Ventilative cooling and improved indoor air quality through the application of engineered Earth Tube systems, in a Canadian climate

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ABSTRACT

This paper will present the context and application of earth tube systems for the provision of ventilative cooling and general make-up air in the heating, ventilation and air conditioning (HVAC) sector of the built environment; with a focus on case studies in Canada.

The first author has a background practising as a Chartered Engineer in both the UK and also in Canada and has been designing and optimising earth tube systems since 1998, with several case studies built in the UK and Canada on both domestic and commercial buildings of various uses. The first author is also undertaking a PhD, investigating the effectiveness of earth tube systems to temper outside air for supply to buildings located in British Columbia in Canada, where there is a in a Cordilleran climate with up to 40 degrees Celsius (°C) and cold snowy winters down to -30°C. This paper will focus on a built case study example that has been investigated as part of the first author's PhD research in Canada. A discussion on methodology, drawn from the results of his case studies, to understand the safety and risks to health that need to be considered when using an earth tube system, especially to prevent mould growth and contamination in the pipe installation, is discussed. As is the different design approaches to earth tube systems for different building types, climate zones, occupancy loads and systems design are considered and evaluated.

The paper presents empirical monitored data from a case study that shows monthly temperature and energy performance of the earth tube system, over a period of one year for 2014. These results demonstrate how building code compliance (energy and ventilation) can be met or exceeded by the application of earth tube systems in the supply of ventilative cooling to buildings in the Canadian climate zone (Cordilleran). The extreme swings in seasonal air temperature impact upon earth tube system performance with interseasonal characteristics. The results presented and discussed are drawn from ground temperature sensors installed from ground level downwards to the underside of the earth tube level, in the case study building presented. The main conclusions drawn from this research show that before starting with an earth tube system design there are fundamental considerations which should be addressed. These include: climate zone, soil conditions, air flow, building occupancy patterns, HVAC system and Building Management System (BMS).

The studies show that once the above considerations have been addressed, then the potential for earth tube systems as part of a ventilative cooling strategy will be capable of meeting core demand for occupant comfort, without relying on conventional oil and gas fuelled HVAC systems. Thus, significantly reducing carbon emissions for cooling and space heating and energy costs.

KEYWORDS

Green retrofit, Earth tube system, Potential cooling and enhanced indoor air quality, Health and wellbeing.

1 INTRODUCTION

This paper focuses on earth tube systems in the cold climate of the Canadian climate zone (Cordilleran), with up to 40 degrees Celsius (°C) and cold snowy winters down to -30°C. The monitored data from a case study building will be presented to demonstrate the ventilative cooling potential of an earth tube system in this climate. Furthermore, the potential for earth tubes to provide pre-heat in winter will also be explored and supported by monitored data from the case study building.

The case study and monitoring methodology is discussed for a residential building in the interior climate zone of British Columbia, Canada. The existing 105 metre squared (m^2) house is 60 years old in 2018, but recently underwent a refurbishment and extension to add an extra $35m^2$. The design of the earth tube system (ETS) is also discussed, which is $48m^2$ or 34% of the total building area. The results of the 12-month monitoring are also discussed.

2 MITIGATING OVERHEATING IN BUILDINGS

With the phenomenon of global warming being linked to an increase in greenhouse gases caused by emissions from fossil fuels, there is a pressing need to look at methods to reduce this alarming trend (UN, 2000). With 40 to 50% of the worlds carbon dioxide (CO_2) emissions due to the built environment (OECD, 2011), and increased demands for mechanical conditioned buildings due to warmer climates (LBNL, 2014), the steps to reduce energy consumption related to buildings will be a key factor in addressing this global crisis.

The traditional methods of cooling buildings were integrated with the materials and architecture of early Middle-Eastern buildings – adobe earth walls, baud-geer ducts, and evaporative pools (Vali, 2009) – and these methods were applied to provide respite from the extreme heat of harsh desert countries. However, since the discovery of the Carnot cycle (Carnot, 1824) and the subsequent invention of mechanically driven air-conditioning systems (Carrier, 1902), the passive environmental control systems have – to a large extent – been cast aside and omitted in 21st century buildings (Blumenfeld & Thumm, 2014). Mass manufacturing of air conditioning systems combined with cheap electricity supplies (NRCan, 2017) have made the widespread adoption of mechanically based building services systems affordable to the market place in Canada, see Figure One below. The ability to provide a guarantee of thermal comfort to any given internal space – regardless of the architecture of the building in which they serve or the operating costs – or more concerningly the greenhouse gas emissions – has contributed in part to the global crisis that is faced by society (UN, 2000).

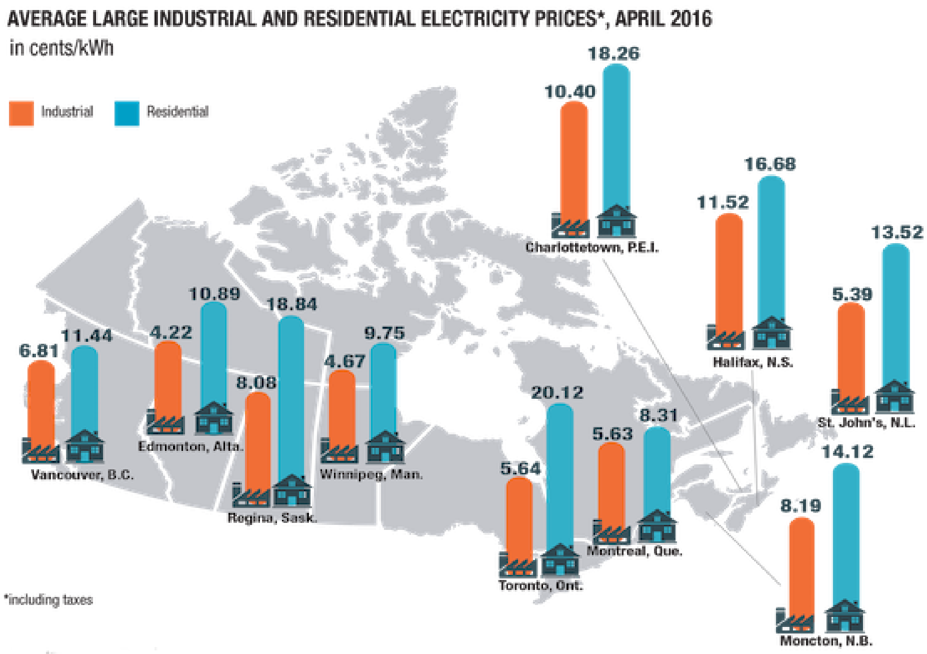

Figure One: Average residential and large industrial electricity prices, including taxes, for one city per province in cents per kilowatt-hour for April 2016, (NRCan, 2017)

The built environment industry has seen some (but not the majority of) architects design glass skinned buildings which appear as monuments to modernity – which are then conditioned using whatever-means-necessary mechanical systems to guarantee comfort (Sahoo, 2010). In recent years – most notably from early 2000's – regulations such as the Energy Performance of Buildings Directive (EU, 2010), Building Energy Codes (BCBC, 2012), Approved Document L (in the UK) there has been a drive energy efficiency in new building construction and this been shown to produce savings in emissions and energy (NRC, 2011). However, despite these regulations there is still an overdependence upon mechanical systems to meet comfort (Alia, Esteban, 2000) – with little thought given to resiliency in the event of mechanical failure or disruption of utility electrical supplies.

The method championed through the Passive House Institute of Darmstadt is directive toward the building envelope providing the means for survival and comfort (Admason & Feist, 1996), with mechanical heating, ventilation and air-conditioning (HVAC) system reduced to minimal requirements for trimming peak loads only (PHI, 1996). The Passive House method champions the architecture and construction teams, but still the mechanical engineering teams are continuing to select conventional engineering systems to provide the HVAC needs of the building. Furthermore, not every client can afford a Passive House standard building – nor are there enough adequate trained practitioners with the necessary skills to deliver such high-performance buildings (Passive House Canada, 2017). So in the interests of health and wellness, energy efficiency, resilience and low greenhouse gas emissions, the author has been developing a growing area of practice in the application of earth tubes as a means of providing a simple solution to these needs.

3 METHODOLOGY FOR THE EARTH TUBE SYSTEM

The type of ETS that is documented in this paper is a single pass supply of outdoor air, primarily to provide cooling to the master bedroom and main living areas of the case study house, see Figure Two below.

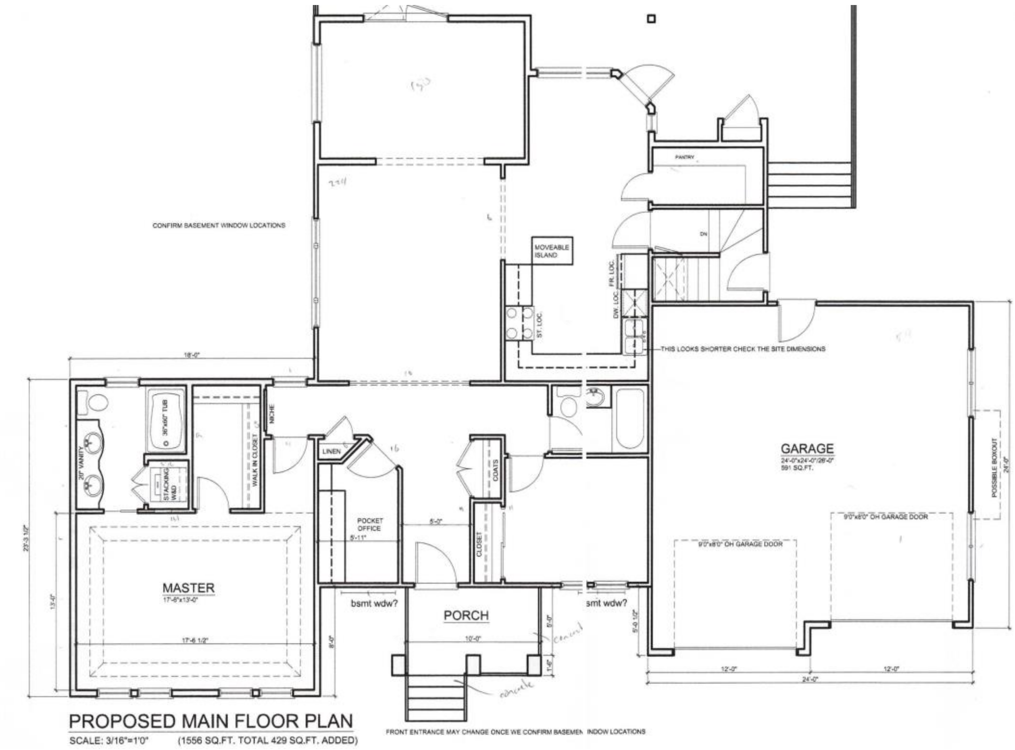

Figure Two: architectural plans of the case study house.

The pipework configuration comprises four pipes, each 100-millimetre (mm) diameter (Ø) running in parallel at an average of 50mm spacing in a common trench. There are two 90-degree bends in the pipe runs with each pipe delivering 18 litres per second (l/s) at an average air velocity of 2.2 metres per second (m/s). The ventilation system is a single in-line fan with direct ducting to supply tempered outdoor air directly to the master bedroom and living areas, see Figure Three below.

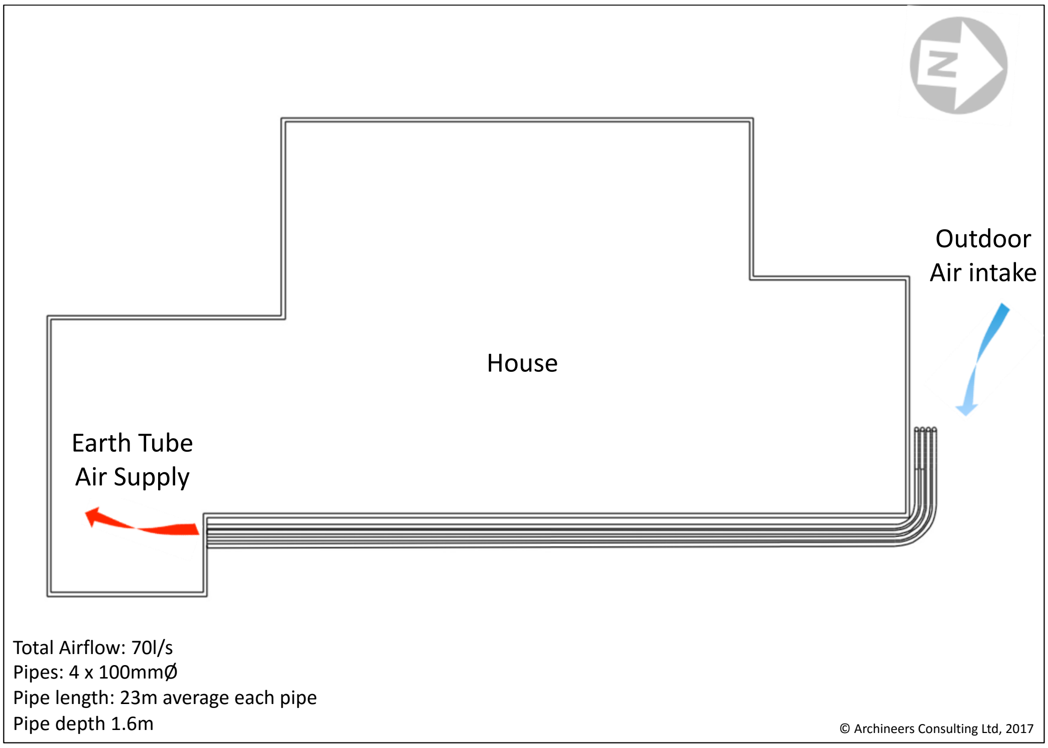

Figure Three: Plan view of earth tube system at case study project

The exposure of the outdoor air inlet is deliberately located on the north side of house, mostly in the shade, to allow the air to be drawn from a space with a cooler microclimate of a quiet suburban garden.

3.1 Material of the earth tubes

The earth tube material is High Density Polyethylene (HDPE) and constructed with a solid and corrugated profile. Each pipe is approximately 23 metres (m) in length in continuous monolithic sections, with no joints to reduce risks of leakage and contamination to the air stream (see Figure three).

3.2 Installation of the earth tubes

The earth tubes are bedded in a trench surrounded by soft sand to protect them, with a soil depth cover (from crown to surface) of 1.6 metres (Figure Four). The earth tubes run adjacent and parallel to the insulated basement foundation wall. The local soil conditions are a mix of loamy sand and clay, the site is well drained being located on a gently sloping hillside, facing south-south-east in a suburban low-density neighbourhood.

Figure Four: Trenching and laying earth tubes for case study project

The site conditions above the earth tube is exposed and open to atmospheric and climate conditions, with a surface treatment of a mixture of lawn and concrete paving, as well as a herbal garden, to assist with air quality improvements (see Figure Five).

The solar exposure above the earth tubes is partially shaded by the house, and a substantial Douglas Fir tree in the front garden, although in the summer months, there will be a degree of direct sunshine in the early morning from sunrise until 08.00 am.

Figure Five: Outdoor air inlet box and filter housing (circled) – case study house

The outdoor air inlet to the earth tubes incorporates filtration of fine insect mesh and a regular 25mm thick filter screen – as commonly used in residential scale air-handling systems and furnaces, see Figure Six below.

Figure Six: Air inlet with screen, mesh and filter – all upstream of the earth tubes.

3.3 Monitoring of earth tubes

The monitored data for the case study has been recorded using wireless sensors linked to gateway, with continual pulsed recording every 30 seconds. The sensors are manufactured by Omnisense, and comprise a series of wireless sensors and a wireless gateway that is hardwired into the internet modem, see Figure Seven below.

Figure Seven: Omnisense, S-900-1, Wireless T, %RH, WME Sensor,

The wireless sensors are located inside the outdoor air inlet box and inside the ductwork header upstream of the supply fan (see Figure Eight below).

The wireless sensors record two points of data, outdoor Air Temperature in degrees Celsius (OAT) and Earth Tube Air Temperature in degrees Celsius (ETAT). The difference between these two temperatures is of particular interest in determining the delta Temperature (ΔT) and ultimately the efficiency of the ETS.

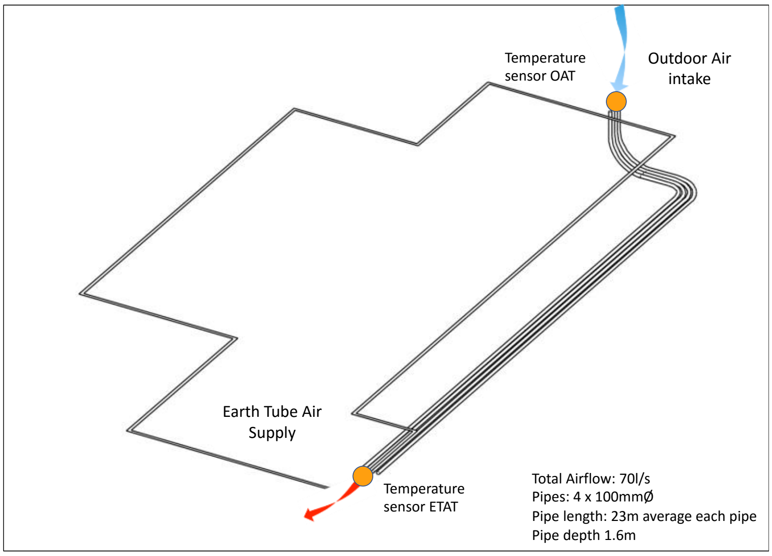

Figure Eight: Isometric of ETS with Temperature Sensors shown

3.4 Earth Tube System description

The ETS supplies tempered outdoor air to a single-family house primarily for the purposes of summertime cooling and wintertime indoor air quality. The ETS meets 100% of the cooling needs of the master bedroom and living spaces within the house, and the volume of cooled air supplied to the spaces is controlled by a variable speed inline fan. The ETS provides tempered outdoor air to the living spaces through the year to improve indoor air quality. The benefits are most notable in the winter when the indoor air quality (IAQ) is enhanced through the supply of tempered outdoor air that is pre-warmed such that there are no cold draughts. Top-up heat is provided to the living spaces through perimeter heating to offset both the envelope losses and the ventilation air that is mixed with room air.

3.5 Cooling options from the earth tube system

As an alternative to the earth tubes for cooling, the owners would most likely have opted for a window air conditioner as their first choice of system. The house has no forced air ductwork (common for heating and cooling in Canada) so a central forced air cooling system would not have been a viable option for the case study house owners (Daikin, et al). Another alternative would have been a ductless mini-split system (Mitsubishi, et al). But the mini-split system does not have the benefit of outdoor air supply, so this is not quite an "equal/approved" system as the earth tube has added benefit of tempered outdoor air exchange. The earth tubes provide tempered outdoor air (all year) and meet the cooling needs in the when the climatic conditions require (typically June to September). Therefore, the most viable alternative would have been the window A/C units.

3.6 Controls of the earth tube system

The ETS supplies tempered outdoor air by an inline fan. The fan is manually operated to control volume of air flow supplied. Depending upon the time of year the home owner will require different volumes of tempered outdoor air to be supplied to their living spaces. The manual operation is deliberate in the manner that it requires a hands-on approach – so that the operator can manage their comfort simply to meet their needs – something very a different o typical HVAC that is electronically controlled. Detailed operational procedures by the owner are not fully recorded. However, through discussions with the owner, there are two main modes of operation that have been established: (i) in summertime, the fan operates based on temperature demand for cooling; (ii) in winter the fan is operated based on indoor air quality needs.

Figure Nine: Ductwork header connected to earth tubes and fan unit.

For the purposes of the analysis, an average period of ten hours per day has been applied during the most occupied period of the day, from 08:00 to 18:00. This allows the efficiency to be compared to a traditional system for heating or cooling the equivalent volumes of air from the outdoor temperature to the delivered temperature. The baseline delivered air temperature has been set based on degree days of 18°C dry bulb (DB). Therefore, the energy saved by the ETS compared to business as usual (BAU) is based on the temperature difference between tempered earth tube air and direct outdoor air to a temperature of 18°C DB.

4 MONITORED DATA

The monitored data is shown in Figure Ten to Thirteen below.

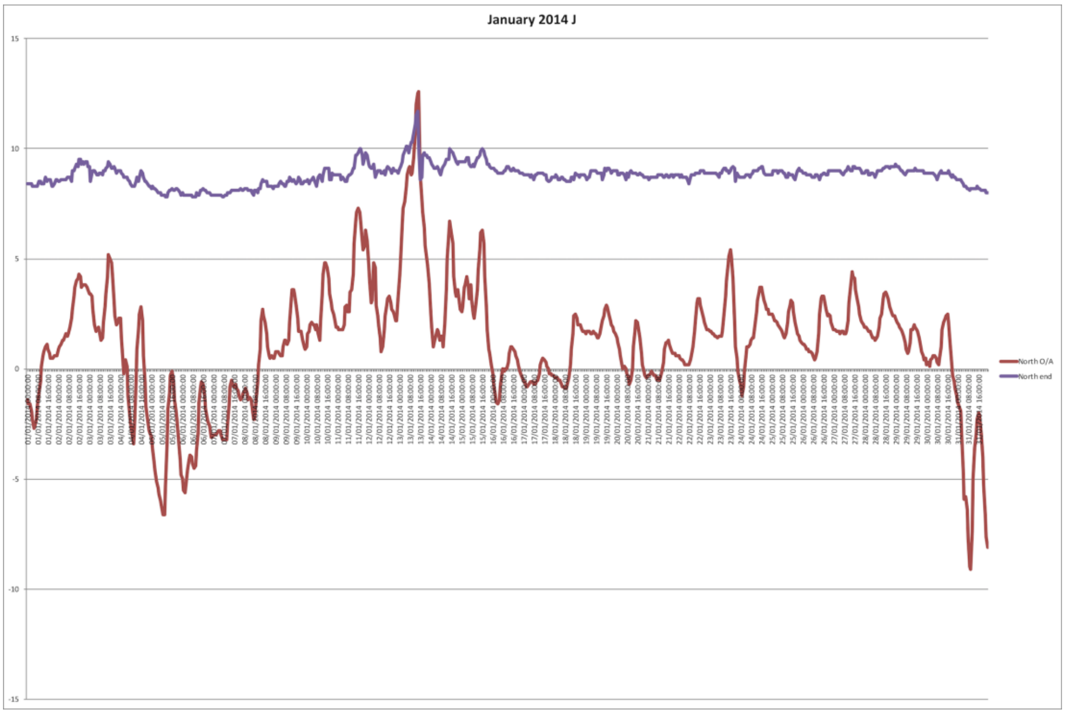

Figure Ten: OAT and ETAT for case study house - JANUARY

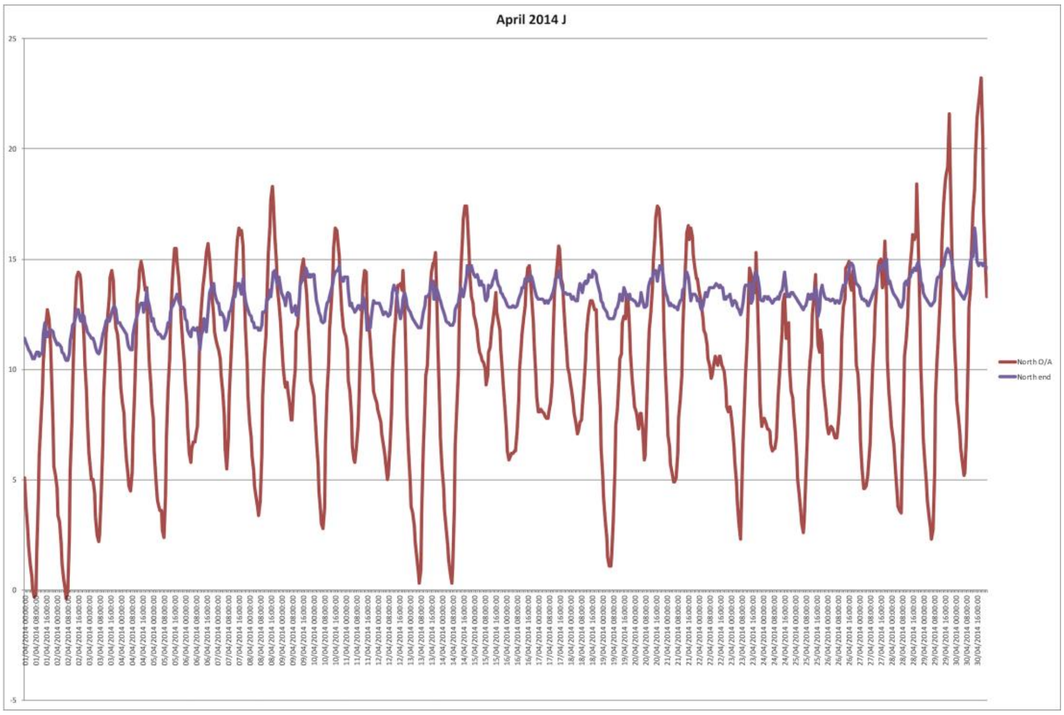

Figure Eleven: OAT and ETAT for case study house - APRIL

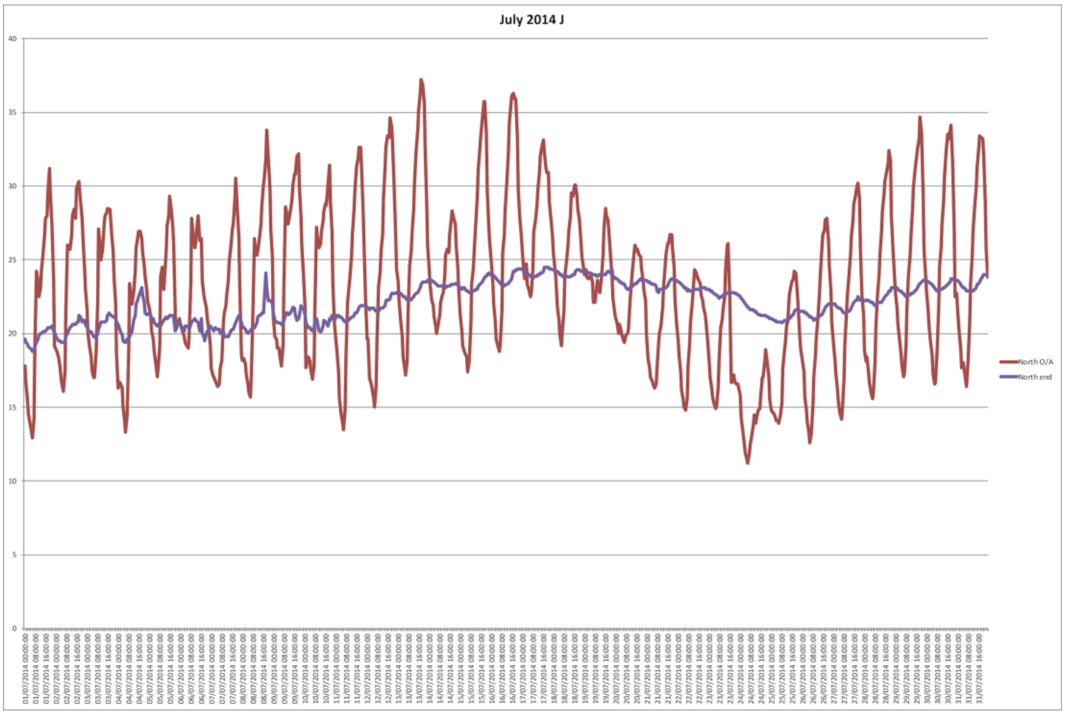

Figure Twelve: OAT and ETAT for case study house - JULY

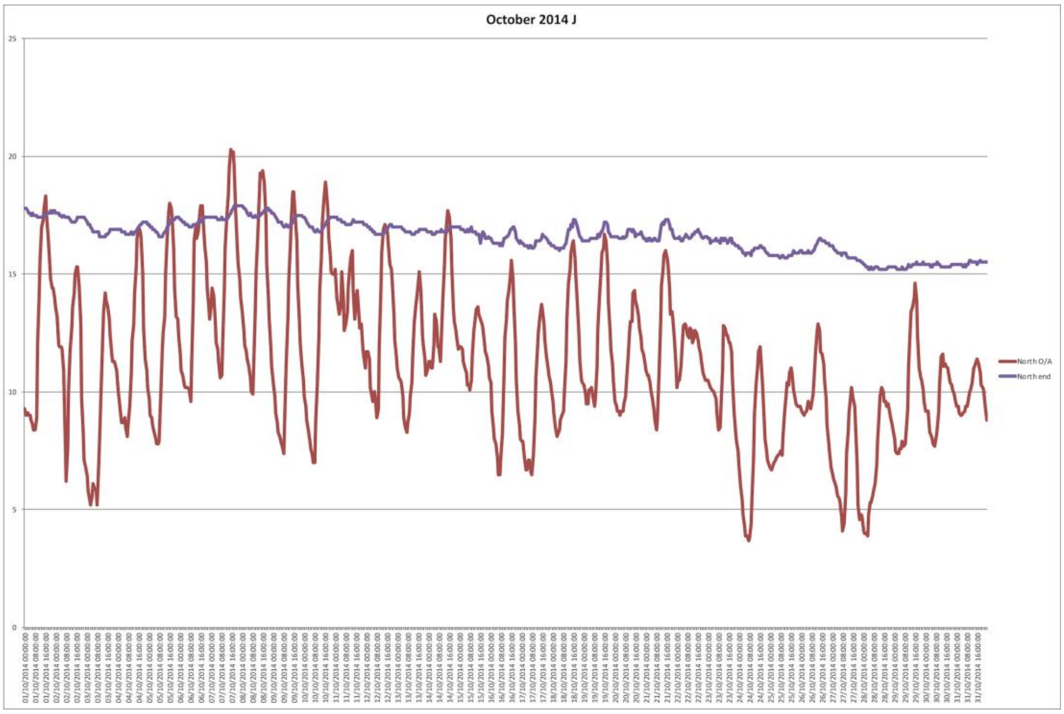

Figure Thirteen: OAT and ETAT for case study house – OCTOBER

5 RESULTS ANALYSIS

The monitored data is recorded with temperature and relative humidity reading taken every ten minutes over a twelve-month period.

The analysis uses average daily outdoor air temperature (OAT) and earth tube air temperatire (ETAT) per Month based on daily averages 10-hour days (8am-6pm).

Degree Days are used as a reference to compare the earth tube performance with business as usual. Degree-days for a given day represent the number of degrees Celsius that the mean temperature is above or below a given base. For example, heating degree-days are the number of degrees below 18 °C. If the temperature is equal to or greater than 18, then the number of heating degrees will be zero. Normals represent the average accumulation for a given month or year. Values above or below the base of 18 °C are used primarily to estimate the heating and cooling requirements of buildings and fuel consumption.

The baseline conventional scenario with no earth tube array was established using the building HVAC system to temper the outdoor air to meet the 18°C degree day standard assessment. The calculation for this is as follows:

$Q = Cp \times m \times (T_{18} - T_{OAT})$, where:

> Q = heat load in kilowatts (kW);
>
> Cp = specific heat capacity of air in kilojoules per kilograms per degree Celsius – assumed as constant 1.2 kJ/kg/°C;
>
> m = mass flow rate in litres per second (l/s);
>
> T_{18} = 18°C as per degree day assessment;
>
> T_{OAT} = temperature of outside air;

The annual energy savings in cooling mode are: 30%

The annual energy saving in heating mode are: 46%

6 POST COMPLETION REVIEW:

The owners of the house have experienced an enhanced internal environmental quality since the completion of their project. This is likely due to several factors, including improved envelope, modernized kitchen and living spaces, as well as the provision of better air quality and cooling from the earth tubes. Following a recent inquiry to the owners, we were informed that they are very happy with the system and also happy to share the monitoring for the furtherment of understanding and application of earth tubes in the Canadian market.

7 DISCUSSION SECTION

The primary driver that led the author into this field of research was related to the health of and well-being building occupants. Health is important – started at the main driver as similar findings (Clements-Coombe, 2008) who found that indoor air quality is poor – especially at times when outdoor air temperature is not suitable for a natural ventilated operation.

The results show that an additional 46% outdoor air can be supplied to the house in winter with zero energy penalty. This is an important factor as it could encourage the homeowner to operate the earth tubes more frequently in winter to improve IAQ.

The summertime cooling (June-Sept) benefits go beyond outdoor air volumes and identify that he the internal conditions of the house are maintained through the very hot summer (July peaked at 37.5°C). The earth tubes were sized for outdoor air tempering, but ended up being primarily used for summertime cooling.

The design of the system has several factors that need to be accounted for, including:

- Climate zone – including seasonal extremes in addition to annual averages/medians of temperature
- Sub-surface conditions – including soil type and soil temperature, ground water, depths of bury
- Air flow requirements – for ventilation air to manage IAQ.
- Air flow requirements – for meeting thermal loads, predominantly cooling but also tempered make-up air in the heating season
- Building occupancy patterns – related to seasonal, monthly and daily use
- Operational HVAC system – optimising effective interface; and
- Building Management System (BMS) controls – sequence of operation (SOO)

8 CONCLUSIONS

The earth tubes are a simple technology – “well known”, but not necessarily ‘known well’. Despite the building energy codes becoming more directive with regard to improving energy efficient through better envelope, there is a still the factors of climate change that result in a growing need to provide cooling to buildings.

The earth tubes are shown to be a proven technology to provide free cooling, but also the factors of improving IAQ in winter – as well as summer – are further benefits, with no operational costs.

The factors such as passive survivability – “A building's ability to maintain critical life-support conditions in the event of extended loss of power”, (CBE Berkeley, 2008) are enhanced through less reliance on complex mechanical equipment. The earth tubes are a simple technology that can assist the passive operation.

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