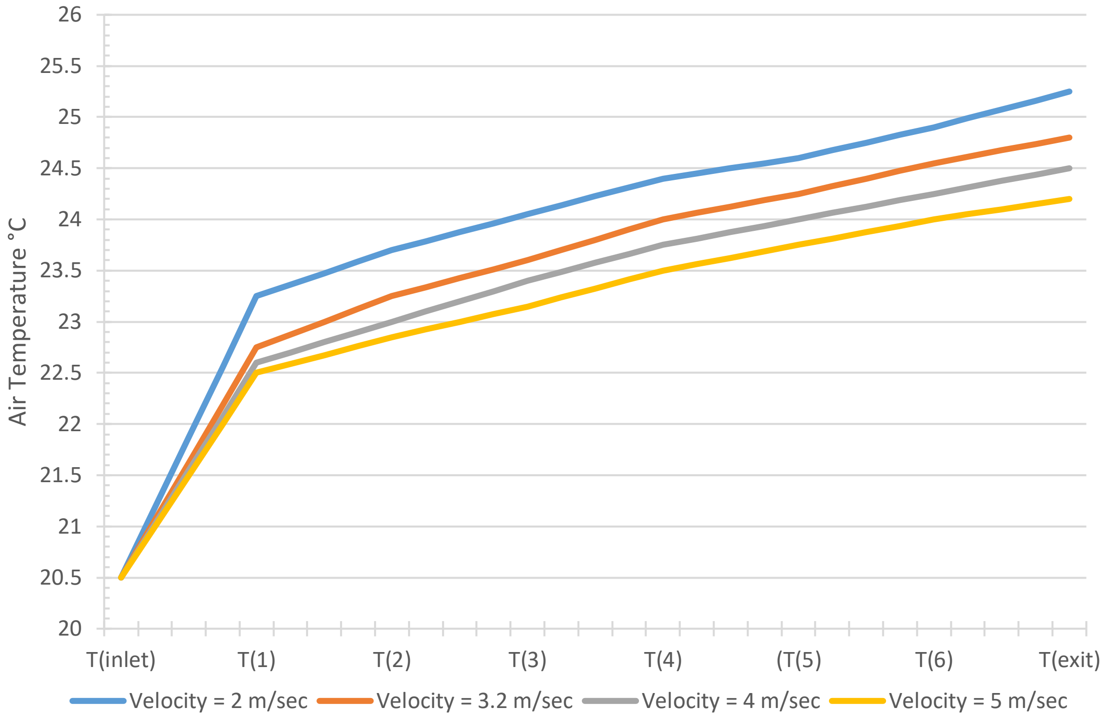


Figure 6: Effect of Velocity on Temperature

Source: (Vikas Bansal, 2009)

Figure 6 illustrates modelled air temperatures along the tube length (T(1) … T(6) are varying points along a 23.42 metre pipe length) at various air velocities. Higher velocities result in a lower exit temperature, compared to lower velocities for the same earth tube geometry. However, the higher velocities result in higher flow rates, resulting in higher total amount of heat transferred than lower velocities for the same tube geometry.

Also, higher velocities usually increase air turbulence, thereby improving air and tube surface heat transfer. The relationship between air velocity, airflow requirement, and tube diameter will provide an improved indication of tube preheating and precooling potential. This is outlined for cooling in Figure 7.

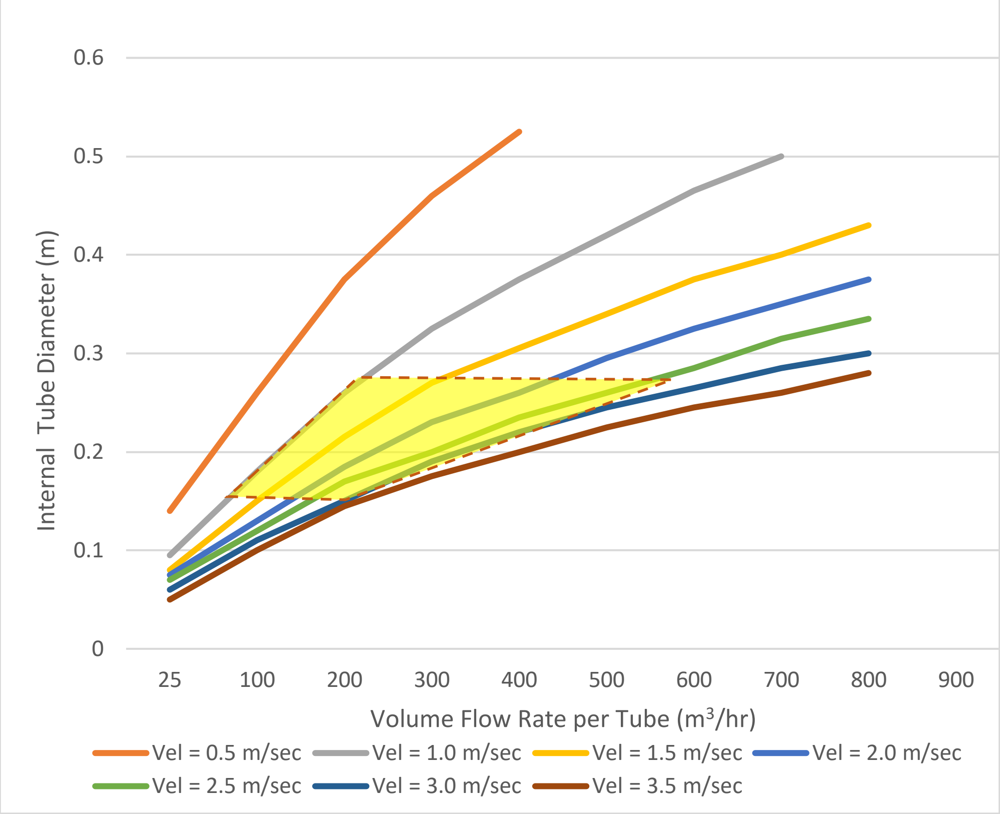


Figure 7: Tube Diameter Related to Velocity and Total Air Flow

Source: (Barnard & Jaunzens, 2001)

Figure 7 provides the recommended tube diameter for a design airflow rate and a desired velocity. A velocity of 2 m/sec is recommended to limit pressure drops (Barnard & Jaunzens, 2001). The recommended design range using the data from Figure 7 would fall within a tube interior diameter of 0.15-0.25 m for air velocities between 1 and 3.5 m/sec, as shown in the shaded area.

It is important to clarify that the earth tube design will be adding pressure to the air handling system, therefore the additional pressure across the tubes and/or header must be included in the air handler fan design.

The system will be designed to provide a required airflow (cfm, L/sec, m^3/sec). Knowing the design requirement and the type of pipe, fittings, elbows, pressure losses, etc., the air velocities can be calculated following fan laws.

The air intake itself requires design consideration. As an air intake to a building, filtering, location, and sizing would need to comply with ASHRAE 62. The air intake must be high enough off the ground to avoid any residues from the ground (moisture, leaf decomposition, lawn treatments) from being easily drawn into the earth to air thermal exchanger (EATEX). Similarly, the air intake should be physically located away from sources of noxious chemicals (away from parking lots, roadways, building exhaust hoods). ASHRAE 62 provides the minimum separation distances between the air intake and areas of potential air contamination.

The sizing of the air intake louvers is a function of the louver free area, louver actual dimensions (height and width), the static pressure drop of the tube(s) and intake pipe, the free air velocity, and the required airflow of the intake. Knowing some of these variables and using tools from louver manufacturers will allow the correct louver sizing for the airflow and air velocity requirements. The Air Movement and Control Association (AMCA) provides standards which indicate how the louver free area is to be calculated based on the dimensions of the louver. Free air velocities below 0.35 m/s (700 fpm) will minimize water induction into the intake (except wind driven or fog/mist). Even if moisture enters the air intake, there needs be a drainage option for the air intake.

The decision of a single air intake supplying multiple earth tubes via a supply header or manifold, versus an air intake dedicated to each tube is more of a logistical and cost consideration than a thermodynamic consideration. The supply air manifold to the entrance of each earth tube will be considered as part of the earth to air thermal exchanger (EATEX) for detailed modelling of performance, as the manifold will thermally interact with the surrounding earth.

2.6 Operations and Controls

Operation of the earth to air thermal exchanger (EATEX) can be continuous, on a schedule, load dependent, seasonal, or a mix of some of these. It is important to note that seasonal operation could eventually affect the long-term performance of the system. The surrounding soil will either gain too much heat from a summer-only operation and be thermally saturated, or lose too much heat from a winter-only operation and be thermally depleted.

When outdoor air temperatures are near indoor setpoint temperatures, bypassing the earth tube and bringing ventilation air directly into the building should be considered. Additionally, bypass should be considered if the earth to air thermal exchanger (EATEX) would produce counterproductive results, such as heating during the cooling season, or cooling during the heating season.

In heating mode, when the tube is active (not bypassed), simply ensure that the outlet air temperature is greater than the inlet air temperature.

In a situation where a bypass is installed, a portion of the incoming air should circulate in the earth to air thermal exchanger to prevent an accumulation of condensate.

2.7 Earth Tube Field Geometry

The design of an earth to air thermal exchanger (EATEX) may involve a single tube, or multiple tubes feeding headers, connected to the building ventilation system. For high airflow rates, multiple tubes are recommended over a single tube, provided that each of the tubes are greater than 10 m in length (Benkert, Heidt, & Schöler, 1997). The spacing between tubes should be no closer than one tube diameter, but recommendations for optimal design vary from three tube diameters (PACTE, 2017) to 1 m (Barnard & Jaunzens, 2001).

The layout can be straight, serpentine, a combination, or installed around the foundation of the building (see Figures 8a, b, c, d, e, f). The decision depends on space availability, however the greater the number of bends, the higher the pressure the fan needs to overcome.

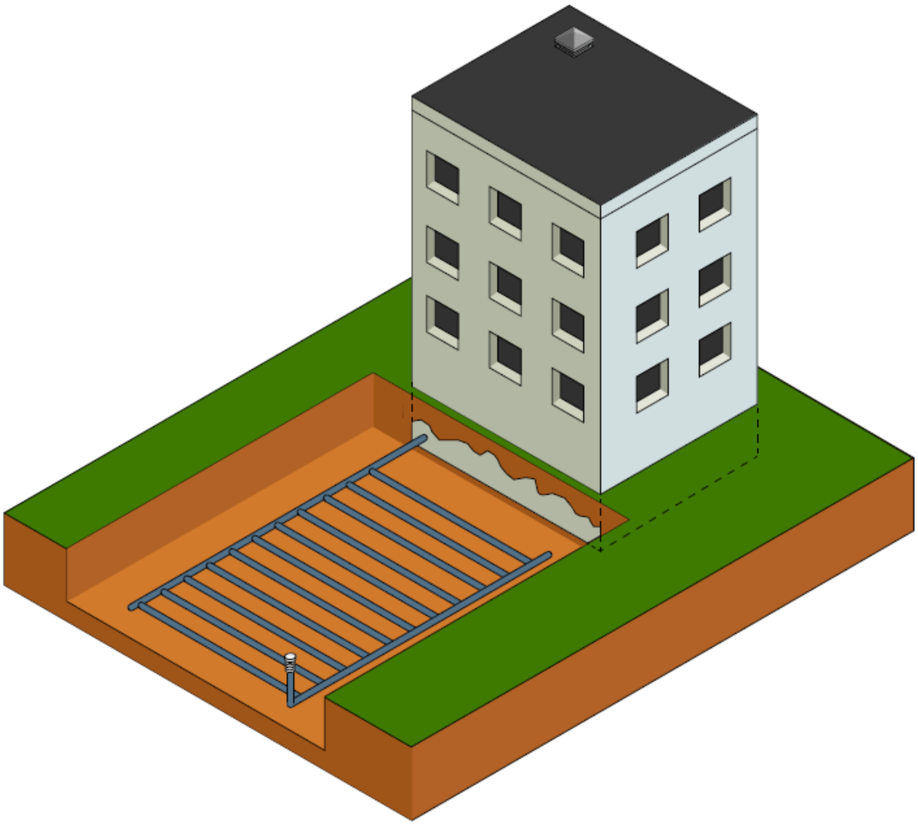


Figure 8a: Multiple Tube Layout Schematic

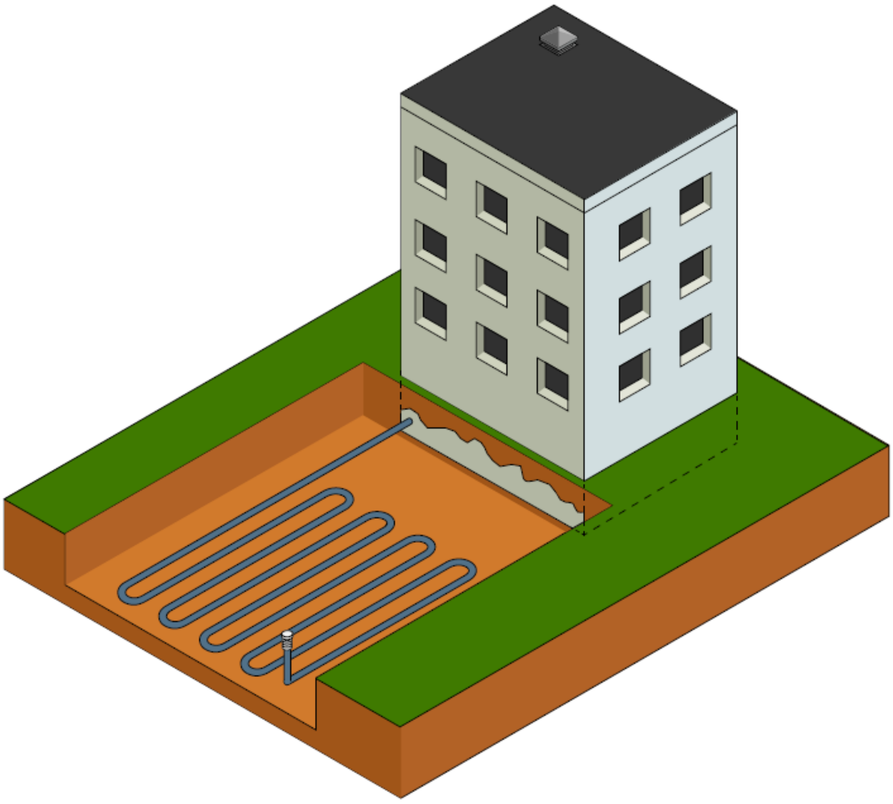


Figure 8b: Serpentine Layout Schematic

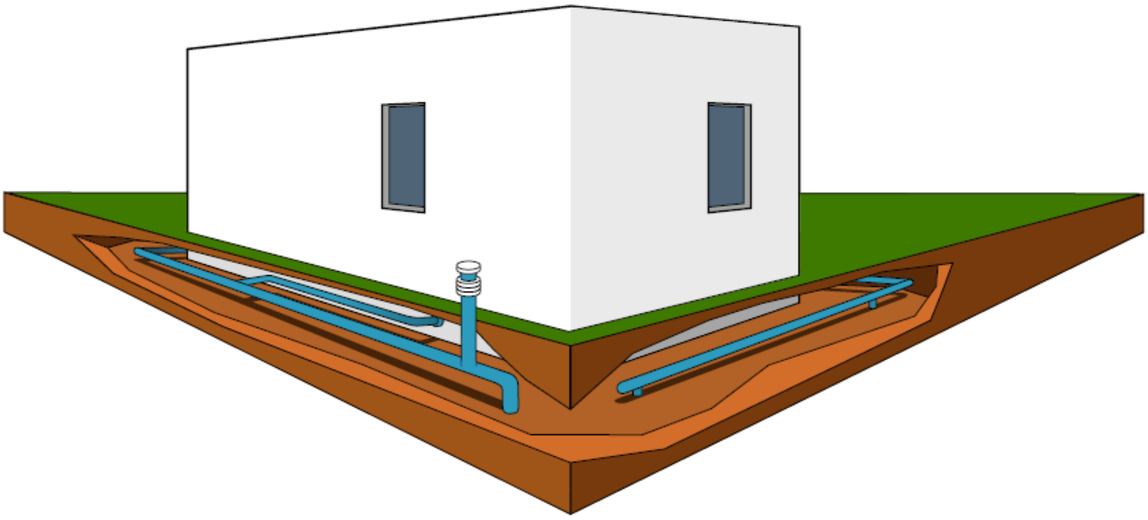


Figure 8c: Foundation Layout Schematic

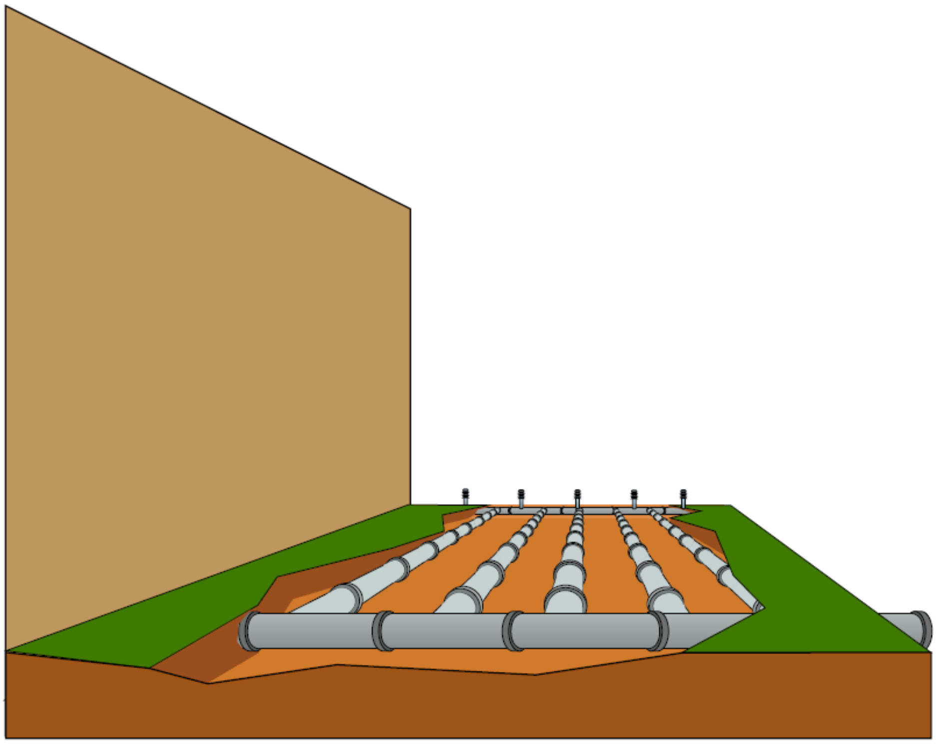


Figure 8d: Multiple Tubes Connected to a Header Tube

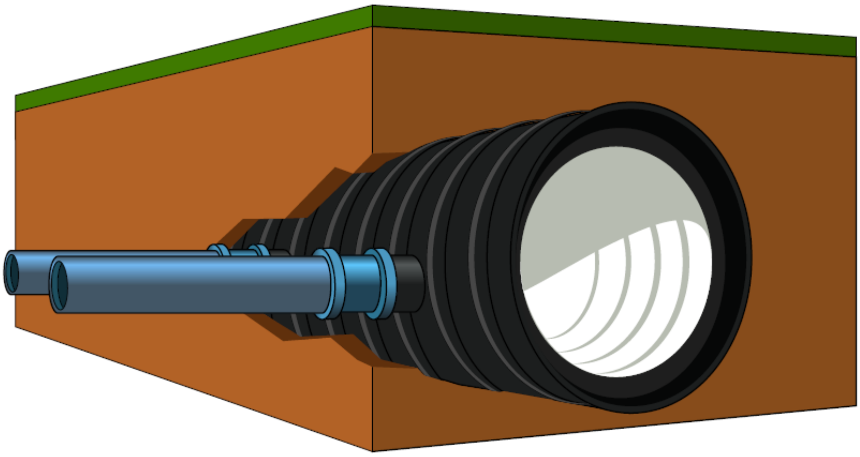
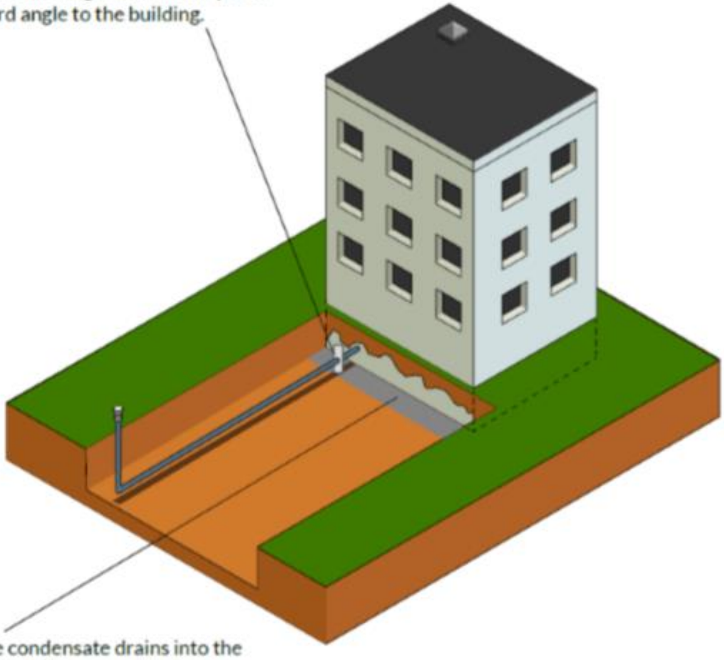


Figure 8e: Header Connection Schematic

Earth tube drainage is a concrete or metal pit with an accessible lid that extends to the building's foundation drainage. The earth tubes enter the pit on a slight angle to promote drainage and exit the pit on an upward angle to the building.



Earth tube condensate drains into the building foundation gravel drainage.

In locations where excessive condensation is an issue, a means of drainage should be considered. Ideally, the drainage may simply involve a drain hole at the base of the intake pipe where the intake pipe meets the horizontal tube. If that is not possible, another option is to create a drainage pit through which the earth tube would pass. In this case, the earth tube passing through the pit would have a hole in it to allow condensation to drain into the pit.

Figure 8f: Drainage Pit Schematic

2.8 Construction Costs

Construction costs are very difficult to generalize in a design guide. Therefore, a few costing considerations will be provided.

2.8.1 Excavation

There are two methods of excavating for earth tube layout: (1) complete excavation of the entire earth tube boundary, or (2) trenching within the earth tube boundary. The choice depends upon budget for excavation and ability to store and move large volumes of soil. For new-build construction projects, it is common that extensive excavation for foundations is carried out in any case, and therefore the earth tubes can be installed prior to backfill with only minor costs associated with groundworks.

The complete excavation method would be used when the layout involves a series of smaller diameter tubes that are placed closely together. In spacing greater than three metres, the volume of material to remove and then replace becomes expensive for contracted excavation, and trenching costs may be more viable for most soil conditions. If excavation costs are not an impediment, then a complete excavation is preferred for multiple tube layouts. A complete excavation will allow consistency of tube placement, depth, slope and backfilling. It also permits installation of drainage devices or insulation above the tube in shallow depth installations (less than 1.5 metres below the surface).

Trenching would be used for a single tube in either a straight or serpentine layout, or for multiple tubes with large spacing.

2.8.2 Tube Materials

The tube and header material itself has cost implications. Concrete and galvanized steel tubing are costlier than PVC/polyethylene piping, even for the same tube diameter. PVC piping should be avoided in connections with building ventilation air – due to chemical off-gassing.

Polyethylene tubing is usually rigid and sold in distinct pipe lengths, which involves purchasing tee and elbow connections for joints and sealing joints. Polyethylene tubing can also be flexible and sold in long rolled tubing format, thereby possibly reducing connection costs. While tee and elbow connections are still required depending on the layout, the number of joints to seal are reduced for flexible polyethylene tubing. Whichever layout and tube material are selected, consider the cost of sealing the joints and dealing with bends.

If concrete or steel piping greater than 1.2 metres in diameter is used, then a method to create air turbulence should be considered to increase heat transfer potential. Vanes and baffles would have to be mechanically fastened to the tube wall, which will add another cost.

2.8.3 Air Intake

The air intake is exposed to the surface conditions; therefore, it must be selected to deal with ambient conditions. It must also include screening and a cover to shed rain and snow and limit wind-induced rain and snow into the intake. Choosing between a single intake and multiple intakes depends on the layout and the airflow requirements of the system.

2.8.4 Drainage

Dealing with drainage can be as simple as allowing condensation to drain naturally into a floor drain (sloping toward building earth tube layout), into the ground at the base of the air intake (sloping away from building earth tube layout), or installing a collection drainage pit with a pump. The decision is dependent on layout; but more importantly, a function of the climate and level of moisture in the air.

2.8.5 Controls

The controls and use of a bypass damper adds costs to the system depending on its operational complexity. However, this would be negligible if the building HVAC system utilised an air-side economiser system for free-cooling.

The initial cost and design should include a maintenance or repair component. With the exception of filter cleaning maintenance, the EATEX system is intended to operate virtually maintenance free for a long period of time. Therefore, the initial design investment should be robust enough such that maintenance is limited to the intake, the accessible drainage pump (if one is installed), and the connection to the building.

Layout, selection of materials, and installation will not only impact the performance and capital costs, but also maintenance and repair costs. By following the recommendations in this guide, a well-designed earth to air thermal exchanger (EATEX) will provide low operational costs, savings in energy consumption, reduced greenhouse gas emissions, as well as a healthier indoor environment for building occupants.

2.9 Design Steps

The design principles described above result in the following general design steps:

1. Determine the total volumetric flow rate required for building ventilation air (l/sec, cfm m^3/hr).

2. Calculate the earth tube diameter to provide the required flow rate by:
    a. Using smaller diameter tubes (0.15 m < diameter < 0.25 m is optimal, see Figure 7)
    b. Using air velocities between 1- 3.5 m/sec is optimal (see Figure 7)

3. Calculate the number of tubes required to meet the total airflow required using the selected tube diameter and velocities. Determine the number and size of the air intakes to meet the airflow requirement.

4. Keeping in mind the number of tubes and their diameters to meet the required airflow, determine the layout: linear with a header, serpentine, building foundation perimeter, or combination. Include the location and number of air intakes in this layout.

5. Determine the moisture drainage strategy by either sloping (2 degrees minimum) the tubes to a drainage pit, creating a drainage pit with a condensate pump, or connecting drainage to storm water run-off device.

6. Determine the length of tubes based on space in the field with a spacing between the tubes or serpentine passes no closer than one tube diameter and ideally one metre. Ensure length is greater than 10 m. Maximum length is around 80 m. The practical length will be governed by the site itself, but a minimum length of 30 – 40 m is necessary for earth tubes to provide sufficient thermal performance. This will provide a general indication of the overall area of the earth tube field.

7. Determine depth of proposed installation based on site conditions and cost, with an optimal depth of 3-5 metres below the surface. At depths over five m, the tube material will require extra consideration related to earth cover loading. If cost or site conditions (bedrock) preclude deep

installation, consider adding 50 mm of extruded polystyrene insulation above the top of the tube and extending the insulation 2-3 tube diameters on either side of tube for the entire length of the tube. The design will have to consider the cost of insulation above the tube versus the cost of trenching deeper or the cost of an additional trench. The incremental cost of the additional trenching may be minimal compared to the material and labour cost of adding insulation above the tubes.

8. Determine, based upon the layout and cost, whether the entire earth tube boundary area will be excavated for installation or whether trenching will be used for installation.

9. Select the tube material (thermal performance, cost, ease of installation, maintenance).

10. Determine the number of tees, elbows, tube connections (to a header or supply air intake), obstructions to airflow to determine the additional fan energy required.

11. Determine the operation of the EATEX system and how it will interact with the building's automation system, air handling system, and overriding controls.

There are a few construction considerations that should be followed:

1. Install on a 2-degree slope and lay tubes as flat as possible to encourage drainage.
2. Avoid tubes with holes (drainage pipes), especially in radon suspect areas and if they are used wrap the tubes in an underground rated cloth.
3. Backfill with materials as dense (e.g. fine sand) and compact as possible to enhance heat transfer.
4. Moisture will likely be present at various times of the year but should dissipate quickly. Ensure that all tube connections are well sealed to avoid ground water and radon points of entry.
5. Ensure air intakes are elevated to avoid entry of radon, and vehicle or other exhaust fumes have adequate screening and rain/snow shielding.
6. Ensure that the air intake has drainage (fog, mist, wind-driven rain, condensation).
7. Establish the location of the air intake in accordance with ASHRAE 62 and by considering the primary need of the EATEX system: shaded areas for cooling priority systems and sunny areas for heating priority systems.
8. If the earth tube is used predominately for precooling, then locate the air intake in a shaded area.
9. Ensure air intakes and exterior access to the earth tubes prohibits wildlife habitation.
10. Filtering is required on the air intake and the screens/filters need to be accessible for cleaning related to dust, sand, pollen, and particulate build-up.
11. If the design includes an inline fan to supply preheated/precooled air directly to a space instead of interconnecting to an air handling system, ensure that the fan is accessible, as the air environment will be humid seasonally which will greatly reduce the life of the fan.
12. If the design depth is limited (less than three metres below the surface), consider anchoring the tubes if seasonal ground water is present or if the depth of winter freezing is close to the top of the tubes.
13. If the earth tube diameter is greater than 1.8 m, consider adding interior devices such as vanes and baffles to encourage air turbulence, thereby increasing heat transfer between the air stream and tube wall surface.

The interaction of various design parameters described above will affect the preheating and precooling performance of the earth to air thermal exchanger (EATEX). They need to be considered together in conjunction with the ventilation heating and cooling requirements and the overall performance requirements of the earth to air thermal exchanger (EATEX). Various design tools and models of different levels of complexity exist to evaluate the parameters affecting earth tube thermal performance.

3.0 Design Tools

A few earth tube design tools are described in the literature (Hollmuller & Lachal, 2014; Muehleisen, 2012; Ahmed, Ip, Miller, & Gidado, 2009; Benkert, Heidt, & Schöler, 1997), but they are either not readily available, difficult to use, or use models that have not been validated with experimental data. The early design tool presented in this guide is easy to use and uses a validated model (Hollmuller & Lachal, TRNSYS compatible moist air hypocaust model, 1998).

3.1 Approach to Design Tool

Using a model by Hollmuller and Lachal implemented in TRNSYS, a series of simulations were conducted for the parameters and inputs shown in Table 4. Two years are simulated to allow for the ground temperatures to stabilize, and only the second year of results are used as outputs. The TRNSYS time step is set to 0.5 hours, but the model may use a smaller internal time step to ensure convergence.

The 2016 version of the Canadian Weather Year for Energy Calculation (CWEC) data files were used for climate data (Meteorological Service of Canada, 2018a). The dry bulb temperature and relative humidity were used as inlet conditions for the earth tubes, and the total horizontal incident solar radiation, wind speed, and dry bulb temperature were used to calculate the sol-air temperature and impose this temperature as the top surface temperature. Average monthly snow depth data (Meteorological Service of Canada, 2018b) was used to estimate thermal resistance caused by snow at the surface. An average density of 300 kg m^{-3} (representative of settled snow) was assumed (Patterson W. , 1994) to calculate a thermal conductivity of 0.126 W $m^{-1}K^{-1}$ (Sturm, Holmgren, König, & Morris, The thermal conductivity of seasonal snow, 1997). It was found that modelling a distance of 14 m below the tubes and 10 m laterally was enough to represent the system, with additional distance in either direction not having significant impact on the results. The bottom and lateral boundary conditions were set to adiabatic. More details on the methodology are available in a paper by Brideau, Lubun, and Tardif (2018).

Outputs from each simulation are: average hourly inlet and outlet temperature profiles for each month, monthly cooling and heating energy to the air stream, and monthly percentage of time when moisture is extracted from the air stream. Data for each geographic location (as defined by the climate files) is saved as a comma separated text file, which we will refer to as a *database*. This modular approach allows the user to only download the required location(s). A database must then imported to the main design tool Excel spreadsheet to analyse the data, with the help of drop down menus, graphics, and formatted data. The user could, in theory, also use only the databases without the design tool Excel spreadsheet, but this is not advised.

Table 4

Input Parameters

Parameter	Input Selections	Notes
Climate file	Various	Using CWEC 2016 files
Inner diameter D_i (m)	0.142, 0.185, 0.273, 0.457, 0.762, 1.07	-
Material	Polyethylene, Concrete, Galvanized	Concrete and galvanized steel only evaluated for largest diameter
Soil Type	Heavy soil saturated Heavy soil damp Heavy soil dry Light soil dry	k (W/(m-K)) and ρC_p (J /(m^{3}-K)): 2.42, 2.6770x10^{6} 1.30, 2.0155 x10^{6} 0.865, 1.6764 x10^{6} 0.346, 1.2357 x10^{6}
Depth (m)	1.5, 3, 5	From grade to top of tube
Tube Spacing	$1D_o$, $2D_o$, $3D_o$	$1D_o$ = 1 diameter of pipe spacing
Length (m)	15, 40, 65, 100	Length per tube
Layout	Header, Serpentine	Header = single or multiple length tubes connected in parallel
Layout	If header: enter number of parallel tubes If serpentine: enter number of tube passes in serpentine loop	
Air velocity (m/s)	1, 1.5, 2, 2.5, 3, 3.5, 4	
Fan Efficiency		Value: 0 – 1.0
Minor Loss Coefficients for a single tube		Value to account for pressure drops due to fittings, elbows in the tube (C value in industry handbooks) Default = 15
Schedule	Always ON, Schedule	Schedule means ON weekdays from 7AM to 8PM

3.2 Input Data

The design tool is an interface to a large database of simulation results. The tool allows user selection of various parameters (listed in Table 4) and determines the potential monthly heating and cooling effects, average supply air temperature impact, and likelihood of condensation. The tool input data is composed of two basic analyses: earth tube analysis and a comparative ventilation air recovery system analysis. Ventilation air preheating and precooling can be accomplished through a number of strategies. A common design trade-off is the decision of earth tubes versus heat recovery for ventilation preheating/precooling. Both can be used in conjuction with the other but usually capital costs impact the decision. Therefore, the tool calculates the energy impact of both options and compares them.

The following steps will guide the user on how to use the design tool:

1. Load the tool by opening “DesignTool_macro_v2.xlsm” (requires Microsoft Excel 2016).

2. Select “Import Data” to access the data for the specific weather file. The Excel data files are located in a folder that contains the tool and are labelled “databaseCITY.csv”.

The tool uses CWEC long-term average weather data, which creates an average weather file representing the measured (or modelled) weather data for 30 years of data through 2014. The CWEC files are available at http://Climate.OneBuilding.org.

An analysis of the results of the earth to air thermal exchanger (EATEX) using CWEC weather compared to actual 2017 and 2018 weather was completed and is described in section 3.4 Weather Impact on Design Tool Output.

Tool Input Parameters

1. Select the type of "Schedule" from the two options: "Always On" or "Schedule".

   Schedule assumes the system (fan operation) is operating from 7 am to 8 pm, Monday through Friday. If the user's schedule is different, it is possible to estimate results for a different schedule. Both types of schedules (AlwaysOn and Schedule) should be run, and the results for a different amount of scheduled operating hours should be interpolated based on those results.

   Example 1. For a certain geometry and flow rate, one wants to know the heating energy results for the month of January for a schedule operation between 7 am and 6 pm 7 days per week.

   Results of both Schedule types are:

   Always On Jan Heating = 1441.11 kWh

   Tubes running for 31 days X 24 hours/day = 744 hours

   Calculate Average Heating Power:

   Ave Power = 1441.11 kWh / (744 hours) = 1.94 kW

   Schedule Jan Heating = 855.28 kWh

   Tubes running 13 hours per day x 5 days per week x 4.43 weeks/month = 287.95 hours

   Calculate Average Heating Power:

   Ave Power = 855.28 kWh / (287.95 hours) = 2.97 kW

   Desired Schedule: 7 days/week – 7 am to 6 pm

   Calculate hours per month for the desired schedule: 11 hours/day x 31 days = 341 hours

   Calculate the average heating power for the desired schedule by interpolating with the amount of hours the tubes are running

   $P_{\text{interpolated}}$ = (341 hours – 287.95 hours) / (744 hours -287.95 hours) * (1.94 kW – 2.97 kW) + 2.97 kW = 2.85 kW

   Estimated kWh for January = 11 hours/day x 31 days x 2.85 kW = 971.85 kWh

2. Select the closest velocity in m/sec (1, 1.5, 2, 2.5, 3, 3.5, 4). If you are unsure of the velocity setting, select any velocity and then continue data entry to obtain the desired airflow rate that the system is preheating/precooling. The tool generates the airflow rate (m^3/h and cfm) based on the velocity, number of tubes, and diameter of tubes.

It is assumed that the velocities are average amongst all tubes in a header configuration. In reality, there can be up to a 20% difference in measured air velocities in parallel tubes (Tardif, Lubun, Ouazia, Booth, & Nordquist, 2014).

3. Select the length of each tube if the design is a header configuration, or the total length if the design is a serpentine or continuous loop (building perimeter installation) configuration. If the header installation is of varying lengths, enter the closest average length. If the length is between the available parameters, you may obtain results above and below the desired length, and interpolate for the desired length.

   Note: Do not include the collection header/plenum or air intake in the tube length entry. The tool only calculates the preheating and precooling of the tubes below grade. The header and air intake will provide additional preheating and precooling, but these calculations are normally small and are beyond the scope of the tool. A detailed earth tube model would be required to account for the added thermal effect.

4. Select the spacing of the tubes as a function of the tube outer diameter D_o. For example, $2D_o$ means 2 diameter spacing between tubes in a parallel header installation or the spacing of tubes passes in a serpentine installation (see Figure 8). Select $3D_o$ for a single tube far from a wall, or for spacing beyond three tube diameters. The spacing is assumed to be the same for all configurations.

5. Select an estimate of depth as 1.5 m, 3 m or 5 m. It is assumed that the tubes are at the same depth for multiple tube installations and the depth is from the grade to the top of the surface of the tube.

6. Select the soil type from the four possible options.

Table 5

Concept Tool Soil Types

Soil Type	Thermal Conductivity	Thermal Diffusivity	Heat Capacity
	W/(m²-K)	m²/sec	J/(m³-K)
Heavy & Saturated	2.42	9.04E-07	2.667E6
Heavy & Damp	1.3	6.45E-07	2.0155E6
Heavy & Dry	0.86	5.16E-07	1.6764E6
Light & Dry	0.346	2.80E-07	1.2357E6

Various soil parameters such as backfill materials, drainage materials, different soils and properties from the surface boundary to the pipe, compaction, and detailed surface materials (sod, leaves) will have an impact, but this conceptual model includes the major soil temperature parameters.

Use the properties of the backfill material to determine the appropriate option. Heavy and saturated is predominately wet sands. Heavy and damp could be either clays, loams, or lighter sands depending on moisture content. Heavy and dry is usually a lighter clay loam mix and light dry is predominately loams. The thermal properties are assumed to be constant throughout the year, as seasonal effects of ground thawing, snow melt, and rainy seasons on the soil moisture and underlying thermal conductivity have not been included in the tool.

If the tube is being installed in gravel, select a value that is suitable, as gravel has a relatively low bulk thermal conductivity and thermal mass because of interstitial air.

7. Select the closest earth tube inner diameter to the material being used. Options are: 0.142 m, 0.185 m, 0.273 m, 0.356 m, 0.457 m, 0.578 m, 0.762 m, and 1.07 m (0.356 m and 0.578 m were not modelled explicitly, but results are interpolated in the tool based on nearest diameters). Corresponding tube wall thicknesses are: 0.01 m, 0.02 m, 0.02 m, 0.03 m, 0.04 m, 0.05 m, and 0.06 m. For the 1.07 m tube, two additional options are available for material: concrete, and galvanized steel. The corresponding tube wall thicknesses are 0.13 m and 0.003 m.

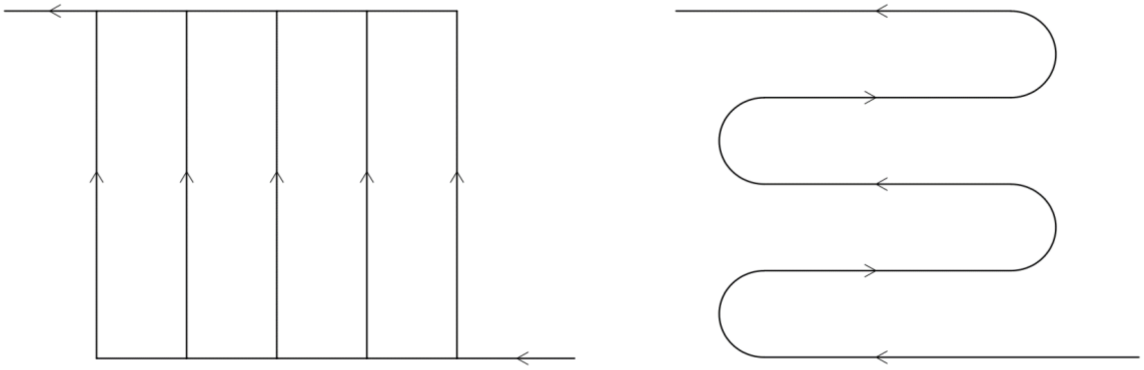
   If the pipe material is corrugated, such as drainage pipe or galvanized steel, use the innermost diameter. However, using corrugated tube is not recommended due to issues with condensate drainage. A common type of polyethylene drainage pipe is a double wall construction, with a corrugated exterior surface polyethylene pipe bonded to a smooth inner surface polyethylene pipe. The diameter would be the thickness of the inner surface pipe.

   Select the type of material for the tube from the three options (polyethylene, concrete, steel). Select polyethylene for any plastic materials, as their thermal conductivities are similar. The other materials are only available in 1.07 m diameter tubes.

8. Enter a fan efficiency between 0 and 1. The fan efficiency is for the fan that pulls the air through the earth tubes. This could be a dedicated fan or an air handler fan. It can be viewed as the additional fan power the earth tubes adds to the air handling system. The output report will provide an estimate of the additional fan power required due to the EATEX system. If the system is small enough that the building air handler fan can accommodate the EATEX system without an increase in size, enter an efficiency of 1.

9. Enter the extra loss coefficient for a single tube to account for bends, pipe friction, obstructions (baffles, filters), and fittings. The loss coefficient is used to generate the additional pressure (static) that the fan must overcome to maintain the entered velocity. The values for the single tube will be used for all tubes in a header configuration and for all passes in a serpentine layout. The loss coefficient (C_o or K) varies according to the diameter of the tube, size and shape of fittings, bends, etc. Add all of the loss coefficients for a single tube, including the supply air intake and connection to the tube and the tube connection to a header or the air handling system.

10. Enter the layout as either header or serpentine (see Figure 9). If the layout is neither, such as a single tube, then enter header with a single tube (next entry). A single tube with small bends is still considered a header layout with a single tube.



Header configuration with 5 parallel lengths   Serpentine configuration with 5 passes

Figure 9: Earth Tube Layout Configurations

11. Enter the number of tubes installed in parallel for a header layout or the number of passes for a serpentine layout. If the layout is irregular, use your best judgment.

    To assess an earth tube installation around the perimeter of a building (see Figure 10), select serpentine layout with one pass and the spacing corresponding to the distance between the tube and the foundation if the tube is looped once around the foundation. If the tube is looped more than once, choose the actual tube spacing, add one to the amount of loops around the building for the amount of passes (e.g. for a building with three loops, enter four passes). The model assumes no interaction with the building (adiabatic boundary condition); therefore, the earth tube performance results may be impacted.

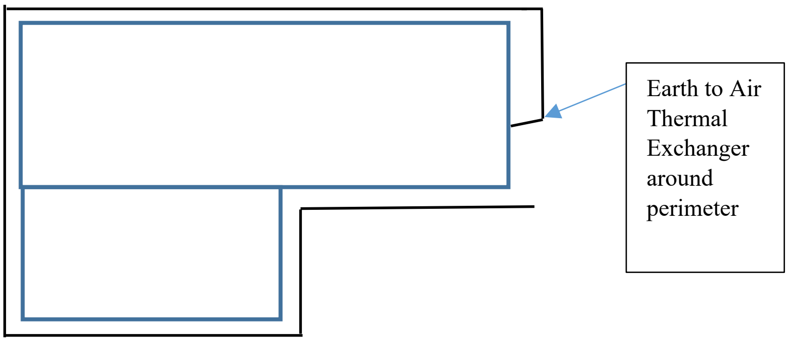


Figure 10: Earth Tube Layout Around Foundation Perimeter

Ventilation Air Heat Recovery Input Parameters

Since the heat recovery analysis is calculated for comparative purposes only, the entries below should match the earth tube velocity or airflow entries. The heat recovery device assumes a balanced airflow.

1. Enter the setpoint temperature during the cooling season. If a setback strategy is employed, enter the average hourly cooling temperature. Natural cooling (economizer or night cooling controllers) is automatically assumed when the outdoor air enthalpy is lower than the indoor air enthalpy. Therefore, enter the mechanical cooling setpoint. This value will be used to determine the potential heat recovery energy.

2. Enter the desired building relative humidity setpoint (% RH) during the cooling season. If night cooling is employed with an enthalpy controller, then determine the average RH that is desired during the cooling season with mechanical cooling.

3. Enter the setpoint temperature during the heating season. As with the cooling setpoint input, calculate the average setpoint temperature based upon setbacks.

4. Enter the desired building relative humidity setpoint (% RH) during the heat season.

5. Enter the heat recovery effectiveness (35 ˚C, 0 ˚C, -25 ˚C). The rated recovery efficiency printed on equipment literature is adequate. Do not include electric preheaters and defrost device impacts on the efficiency, as the required input is the core effectiveness related to temperature and humidity only. A defrost strategy is not included in the comparative analysis.

6. Enter the first and last month of the cooling season. This is the period of the cooling comparative analysis and the calculation will be completed for all hours in the month.
7. Enter the pressure (in pascals) across the heat recovery core on the supply side of the heat recovery/energy recovery device. This is used to calculate the power requirements of the supply fan/motor. It includes the effects of air filters, defrost devices, preheaters, bypass dampers, and ducting. Typical values are 4-45 pascals for enthalpy wheels and 7-30 pascals for plate type and glycol loops.
8. Enter the pressure (in pascals) across the heat recovery core on the exhaust side of the heat recovery/energy recovery device. This is used to calculate the power requirements of the exhaust/return fan/motor. It includes the effects of filters, bypass dampers, and ducting. Typical default values are similar to supply side assumptions.
9. Enter the efficiency of the supply and exhaust fan/motor as a decimal value.

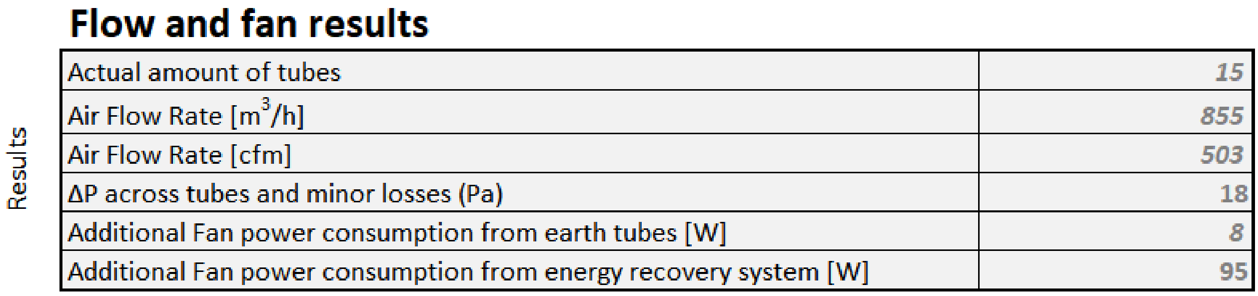
3.3 Tool Ouput Report

Once inputs are entered, outputs are automatically calculated and the spreadsheet is populated. First, a summary report is shown (see Table 6). In the orange cell is the location of the database, in the blue cells are the inputs, and in red fonts are the summary outputs. The summary outputs include:

1. Number of actual tubes
2. Airflow rate (m^3/h and cfm)
3. Additional fan power (watts) based on flow rate, pressure drop, and fan efficiency
4. Pressure drop (Pa) across the tubes (excludes the intakes and header pressure influences unless these have been factored into the loss coefficients)

Table 6

Output summary report



Flow and fan results

Results	Actual amount of tubes	*15*
	Air Flow Rate [m^3/h]	*855*
	Air Flow Rate [cfm]	*503*
	ΔP across tubes and minor losses (Pa)	18
	Additional Fan power consumption from earth tubes [W]	*8*
	Additional Fan power consumption from energy recovery system [W]	95

Graphs of monthly heating and cooling heat transfer across the tubes are also provided. An example is provided in Figure 11 and the total heating/cooling potential in comparison with the entered heat recovery comparison system is provided in Figure 12. The entry of the cooling season for the heat recovery comparative system determines the heat recovery potential as either heating or cooling, whereas the EATEX calculates net energy potential for the specific month (months can be partially heating and cooling). In Figure 12, April was selected for heat recovery for space heating, whereas the EATEX system calculated April's cooling potential as predominant. Placing the mouse cursor on the bar graph (in the tool) reveals the actual kWh value. Using the data for April, Figure 11 had a heating potential of 129.75 kWh and a cooling potential of 421.56 kWh. The data shown in Figure 12 is the net effect of this (290 kWh).

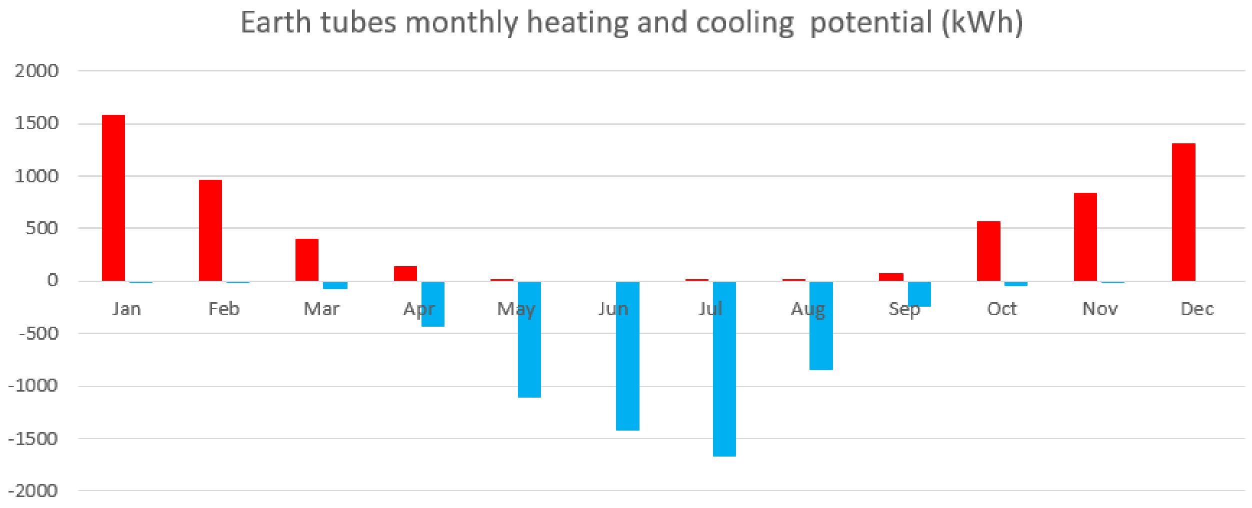


Figure 11: Monthly Total Heating and Total Cooling Potential

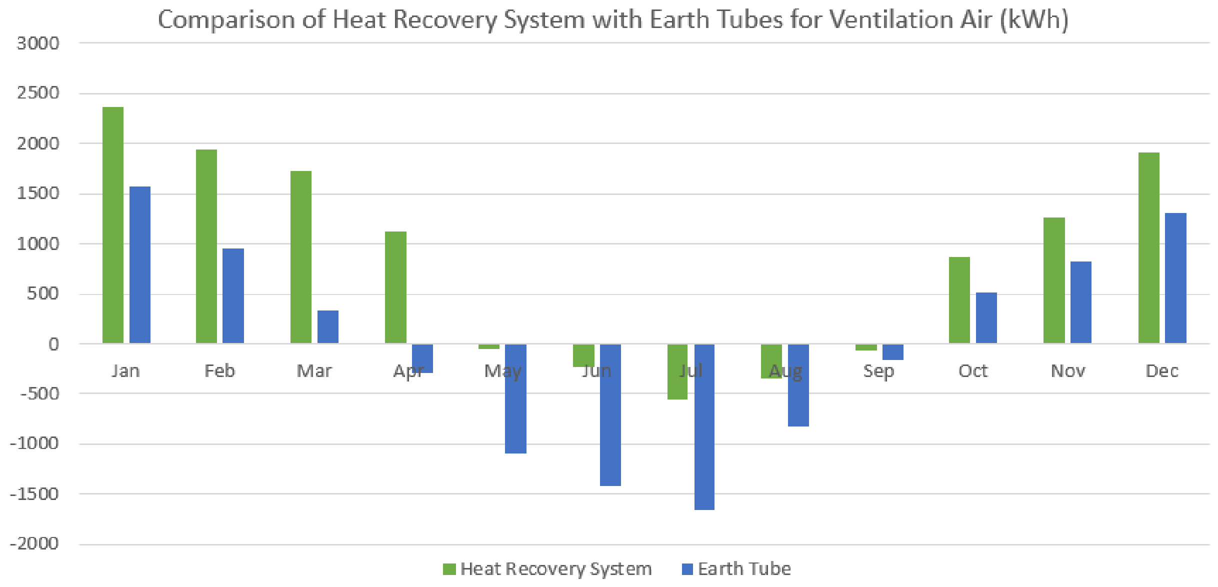


Figure 12: Heating and Cooling Comparison of Eath Tubes and Heat/Energy Recovery Systems

A graph for the “Average Daily Temperature Profile by Month” is provided in Figure 13. It provides a summary of the earth tubes’ inlet (ambient dry bulb) temperature and outlet (preheated/precooled) temperature. This is the average hourly profile for the month.

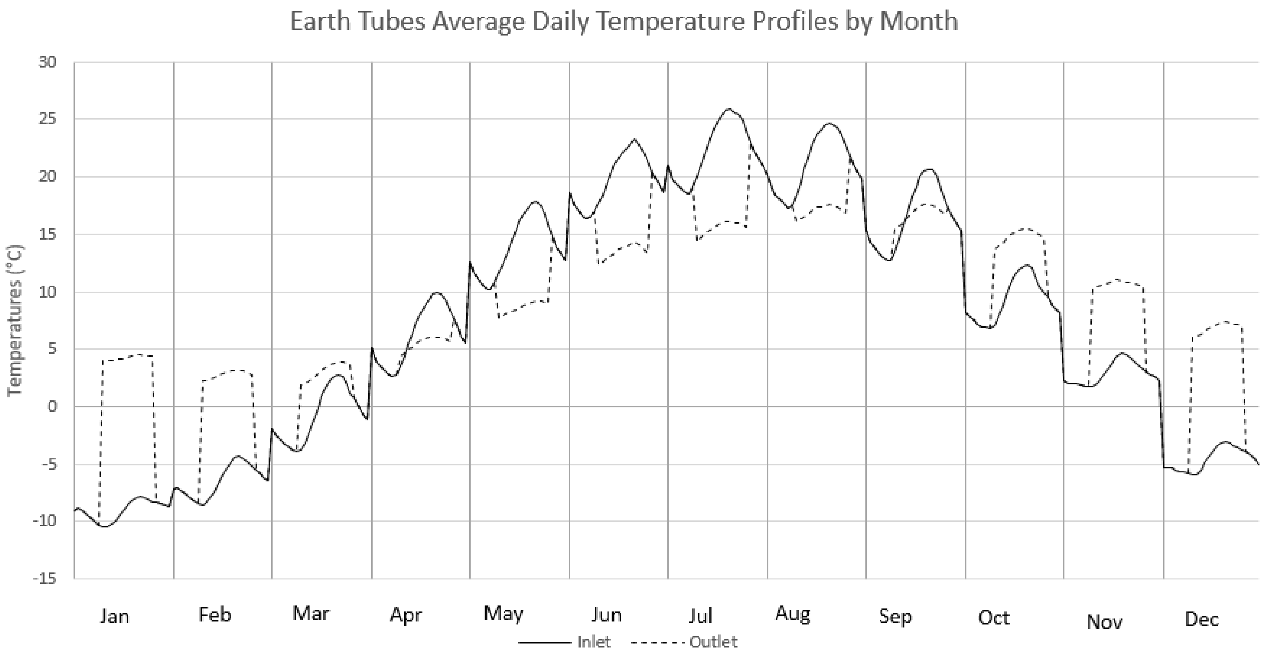
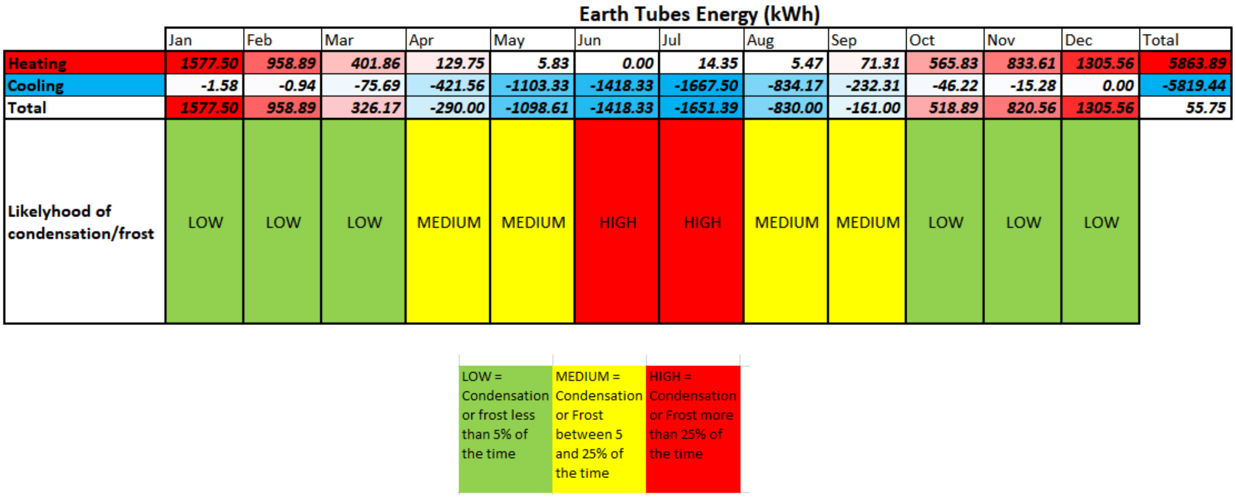


Figure 13: Average Daily Temperature Profile by Month Example Output

Figure 14 provides the data shown in Figures 11 and 12 for heating and cooling energy. Additionally, a likelihood of condensation or frost in the tubes is given for every month.



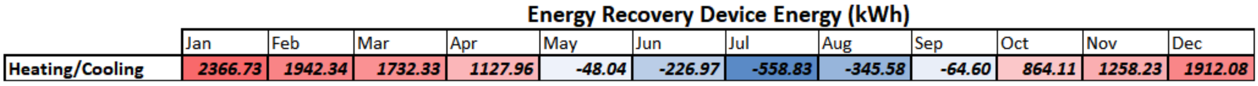
Earth Tubes Energy (kWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating	*1577.50*	*958.89*	*401.86*	*129.75*	*5.83*	*0.00*	*14.35*	*5.47*	*71.31*	*565.83*	*833.61*	*1305.56*	*5863.89*
Cooling	*-1.58*	*-0.94*	*-75.69*	*-421.56*	*-1103.33*	*-1418.33*	*-1667.50*	*-834.17*	*-232.31*	*-46.22*	*-15.28*	*0.00*	*-5819.44*
Total	*1577.50*	*958.89*	*326.17*	*-290.00*	*-1098.61*	*-1418.33*	*-1651.39*	*-830.00*	*-161.00*	*518.89*	*820.56*	*1305.56*	*55.75*
Likelyhood of condensation/frost	LOW	LOW	LOW	MEDIUM	MEDIUM	HIGH	HIGH	MEDIUM	MEDIUM	LOW	LOW	LOW	

LOW = Condensation or frost less than 5% of the time	MEDIUM = Condensation or Frost between 5 and 25% of the time	HIGH = Condensation or Frost more than 25% of the time

Figure 14: Heating and Cooling Energy Results

Figure 15 shows annual heating and cooling potential of the heat recovery device entered for comparative purposes. This is core energy recovery potential net of fan energy, and does not include the effect of preheaters and defrosting energy.



Energy Recovery Device Energy (kWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating/Cooling	2366.73	1942.34	1732.33	1127.96	-48.04	-226.97	-558.83	-345.58	-64.60	864.11	1258.23	1912.08

Figure 15: Energy Recovery Device Energy

Another graphic is presented in the DetailedResults tab of the tool. This graphic provides the average hourly inlet and outlet temperature of the earth tube for each month for the specific data input. This is the data used in the average daily profiles (Figure 13). The data is presented for information and can be entered into an hourly simulation engine for detailed design modelling purposes.

3.4 Weather Impact on Design Tool Output

The tool uses CWEC weather data, which is a created hourly data file based upon 30 years of recorded or modelled data (1984 – 2014). While long-term average data provides an average trend in the future, the performance of an earth tube or any HVAC equipment is based on localized actual data. To understand how the long-term average correlates to actual measured weather data, the tool was run with CWEC data and actual data for 2017 and 2018 for Ottawa for the following earth tube configuration (see Table 7).

Table 7

List of inputs required

Schedule	AlwaysON
Velocity (m/s)	1
Length (m)	65
Spacing Factor	2Do
Depth (m)	3
Soil Type	Heavy soil damp
Inner Diameter (m)	0.185
Material	Polyethylene
Fan efficiency (0.0 < η ≤ 1.0)	0.9
Sum of minor loss coefficients for single tube (CO)	15
Type of layout	Headers
If header configuration: amount of parallel tubes. If serpentine configuration: number of tube passes (ℤ≥0)	6

The results are presented in Figures 16 to 18. The difference as a percentage compared to the CWEC results was 2.6% higher heating energy production using 2018 actual weather data and 7% reduced heating energy production using 2017 actual weather data. The difference as a percentage compared to the CWEC results was 18.8% higher cooling energy production using 2018 actual weather data and 6.7% increased cooling energy production using 2017 actual weather data.

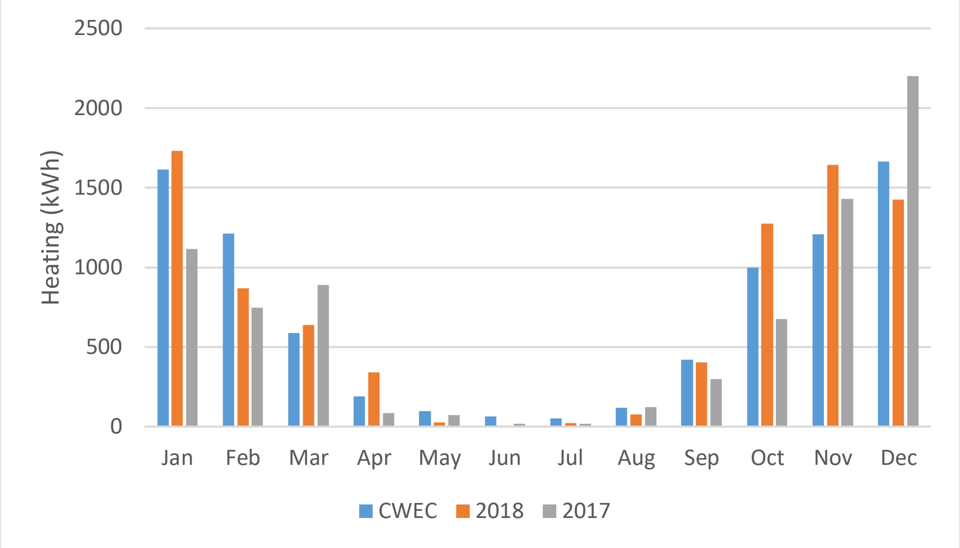


Figure 16: Monthly Heating Production

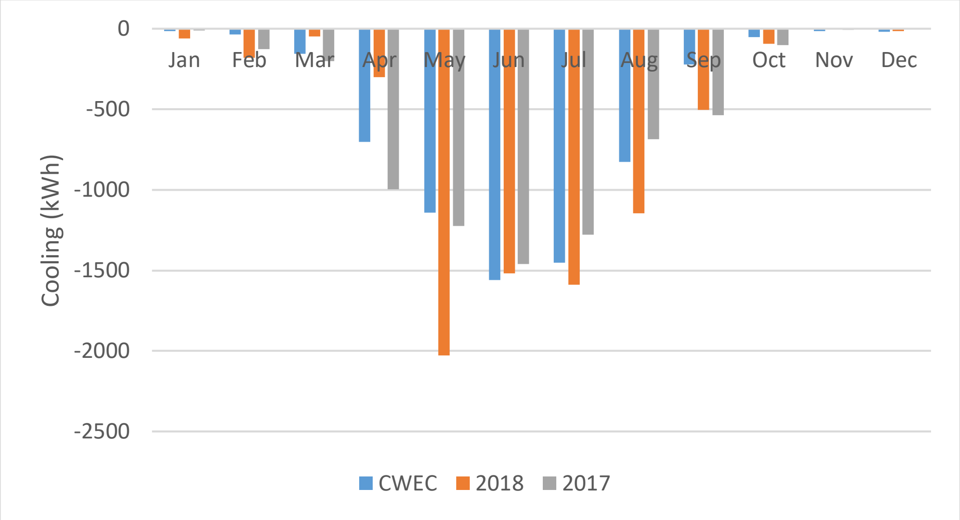


Figure 17: Monthly Cooling Production

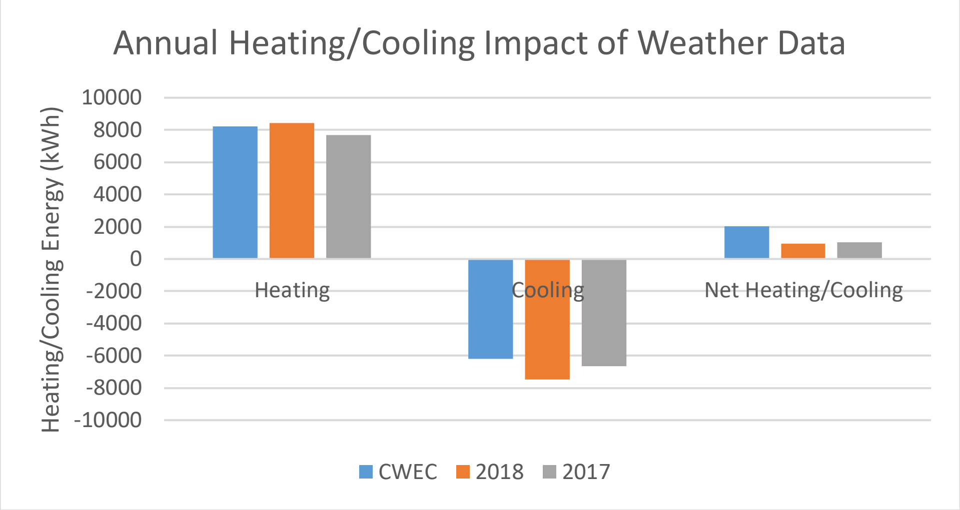


Figure 18: Heating, Cooling and Net Annual Production

3.5 Design Tool Prediction Comparison with Measured Data

A detailed monitoring program was completed on two EATEX projects in the Toronto area between 2015 and 2018. The monitoring that occurred at the University of Toronto: Scarborough Campus is presented here, as this site allowed more detailed monitoring and included seasonal soil conductivity and diffusivity measurements (using a KD2 Pro Thermal Properties Analyzer). The site has six 2 m diameter concrete earth tubes of varying lengths (20 to 30 metres), each with an air intake. The tubes connect to a large supply plenum header, which is connected to the building's air handling system. The entire EATEX system is preheating and precooling between 12,270 and 17,000 L/sec (26,000 and 36,000 cfm) of outside air.

Detailed monitoring occurred at three of the six tubes, while minimal monitoring occurred at the remaining three tubes. Under the detailed monitoring, monitoring stations were installed at the entrance of each tube, at the midpoint, and at the discharge into the supply plenum header. At each station, earth tube surface temperature sensors and ground temperature sensors were installed at the four cardinal directions and air velocity, temperature, and humidity were measured in the air stream. In addition, a soil conductivity probe was installed. The minimal monitoring for the three remaining tubes included air temperature, humidity, and velocity at the entrance, midpoint, and discharge point of each tube. The tube surface and soil temperatures were omitted. The data was continuously measured and 3-minute average data was archived over a 13-month period (August 2017-September 2018).

The results of the monitoring were compared to the model predictions and the results are presented in Figure 19 for one of the tubes (results fairly similar for the other two tubes monitored in detail). The unit for data presented on the y-axis is Kilojoules. The measured and modelled data track reasonably well, except the winter. This is due to a building automation system (BAS) control strategy employed affecting the measured data, which involves bypassing the earth tube when the outside air temperature is lower than - 5 °C.

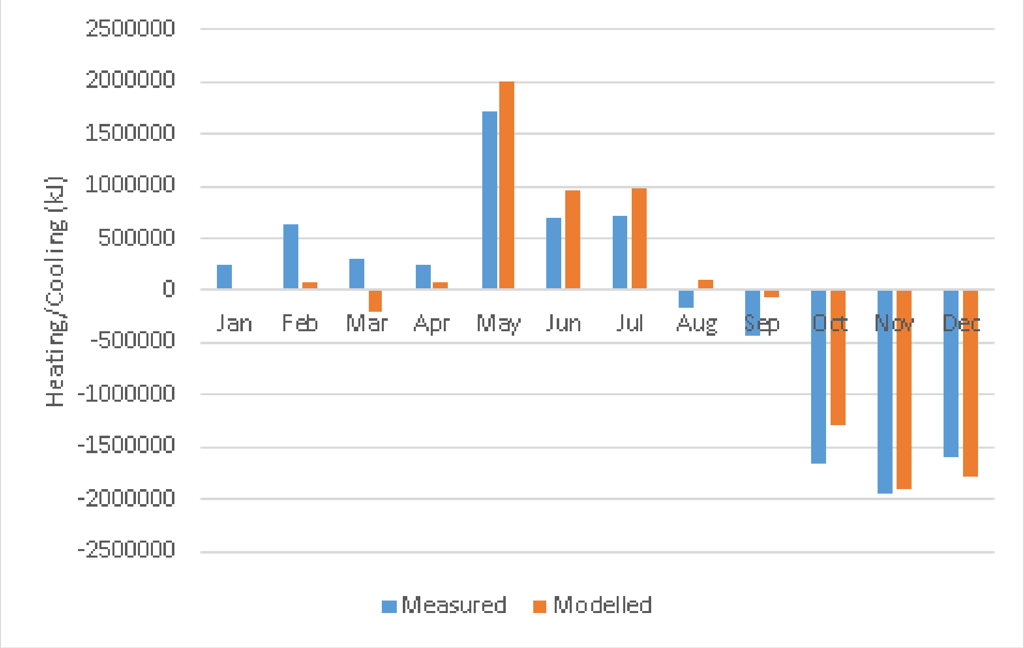


Figure 19: Comparison between Measured and Modelled Data

4.0 In-Situ Monitoring of Earth Tubes Energy Performance

This section outlines some recommended monitoring points for simple assessment of the performance of earth tubes. It is recommended that measurements are taken sub-hourly (hourly averages of sub-hourly measurements are appropriate). These are not comprehensive recommendations and each project should be assessed carefully.

Inlet and outlet temperatures and relative humidity (RH)

The inlet and outlet temperatures should be monitored with the sensors installed in approximately the centre of the tube (see Figure 20). If possible, adding RH sensors to the inlet and outlet is a great addition to temperature sensors, and adds little cost. Having temperature and RH allows for verifying if condensation occurred in the tube by comparing the inlet and outlet dew point temperatures, as well as calculating latent cooling.

If multiple tubes are installed in parallel, install the outlet temperature/RH sensor near the end of the header if it is not possible to measure all tubes individually.

Figure 20: Location of Temperature and Air Velocity Sensors

Airflow rate

Installing an air velocity sensor

To measure the volumetric flow rate, a velocity sensor should be installed in at least one tube or header. The volumetric flow rate will not be perfectly balanced between multiple tubes, so the header might be more appropriate, if possible, to measure total flow rate. The velocity sensor should be installed in the centre of the tube.

Thermal energy output

The sensible heat transfer rate in the tube can be calculated using the following equation:

$$\dot{Q}_s = \rho \dot{V} C_p (T_{out} - T_{in})$$

where ρ is the air density, $\dot{V}$ is the volumetric flow rate, $C_p$is the specific heat of air, and T_{out} and T_{in} are outlet and inlet temperatures.

The latent heat transfer rate can be calculated using the following equation:

$$\dot{Q}_l = \rho \dot{V} i_{fg} (W_{out} - W_{in})$$

Where i_{fg} is the enthalpy of vaporization of water, W_{out} is the humidity ratio at the outlet, and W_{in} is the humidity ratio at the inlet.

Other monitored data points

Other points to consider for monitoring include electrical equipment power consumptions (e.g. UV lamps for air quality and fans), far-field soil temperatures, near soil temperatures, and inner and outer tube surface temperatures.

Sharing monitored data to improve the design tool

CanmetENERGY would greatly appreciate any opportunity have access to new datasets of monitored data. New monitored data could help us validate our design tool and serve as case studies for other designers (with permission). Please let us know if you have monitored data that you would be willing to share.

For any questions related to the monitoring aspect, please contact:

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References

Ahmed, A., Ip, K., Miller, A., & Gidado, K. (2009). Thermal performance of earth-air heat exchanger for reducing cooling energy demand of office buildings in the United Kingdom. *Building Simulation* (pp. 2228-2235). Glasgow: IBPSA.

Barnard, N., & Jaunzens, D. (2001). *Low Energy Cooling: Technology Selection and Early Design Criteria IEA-BCS Annex 28 Report 2.* London: Construction Research Communications Ltd.

Baten, M., Akter, M., Miah, M., Hassan, M., & Mobin, M. (2015). Textural Infulence on Surface and Subsurface Soil Temperatures under Various Conditions. *Journal of Environmental Science and Natural Resources*, 147-151.

Benkert, S., Heidt, F., & Schöler, D. (1997). Calculation tool for earth heat exchangers GAEA. *Building Simulation.* Prague: IBPSA.

Birch, F. (1995). *Handbook of Physical Constants, Section 17 Thermal Conductivity and Diffusivity.* Geological Society of Ameria.

Brideau, S., Lubun, M., & Tardif, M. (2018). Early Design Tool for Earth Tubes in Canada. *RoomVent and Ventilation 2018.* Espoo, Finland.

Butler, T. L. (2018). Enhanced IEQ through Passive Earth Tubes in Canada. *39th AIVC - 7th TightVent & 5th Venticool Conference.* Juan-les-Pins: AIVC.

Darius, D., Misaran, M., Rahman, M., Ismail, M., & Amaludin, A. (2017). Working parameters affecting earth-air heat exchanger (EAHE) system performance for passive cooling: A review. *International Conference on Materials Technology and Energy.* IOP Publishing Ltd.

de Jong van Lier, Q., & Durigon, A. (2012). *Soil Thermal Diffusivity Estimated From Data of Soil Temperature and Single Soil Component Properties.* Sao Paulo.

Elminshawy, N. A., Siddiqui, F. R., Qazi, F. U., & Addas, M. F. (2017). Experimental investigation on the performance of earth-air pipe heat exchanger for different soil compaction levels. *Applied Thermal Engineering*, 1319-1327.

Farouki, O. (1986). *Thermal Properties of Soils.* California.

Gan, G. (2014). Dynamic interactions between the ground heat exchanger and environments in earth–air tunnel ventilation of buildings. *Energy and Buildings, 85*, 12-22.

Garde, D. F., Ayoub, J., Aelenei, D. L., Aelenei, D. D., & Scognamiglio, D. A. (2017). *Solution Sets for Net Zero Energy Buildings.* Berlin: Ernst & Sohn.

George, C. K. (2010). Earth-tubes for Building Heating and Cooling in Drylands. *Annal of Arid Zone 40*, 285-301.

Hollmuller, P. (2002). Utilisation des échangeurs air/sol pour le chauffage et le rafraîchissement des bâtiments : mesures in situ, modélisation analytique, simulation numérique et analyse systémique. *Doctoral Thesis*. Université de Genève.

Hollmuller, P., & Lachal, B. M. (1998). *TRNSYS compatible moist air hypocaust model.* Université de Genève.

Hollmuller, P., & Lachal, B. M. (2014). Air–soil heat exchangers for heating and cooling of buildings: Design guidelines, potentials and constraints, system integration and global energy balance. *Applied Energy, 119*, 476-487.

Kaushal, M. (2017). Geothermal cooling/heating using ground heat exchanger for various experimental and analytical studies: Comprehensive review. *Energy and Buildings*, 634-652.

Kelker, S., Choudhary, S., Kushwaha, S., Kumar, S., Siddhey, S., & Vishwakarma, S. (2016). Earth Tube Heat Exchangers. 31.

Kusuda, T., & Achenbach, P. (1965). *Earth Temperature and Therma Diffusivity at Selected Stations in the United States.* Washington: National Bureau of Standards.

Lee, K. H., & Strand, R. K. (2008). The cooling and heating potential of an earth tube system in buildings. *Energy and Buildings, 40*, 486-494.

McAdams, W. H. (1954). *Heat Transmission* (Third ed.). New-York: McGraw-Hill.

Meteorological Service of Canada. (2018a). *Engineering Climate Datasets*. Retrieved February 8, 2018, from http://climate.weather.gc.ca/prods_servs/engineering_e.html

Meteorological Service of Canada. (2018b). *Canadian Climate Normals*. Retrieved February 8, 2018, from http://climate.weather.gc.ca/climate_normals/

Moncef, K., & Kreider, J. F. (1996). Analytical model for heat transfer in an underground air tunnel. *Energy Conversion and Management, 37*(10), 1561-1574.

Moseley, M. (n.d.). Retrieved from www.rehau.com.

Muehleisen, R. T. (2012). Simple design tools for earth-air heat exchangers. *SimBuild* (pp. 723-730). Madison, WI: IBPSA-USA.

Ouellet, C. (1975). *Soil and Air Temperatures at Ottawa: Publication 1541-1975.* Ottawa: Agriculture Canada.

PACTE. (2017). *Calepin de Chantier: Puits Climatiques en Habitat Individuel et en Tertiaire*. Retrieved from www.programmepacte.fr.

Patterson, W. (1994). *The Physics of Glaciers.* Tarrytown, New York: Elsevier Science Inc.

Patterson, W. (1994). *The Physics of Glaciers.* Tarrytown: Elsevier Science Inc.

Peretti, C., Zarella, A., De Carli, M., & Zecchin, R. (2013). *The design and environmentalk evaluation of earth-to-air heat exchangers (EAHE). A literature review.* Padova.

Pollack, H. N., Hurter, S. J., & Johnson, J. R. (1993). Heat flow fromm the earth's interior: analysis of the global data set. *Reviews of Geophysics, 31*(3), 267-280.

Sturm, M., Holmgren, J., König, M., & Morris, K. (1997). The thermal conductivity of seasonal snow. *Journal of glaciology, 43*(143), 26-41.

Tardif, M., Lubun, M., Ouazia, B., Booth, D., & Nordquist, B. (2014). Energy Performance of Concrete Earth Tubes for Pre-Heating and Pre-Cooling of Supply Air in Cold Climates. *9th International Masonry Conference*, (p. 7). Guimaraes, Portugal.

Vikas Bansal, R. M. (2009). Performance analysis of earth-pipe-air exchanger for winter heating. *Energy and Buildings 41*, 1151-1154.

Vlad, G.-E., Ionescu, C., Necula, H., & Badea, A. (2013). *Thermoeconomic design of an earth to air heat exchanger used to preheat ventilation air in low energy buildings.* Bucharest.

Williams, G. P. (1976). *Ground Temperatures.* Ottawa: Canadian Building Digest 180 National Research Council of Canada.

Zhang, J., & Haghighat, F. (n.d.). *CFD Modelling of Heat Convection in a Large Cross-Section Earth-to-Air Heat Exchanger.* Montreal: Department of Building, Civil and Environmental Engineering Concordia University.