Air–soil heat exchangers for heating and cooling of buildings: Design guidelines, potentials and constraints, system integration and global energy balance

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Abstract

Air-soil heat exchangers for heating and cooling of buildings are analyzed under various aspects. Based on the analytically resolved case of a constant airflow subject to sinusoidal temperature input, we start by deriving climate independent design guidelines, for dampening of the daily and/or the yearly temperature oscillation. In a second step, constraints and potential of buried pipe systems are analyzed for the case of a typical Central European climate, for which the constraint between climate and comfort threshold induces a fundamental asymmetry between preheating and cooling potential. Finally, it is shown that the net yield of an air-soil heat exchanger has to take into account more than the mere input-output temperature differential.

Keywords
air-soil heat exchanger, earth-air tunnel, buried pipe system, passive cooling and heating.

**Symbols**

**Latin letters**

- \( c \)  J/K.kg  Specific heat of air
- \( c_s \)  J/K.kg  Specific heat of soil
- \( h \)  W/K.m²  Overall heat transfer coefficient (air/soil)
- \( h_a \)  W/K.m²  Convective heat transfer coefficient (air/pipe)
- \( h_s \)  W/K.m²  Diffusive heat transfer coefficient (pipe/soil)
- \( \dot{m} \)  m³/s  Total airflow rate
- \( \dot{m}_0 \)  m³/s  Base airflow rate (standard ventilation)
- \( \Delta \dot{m} \)  m³/s  Additional airflow rate (over-ventilation)
- \( P_{ext} \)  W  Gross heat gain, ventilation from outdoor
- \( P_{pipe} \)  W  Gross heat gain, buried pipes
- \( P_{vent} \)  W  Gross heat gain, ventilation system
- \( \Delta P_{dif} \)  W  Net heat loss by heat diffusion
- \( \Delta P_{pipe} \)  W  Net heat gain, buried pipes
- \( \Delta P_{pipe+rec} \)  W  Net heat gain, combined buried pipes and heat recovery
- \( \Delta P_{rec} \)  W  Net heat gain, heat recovery
- \( \Delta P_{vent} \)  W  Net heat gain, ventilation system
- \( Pr \)  -  Prandtl number
- \( r \)  m  Pipe radius
- \( Re \)  -  Nusselt number
- \( S \)  m²  Pipe exchange surface
- \( t \)  s  Time
- \( T_{bld} \)  °C  Temperature of building
- \( T_{ext} \)  °C  Temperature outdoor
- \( T_{pipe} \)  °C  Temperature outlet of pipe
- \( T_{pipe+rec} \)  °C  Temperature outlet of combined buried pipes and heat recovery
- \( T_{rec} \)  °C  Temperature outlet of heat recovery
- \( T_{vent} \)  °C  Temperature outlet of ventilation system

**Greek letters**

- \( \delta \)  m  Heat penetration depth
\[ \delta_{\text{day}} \quad \text{m} \quad \text{Heat penetration depth, daily oscillation} \]
\[ \delta_{\text{year}} \quad \text{m} \quad \text{Heat penetration depth, yearly oscillation} \]
\[ \eta_{\text{rec}} \quad - \quad \text{Efficiency of heat recovery} \]
\[ \theta_{\text{ext}} \quad \text{K} \quad \text{Oscillation amplitude, outdoor} \]
\[ \lambda_{\text{a}} \quad \text{W/K.m} \quad \text{Thermal conductivity of air} \]
\[ \lambda_{\text{s}} \quad \text{W/K.m} \quad \text{Thermal conductivity of soil} \]
\[ \rho_{\text{s}} \quad \text{kg/m}^3 \quad \text{Specific mass of soil} \]
\[ \tau \quad \text{s} \quad \text{Oscillation period} \]
\[ \omega \quad \text{rad/s} \quad \text{Oscillation frequency} \]

1 Introduction

1.1 Context and objective

As building envelopes improve, there is a rising interest for winter heating or summer cooling systems based on renewable energies. One of them, which can in principle fulfill both purposes, consists in forcing air from outdoor through an air-soil heat exchanger (also called earth-to-air heat exchanger, earth-air tunnel, buried pipe system), for dampening of the temperature amplitude carried by the airflow, the building underground serving as an energy buffer.

Our interest in this technique started with long term in-situ monitoring of various full scale demonstration projects (see section 1.2). At that stage, literature review as well as discussion with professionals from the building energy sector revealed: i) the lack of understanding of the underlying physical phenomena, which explained the absence of general design rules; ii) incomplete understanding of the thermal performance of air-soil heat exchanger, which does not only relate to the input - output temperature differential of the system; iii) the absence of system analysis and overall energy balance, taking into account integration in the technical system and in the building.
Filling of this gap was undertaken during the evaluation of the diverse monitored installations, as well as by way of specifically developed numerical simulation and analytical modeling [1]. The purpose of this paper is to report the key results of that work.

1.2 State of the art

Analytical models

Unlike a liquid heat storage medium, which can generally be fairly well described by means of two separate conductivity and capacity parameters (one-node model), thermal exchange with a solid medium is of diffusive nature (conduction/capacitance continuum), inducing amplitude-dampening and phase-shifting of transient temperature input, which are often difficult to predict intuitively. Lacking better tools, most authors are dimensioning air/soil heat exchangers by way of simple static exchange models (Schiller [2], Santamouris and Lefas [3], Rodriguez and al. [4], Levit and al. [5], Seroa da Motta and Young [6], Elmer and Schiller [7], Chen and al. [8], Bansal and al. [9], Tiwari and al. [10], Athienitis and al. [11], Serres and al. [12], Tzaferis and al. [13], Badescu and Ivoranu [14]). Although these models are easy to handle, the overall air/soil heat transfer coefficient is evaluated by way of diverse suppositions which do not explicitly take into account the complex phenomenon of heat diffusion in the soil, resulting in inaccurate calculation of transient regimes, in particular periodic input with combined yearly and daily oscillation frequencies.

Some analytical and semi-analytical approaches which explicitly treat heat diffusion in the soil actually concern steady-state problems (Koschenz and Lehmann [15] for water driven systems, Chung and al. [16] for air driven systems). One of the first analytical approaches concerning periodic heat diffusion from a pipe embedded in a semi-infinite medium is proposed by Claesson and Dunand [17]. It is based on the mathematical solution for an infinite medium, corrected by addition of a mirror sink above the free surface and yields the solution for the temperature field in
the soil. The induced effect on the longitudinal temperature variation of the airflow was studied by Sawhney and Mahajan [18], who however didn’t carry out appropriate physical interpretation and operational presentation of the results in terms of design guidelines. A similar but somehow more complex problem includes the interference of neighbouring pipes (Kabashnikov and al. [19]), but it also concerns deeply buried pipes and doesn’t either discuss the expected effect nor the related sizing.

As an added value to preceding state of the art, we resolved the case of a constant airflow submitted to sinusoidal temperature oscillation at entrance of a cylindrical pipe, with explicit treatment of diffusive heat storage into a finite cylindrical soil layer, with adiabatic or isothermal boundary condition [20]. As a main result, the diffusive heat transfer coefficient and thereby the global air/soil heat transfer coefficient are derived as a function of the available soil layer, which leads the way to the design rules developed in this article. As a second result it is also shown that, for a particularly thin layer submitted to adiabatic boundary condition, it is possible to completely phase-shift the periodic input while barely dampening its amplitude, a phenomenon that lead to the development of a new passive cooling technique [21, 22], which will not be treated in this article.

**Numerical models**

As an alternative to the analytical approach, several numerical simulation models based on finite differences have also contributed to characterize diffusive heat exchangers. Some of them are limited to description of only one "typical" pipe (Bojic and al. [23], Mihalakakou and al. [24], Huber and Remund [25], Bansal and al. [26 - 28]). Other ones represent several parallel running pipes, with or without possibility to treat more complicated cases than steady flow rate, homogenous and laterally adiabatic soils, or sole sensible heat exchange (Gygli and Fort [29], Boulard and al. [30], Gauthier and al. [31], De Paepe [32]). However, when validation against monitoring is carried out, latter in all cases remains limited to a few hours or days and does
generally not concern real scale installations, thereby not providing necessary proof of robustness one would expect. Corroboration against an analytical solution is furthermore never given, except for the last one of these models and for the trivial case of one-dimensional heat diffusion without airflow.

As a further modeling step, the numerical model used in this study allows for variation in airflow rate and direction, inhomogeneous soils, non-adiabatic lateral boundary conditions, as well as description of latent heat exchanges and thermal effect of charge losses. Extensive validation against several long-term monitored real scale installations proved good robustness, and validation with preceding analytical solution gave excellent results [33].

**Guidelines, system integration and comparative analysis**

No general and climate independent design guidelines for dampening of the meteorological oscillation come out of preceding modeling studies. They do not either address the question of system integration, overall energy balance or comparative analysis with other passive heating or cooling systems. Neither do a few articles specifically related to experimental case studies (Eiker et al. [34], Misra et al. [35], Oliveira and Gonçalves [36]).

In this respect, following studies are notable exceptions. Pfafferott performs a comparative evaluation of three air-soil heat exchangers integrated in German office buildings [37]. For each system, monitoring data in 5 minute time step over an entire year is analyzed by way of an input/output model, in terms of amplitude dampening and phase-shift, as well as overall air/soil heat transfer coefficient. The results are discussed in relation with specific pipe surface and interaction with the building. However, no clear distinction between yearly and daily regimes is made, the overall energy balance is not discussed in relation with system integration, and no design guidelines are derived from the findings.
Another well documented case study by Zimmermann [38] concerns an office and industrial building in Switzerland, where passive cooling by buried pipes is used in combination with night over-ventilation. The cooling potential of air-soil heat exchangers is further discussed in terms of system integration, construction hints, control strategies and possible combination with other cooling techniques [39]. With the aid of numerical simulation, design guidelines in terms of pipe length to airflow ratios are developed for the case of Zurich, with correction factors for other European cities. However, although both dampening of yearly and daily oscillation are addressed, the guidelines only concern deeply buried pipes. An explicit discussion and evaluation method for overall energy balance, taking into account the effect of over-ventilation, is also missing.

Finally, Giessler and al. compare the efficiency of coupled or stand-alone air-soil heat exchanger and heat recovery on exhaust air [40]. They highlight the non additive thermal gain brought about by the coupled system, along with the potential electricity savings for de-freezing. Numerical simulation of the systems coupled to a typical low-energy building is further used for cost analysis, including investment and primary energy savings (accounting for both thermal and electrical energy), with a sensitivity study on four different North European climates. Similarly, and for the specific case of a Passivhaus in Mannheim, Schnieders [41] explores the interaction of the air-soil heat exchanger with the heat recovery as well as with the heat losses through the building slab.

In this context, following of our case studies allowed to gain further insight on the potentials and constraints of air/soil heat exchangers for preheating and cooling of buildings, and may serve as possible illustrations of the discussion on system integration and overall energy balance at the end of this article.

Monitoring and complementary numerical simulation of a large scale system on a residential building, including combined buried pipe and heat recovery on exhaust air, allowed to highlight the fundamental asymmetry between preheating and cooling potentials of the pipes for Central Europeana climates, as well as the reduced net energy gain due to coupling with heat recovery [42].
Analysis of another installation of this type in a commercial and administrative building showed the possible effects of water infiltration in the pipes, and related latent heat exchanges, with their influence on the overall energy balance [1].

Monitoring and simulation of an existing air/water/soil heat exchangers (buried water loop connected to the ventilation system by way of an air/water heat exchanger) allowed to evaluate the advantages and disadvantages as compared to air/soil heat exchangers, as well as to highlight the negative effect of additionally induced heat diffusion from the building, the overall balance resulting into a net heat loss instead of gain [43].

An extensive numerical simulation study, including dynamic building response, compares the cooling potential of diverse passive cooling techniques linked to ventilation (buried pipes, controlled thermal phase-shifting, evaporative cooling) for the case of an administrative building located in a moderate climate, with a specific attention to urban versus rural location, as well as normal versus extreme summer conditions [44]. Simulated building response is analyzed for a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains), in free floating mode as well as with auxiliary cooling backup. A similar study concerns a typical residential and commercial building for a variety of Brazilian climates [45].

Finally, as an alternative use, an extensive monitoring campaign on three identical agricultural greenhouses, of which one was equipped with an air/soil heat exchanger, allowed to characterize the benefit of this kind of system for storage of excess diurnal solar gains [46].

2 System description

Throughout this article, an air-soil heat exchanger consists of an array of horizontal pipes, possibly a unique pipe, buried underneath or next to a building and situated at the inlet of the ventilation system (fig. 1). Purpose is to take advantage of the soil’s thermal inertia, so as to absorb and dampen the winter/summer or the day/night meteorological oscillation carried by the airflow, hence
cutting off the cold or hot thermal peaks which would otherwise be transferred to the building. In principle this technique may be used as well for winter heating as for summer cooling purposes, although we will see that under Central European climates these modes differ both in terms of the desired outcome (yearly versus daily amplitude dampening), as in terms of synergy with the rest of the ventilation system and with the building itself.

As is schematically depicted here (fig. 1), and as will be discussed further down in all details, the main working characteristics of an air-soil heat exchanger are as follows: i) winter preheating and summer cooling are characterized both by daily amplitude-dampening (the day/night meteorological extremes contracting around the daily average) and by yearly amplitude-dampening (the daily average approaching the yearly meteorological average); ii) while yearly heat storage propagates about 3 m around the pipes, daily heat storage uses only about 15 cm. Due to this smaller penetration depth and a better related exchange coefficient, daily amplitude-dampening is more effective than yearly amplitude-dampening, and requires a much smaller storage volume.

3 Design guidelines

3.1 Governing principles and parameters

In order to establish appropriate design guidelines, we will start by characterizing the thermal exchange phenomena that are at work and their link to amplitude-dampening along the pipes. We therefore base on the simplified and analytically resolved case of a constant airflow subject to sinusoidal temperature input, with explicit treatment of diffusive heat storage into the soil [20]. Besides the strong hypothesis of no perturbations from the upper surface, latter study further assumes that the airflow is constant, the soil homogeneous, and that no latent heat exchange is at work. Expressed in a simplified form, the results of the study yield following main insights.
As long as the soil layer around each pipe is at least that thick, heat charge and discharge around the pipes naturally extends over a penetration depth $\delta$ which depends on the oscillation period:

$$\delta = \sqrt{\frac{\lambda_s}{c_s \rho_s \pi}}$$  

(1)

In the case of a sample soil which will be taken as a reference (conductivity $\lambda_s : 1.9$ W/K.m; capacity $c_s \rho_s : 1.9$ MJ/K.m$^3$), and as pointed out previously, the daily heat wave hence extends on approximately 17 cm around the pipes, against 3 m for the yearly heat wave:

$$\delta_{day} \approx 17 \text{ cm}$$

$$\delta_{year} \approx 3 \text{ m}$$

Thanks to the diffusive heat transport in the soil, the sinusoidal temperature input carried by the airflow:

$$T_{\text{ext}} = \theta_{\text{ext}} \sin(\omega t)$$  

(2)

dampens exponentially along the pipe exchange surface $S$:

$$T_{\text{pipe}} = \theta_{\text{ext}} \exp\left(-\frac{Sh}{cm}\right) \sin(\omega t)$$  

(3)

Strictly speaking, and as for all types of diffusive heat transport, this amplitude-dampening phenomenon actually goes along with delaying or phase-shifting of the input signal. It is however shown that, as long as heat transport is not restricted by geometrical constraints and may extend over its natural penetration depth $\delta$, phase-shifting remains unimportant (residual amplitude of less than $\exp(-\pi) \approx 4\%$ for a half period phase-shift), reason why it will here be ignored.

The amplitude-dampening coefficient $h$, which will govern the design guidelines, basically results from serial linking between the convective exchange coefficient $h_a$ (air/pipe) and a diffusive exchange coefficient $h_s$ (pipe/soil):
The convective exchange $h_a$ coefficient can be described by way of a simplified form of the Gnielinski relation [47], which relates air conductivity $\lambda_a$ and pipe radius $r$ to Reynolds and Prandtl numbers $Re$ and $Pr$:

$$h_a = \frac{\lambda_a}{2r} 0.0214(Re^{0.8} - 100)Pr^{0.4} \text{ (for } Re > 2300)$$

(5)

The diffusive exchange coefficient $h_s$ relates to heat charge and discharge in a soil layer of thickness $\delta$, and can be approximated by the corresponding static conduction coefficient. Depending on whether heat diffusion occurs in cylindrical way around the pipe, or in plane way downwards into the ground (as will be discussed further down for two basic geometries), it is hence given by:

$$h_s \approx \frac{\lambda_s}{r \cdot \ln(1 + \delta/r)} \text{ (in cylindrical mode)}$$

(6a)

$$h_s \approx \frac{\lambda_s}{\delta} \text{ (in plane mode)}$$

(6b)

### 3.2 Basic geometries

As indicated by the relationships described above, guidelines for design of air-soil heat exchangers relate to careful examination of convective and diffusive heat transfer coefficients, which themselves depend on geometrical parameters (eq. 5-6). As given by eq. 5, the convective air/pipe heat exchange increases almost linearly with air velocity, with a lesser dependence on pipe diameter, reaching values between 4 and 16 W/K.m$^2$ for velocities between 1 and 4 m/s (fig. 2). Diffusive heat exchange in its turn depends on the available soil layer around the pipes and the way heat diffusion can actually take place. We therefore will consider two distinct geometries (fig. 3), with quite different behaviors:
The first case concerns a loose geometry, with deeply and wide apart buried pipes (or possibly a unique deeply buried pipe), at around 3 m depth and with 6 m inter-axial distance, so that both daily and yearly heat diffusion may fully propagate in cylindrical mode (fig. 3, left). For both these frequencies, the diffusive coefficient $h$ takes values in the same order of magnitude as the convective coefficient $a$, although more important in daily than in yearly mode (fig. 4 top, left and center). Hence, depending on air velocity and to a smaller extent on pipe diameter, the overall amplitude-dampening coefficient $h$ takes values between 3 and 10 W/K.m$^2$ in daily mode, and about half these values in yearly mode (fig. 4. bottom, left and center). As a consequence, with such a geometry daily and yearly amplitude-dampening always go on par, although latter somewhat less effectively.

Note that in reality, due to excavation cost, the theoretical 3 m depth may become prohibitive. In such cases a slightly smaller depth (and possibly a smaller inter-axial distance) can also bring about the desired reduction of the yearly amplitude, however with a slightly increased pipe length for compensating of the reduced lateral storage volume (see guidelines further down).

The second case concerns a compact geometry, with pipes buried close to the surface and to each other, with approximately 20 cm soil around each (fig. 3, right). The daily heat wave carried by the airflow may be charged and discharged in the soil in the same cylindrical way as before. On the contrary, the yearly heat wave saturates the immediate vicinity of the pipes and can only propagate downwards into the ground, in plane mode, on a surface $S$ which is defined by the size of the pipe array (length by width). Accounting for the reduced available capacity, the diffusive coefficient $h$ of the yearly mode is reduced to 0.6 W/K.m$^2$, which forces the resulting amplitude-dampening coefficient $h$ to some 0.5 W/K.m$^2$, independently of air velocity (fig.4, right). As a consequence, such a geometry allows to reach daily amplitude-dampening with the same pipe length as before, but almost without dampening of the yearly amplitude. Note that such a compact geometry may
also be realized in a multi-layer configuration, in which case the slight dampening of the yearly amplitude however will turn out all the more negligible.

3.3 Guidelines

For both the above defined geometries it is now possible, via equation 3, to establish design rules in terms of necessary pipe length for “complete” amplitude-dampening, which we define as a residual amplitude of $e^{-2} \sim 15\%$. The resulting guidelines are as follows (fig. 5).

If the point of interest concerns dampening of the yearly oscillation, it is necessary to work with distant of each other and deeply buried pipes, with approximately 3 m soil around each. In this case, a rough design rule for complete amplitude-dampening is 20 - 40 m pipe per 100 m$^3$/$h$ airflow (fig. 5, left), for diameters yielding an air velocity in the range of 1 to 4 m/s. As pointed out above, the daily amplitude will have vanished on approximately half that distance (see rule hereafter). In the case of a reduced soil layer around the pipes (joint reduction of depth and inter-axial distance), the necessary increase in pipe length for dampening of the yearly oscillation can be calculated by way of the corresponding analytical solution [20]. It is shown that a 10% increase in pipe length can allow to reduce the soil layer around the pipe down to 1.4 – 2.4 m, depending on the pipe diameter and air velocity (fig. 6). Even better results will be achieved with reduction of pipe depth only, but the exact effect has to be calculated by way of numerical simulation (as also the effect of a non-adiabatic upper border condition, see further down).

If the point of interest concerns dampening of the daily oscillation, only with slight or negligible dampening of the yearly component, it is sufficient to work with close to each other and shallow buried pipes, with approximately 20 cm soil around each. Typical required length is roughly 10 - 20 m per 100 m$^3$/$h$ airflow (fig. 5, right), a relation which varies with the pipe diameter and associated air velocity.
Note that preceding guidelines for pipe length, which concern a residual amplitude of $e^{-2}$, may be extrapolated by way of the exponential form of equation 3. As an example, the guidelines for the distant pipe configuration (fig. 5, left) indicate that a 200 m$^3$/h airflow in a 20 cm diameter pipe (~1.8 m/s) would require 70 m for complete yearly dampening (residual amplitude of $e^{-2}$); hence, a 30 m pipe would yield a residual amplitude of $e^{-2 \left(\frac{30}{70}\right)} = 42\%$.

3.4 Validation

Validation as well as illustration of these behaviors and guidelines will now be given on hand of an extensively validated finite element numerical model for buried pipe systems [33], which accounts for fully three dimensional heat diffusion in soil and flexible border conditions, as well as for sensible and latent heat exchanges (latter not used here).

Both the considered configurations consist of a layer of pipes with 20 cm diameter, each swept by a 200 m$^3$/h dry airflow, with hourly input given by the standard annual meteorological temperature for Geneva. The pipes are buried in a soil with same thermal characteristics as above, in one case at 310 cm depth (center of pipe) and with 620 cm inter-axial distance, in the other case at 25 cm depth and with 50 cm inter-axial distance. Upper border condition is in both cases taken as adiabatic, whereas a 15 m soil layer with adiabatic border condition below the pipes largely allows for the yearly heat to expand on its natural penetration depth. The array is supposed to consist of a sufficient amount of pipes for lateral border effects to be negligible, so that the system can be described by way of a unique pipe (adiabatic conditions at inter-axial distance).

Simulated hourly temperatures are depicted in form of daily minima and maxima profiles at 0, 20 and 50 m distance (fig. 7, top), and confirm preceding analysis: deep and wide apart buried pipes induce combined daily and yearly amplitude-dampening, eventually reaching the constant annual
average, whereas the compact pipe configuration essentially allows for daily amplitude-dampening, with a constant output over the day/night period but an almost unaltered seasonal trend. The hourly data at every 10 m is Fourier analyzed, so that yearly and daily residual amplitudes may be compared to the values given by the above design rules (fig. 7, bottom): a good correlation is manifest in either case, the guidelines slightly overestimating the residual amplitudes given by numerical simulation.

3.5 Pre-design tool
The analytical solution on which preceding guidelines are based was further used for setting up of a pre-design tool. Given a specific climate, it enables for easy and rapid calculation of the hourly temperature output of a buried pipe over an entire year, as a function of a very few parameters (airflow, pipe length and diameter, available soil layer around the pipe, soil thermal conductivity and specific heat). The tool operates via Fourier decomposition of the input temperature in a complete sum of harmonics (from yearly up to hourly frequency), from which the complete analytical output is reconstructed.

As a complement to preceding guidelines, the tool enables to take into account the dampening effect not only of the basic yearly and daily frequencies, but also of all the other ones that are embedded in the meteorological dynamic. Apart for checking the dynamic response in function of pipe length, it hence allows to test other pipe depths and inter-axial distances than the one given by above geometries (for example for dampening of temperature overshoots of a few days or weeks), as well as to check the effect of diverse soil characteristics.

3.6 Disturbing factors
It should finally be stressed that the above guidelines and tool remain at the level of preliminary design, as they are based on an analytical model which does not take into account disturbance of the
storage mechanism due to thermal drive from the upper surface (ambient or building), nor the possible effects of transient airflow or latent heat exchanges. As a complement to the basic guidelines elaborated in this study, these effects must be investigated by way of numerical simulation. Although a systematic characterization of these disturbances has not yet been undertaken, we will give here a few preliminary thoughts and results concerning these matters.

The effect a non adiabatic upper surface will depend on the type of border condition. If the surface is submitted to outdoor temperature (same thermal drive as at pipe inlet), dampening of the yearly and daily oscillation will be limited by the natural temperature oscillations of the undisturbed soil (result of the upper thermal drive). If the surface is at a constant temperature (as for example under a heated building), the thermal drive will not only affect the dampening of the diverse oscillations (in a way which depends on the depth of the pipes), but also modify the yearly temperature average (as for example by heating up of the airflow). Note that a similar phenomenon arises for a joint drive by ambient air and solar radiation. A preliminary numerical study of these effects was conducted for the case of the specific climate of Geneva [1], but general understanding and corresponding adjustment of the design guidelines is still missing.

Transient airflow corresponds as well to varying of the airflow rate (for example for heating or cooling purposes, see further down), as to operation limited to specific periods or control strategies (for example for cooling purposes, during summer only or during daytime only). In this case, the airflow might not provide for sufficient thermal recharge of the soil, which will depend only on coupling with upper surface and possibly with surrounding soil. So far, the effect of transient airflow on preceding guidelines has not been analyzed in a systematic way.

A regular worry concerns latent heat exchanges (condensation/evaporation) which might take place within the pipes. For the specific climate of Geneva, following insight is given by the same
numerical study as in section 3.4, now with meteorological input in terms of both temperature and humidity, as compared to totally dry air (fig. 8). In the case of the compact pipe configuration, condensation remains quite insignificant and only occurs very occasionally, the condensed water evaporating in the following hours. It however plays an important role in the deep and distant pipe configuration, with condensed water remaining within the pipes during several weeks, which could lead to sanitary problems, unless an efficient drainage is designed. Note that despite an important effect in terms of water transfer, outlet temperatures remain very close to the ones obtained with totally dry air: the hourly mean square difference is 0.4 K and the maximum difference 1.4 K (as compared to 0.1 K and 0.9 K for the compact pipe configuration), so that the guidelines of section 3.3 also remain valid when latent heat is at work. It should finally be stressed that in practice the presence of water in the pipes and subsequent evaporation may in certain cases result from leaky fittings rather than from previous condensation.

4 Preheating and cooling: the case of Central Europe

With the case of Geneva as an example, we will analyze the constraints and potential of buried pipe systems for preheating and cooling of buildings in Central European climates which, due to the seasonal asymmetry of the meteorological constraint, will be seen to be asymmetric. For both seasons, the specific interest of buried pipe systems will further be compared to other passive heating and cooling techniques related to ventilation, namely heat recovery on exhaust air and direct night ventilation from outdoor.

4.1 Meteorological constraint

In Geneva, the constraint between climate and comfort threshold induces a fundamental asymmetry between preheating and cooling potential by way of air-soil heat exchangers (fig. 7).
The heating season covers some 8 months of the year (approximately 3'000 degree days on 20/12°C basis) during which the renewal of air of buildings accounts for an energy loss of about 70 MJ/m².year (for a standard ventilation rate of 0.4 ach and a ceiling height of 2.5 m). As the legal limit for the heating index of new collective residential buildings is 140 MJ/m².year (average value, depending on the building shape factor), it is imperative to reduce this loss by passive solutions. Among these, air-soil heat exchangers are, in principle, meant for dampening of the yearly meteorological oscillation, with the aim of heating the air flow up to the average annual temperature of 10 °C. Latter is quite underneath the lower comfort threshold of 20 °C, so that the benefit of the buried pipes limits to a preheating function. It is possible (and common) to link the buried pipes upstream of heat recovery unit, which allows to improve latter’s performance, but in this case it is important to properly assess the synergy of the combined system (see section 5.2).

While the winter outdoor temperature generally remains below the lower comfort threshold of 20 °C, in summer it does not exceed, on daily average, the upper comfort threshold of 26 °C. Under these conditions, traditional buildings do usually not require any active cooling. Only those with strong internal or solar gains, or those with low inertia, may more or less punctually require active cooling, so as to avoid diurnal temperature overshoots. Therefore, cooling by way of air-soil heat exchangers is not necessarily related to dampening of the yearly meteorological oscillation: dampening of the daily oscillation generally yields a temperature below the comfort threshold. As such, and if the pipes are sized appropriately, the airflow may be increased to higher rates (over-ventilation), for removal of the excess heat loads of the building, eventually replacing active cooling.

The asymmetry of the climate constraint is all the more relevant when keeping in mind that dampening of the daily oscillation requires a lesser soil layer (about 20 cm around each pipe), but also a shorter pipe length (about 10-20 m per 100 m³/h of air), than dampening of the yearly
oscillation (3 m layer, 20-40 m per 100 m³/h of air). Therefore, capital cost for a buried pipe system dedicated to cooling will be lower than for a system dedicated to preheating.

4.2 Preheating: buried pipes versus heat recovery
For the winter case, the potential of buried pipes is not only limited thermally (limitation to preheating) and economically (depth, size): the technique also lacks competitiveness with heat recovery on exhaust air. Latter technique benefits from a heat source at 20 °C, instead of the 10 °C yearly average temperature, turning it more efficient and generally less expensive. When both techniques are linked in series, the net contribution of the pipes is further limited by the efficiency of the heat recovery unit (see section 5). Over-sizing of the heat recovery unit may hence turn out more efficient and less costly than adding up of buried pipes for dampening of the yearly meteorological oscillation.

However, an air-soil heat exchanger designed for dampening of the daily oscillation allows to drastically reduce the occurrence of frost in the heat recovery unit, even with a short pipe length (fig. 7 and tab. 1). Such will barely result in any thermal gain (the temperature average entering the heat recovery unit remaining unchanged), but can induce electricity savings for de-freezing.

Finally, in the case of serial link of buried pipes and heat recovery, it is important to provide for a possible bypass for the summer (fig. 1).

4.3 Cooling: buried pipes versus night ventilation
As we have seen, the summer pipe outlet temperature remains below the upper comfort threshold, so that its use is no longer limited to energy saving, but allows for cooling production of its own: in principle, the airflow can now be set to larger ventilation rates of a few ach, for over-ventilation of the building with fresh air and removal of the heat excess. The technique is similar to night over-
ventilation, and as for latter the cooling potential is determined by the temperature differential between the building and the ventilation source, in this case at pipe outlet (see section 5).

The main difference between these two techniques appears clearly on the hot summer period (fig. 7), during which the average outdoor temperature is close to the upper comfort threshold of 26 °C. While air renewal induces an undesirable heat gain during the hottest hours of the day, over-ventilation allows for an increased input of fresh air at night. So as to be useful during daytime, this surplus of cooling must however be stored in the building, requiring access to sufficient thermal capacity. The air-soil heat exchanger in its turn directly acts as a daily buffer, so that over-ventilation can be maintained 24 hours a day. While both techniques induce a similar global contribution on the whole period, the pipes permit to average this contribution on a much more regular basis. The comparative advantage of the pipes thus mainly consists in the possibility of controlled access to additional thermal mass that would not be present in the building.

To allow for such over-ventilation it is however necessary to size the pipes consequently (proportionally to the airflow, according the rules seen above). Beyond the constructive aspect, over-ventilation will also imply an overconsumption of electricity for the fans (as opposed to night ventilation, if latter is driven naturally). It hence becomes most important to carefully evaluate this overconsumption case by case, taking into account charge losses for distribution within the building.

4.4 Economic aspects

Preceding insights can have a strong economic impacts, as can be seen on the example of an air-soil heat exchanger connected to a multifamily and commercial building in Geneva [42], for which disaggregated investment costs are available (excavation, piping material, refilling, engineering), and for which we investigated various geometrical layouts by way of numerical simulation.
In the case of preheating of the 2500 m$^3$/h sanitary air flow, a compact configuration (49 pipes, 12.5 cm diameter, 25 m length, 30 cm axial distance) leads to 22.4 kWh gross heat gain by the air-soil heat exchanger. However, when taking into account the 60% efficiency of the heat recovery unit (section 5.2), the net heat gain drops down to 9.0 kWh, representing a net avoided heating cost of 34.0 cts/kWh, which is around four times more than for heat from fossil fuels.

For the case of cooling, a twice longer system with 3.5 times higher summer air flow (and 21 cm diameter pipes for maintaining same friction losses) allows a significant summer cooling potential of 66.8 kWh (while leaving the winter preheating potential almost unchanged). The potential avoided cooling cost of this configuration is 13.0 cts/kWh, which is similar to the one obtained via a cooling machine with an EER of 2, when taking into account the cost of electricity only. Furthermore, and unlike for preheating, the air-soil heat exchanger may in certain cases allow to cut short on capital costs for auxiliary cooling, and eventually become a cheaper option.

5 System integration and global energy balance

The yield of an air-soil heat exchanger is usually given in terms of its gross heat gain, as expressed by the output-input temperature differential (which depends on previously examined amplitude-dampening behaviors):

$$P_{pipe} = c\text{mi}(T_{pipe} - T_{cut})$$

As will however be seen in this section, which deals with system integration and global energy balance, such a basic input-output evaluation is not always sufficient or pertinent.

5.1 Effect of airflow rate

For any ventilation system (including heat recovery, buried pipes, direct night cooling, evaporative cooling …) the gross heat gain carried into the building is:
\[ P_{\text{vent}} = c(\dot{m}_0 + \Delta \dot{m})(T_{\text{vent}} - T_{\text{bld}}) \]  

(8)

where \( \dot{m}_0 \) is the base required flow rate and \( \Delta \dot{m} \) a possible additional flow rate for thermal conditioning. When compared to the base case with direct ventilation from outdoor:

\[ P_{\text{ext}} = c\dot{m}_0(T_{\text{ext}} - T_{\text{bld}}) \]  

(9)

the net thermal gain hence writes as:

\[ \Delta P_{\text{vent}} = P_{\text{vent}} - P_{\text{ext}} = c\dot{m}_0(T_{\text{vent}} - T_{\text{ext}}) + c\Delta \dot{m}_0(T_{\text{vent}} - T_{\text{bld}}) \]  

(10)

In the particular case of a buried pipe system, it writes as:

\[ \Delta P_{\text{pipe}} = c\dot{m}_0(T_{\text{pipe}} - T_{\text{ext}}) + c\Delta \dot{m}(T_{\text{pipe}} - T_{\text{bld}}) \]  

(11)

If the airflow is limited to its minimum \( \dot{m}_0 \), which is usually the case in preheating mode, the net heat gain effectively corresponds to the output-input temperature differential. If the system is however designed for a higher flow rate, as may be the case for cooling purposes, the net thermal gain will also have to take into account the pipe-building differential (or building-pipe differential, if counted in terms of cooling gain).

Such an analysis presumes to know the building temperature, which needs an integrated system analysis. Since latter is not always feasible, an alternate possibility is to characterize the potential of the air-soil heat exchanger, by replacing the effective building temperature in equation 11 by a desired or acceptable comfort threshold.

5.2 Effect of heat recovery

Air-soil heat exchangers are often used as a support to a heat recovery unit on exhaust air (fig. 1). In that case careful analysis of the synergy between both subsystems has to be made. As a matter of fact, in stand alone mode a heat recovery unit with efficiency \( \eta_{\text{rec}} \) brings about following thermal gain:
\[ \Delta P_{\text{rec}} = c\dot m_0(T_{\text{rec}} - T_{\text{ex}}) \\
= c\dot m_0\eta_{\text{rec}}(T_{\text{bld}} - T_{\text{ex}}) \]  

(12)

Adding of an upstream buried pipe system allows to raise the input and hence the output of the heat recovery unit. The global heat gain offered by the combined system writes as:

\[ \Delta P_{\text{pipe-rec}} = c\dot m_0(T_{\text{pipe-rec}} - T_{\text{ex}}) \\
= c\dot m_0(T_{\text{pipe-rec}} - T_{\text{pipe}}) + c\dot m_0(T_{\text{pipe}} - T_{\text{ex}}) \\
= c\dot m_0\eta_{\text{pipe}}(T_{\text{bld}} - T_{\text{pipe}}) + c\dot m_0(T_{\text{pipe}} - T_{\text{ex}}) \]  

(13)

As compared to the stand alone heat recovery unit, the net heat gain of the buried pipes limits to:

\[ \Delta P_{\text{pipe}} = \Delta P_{\text{pipe-rec}} - \Delta P_{\text{rec}} \\
= c\dot m_0(1 - \eta_{\text{rec}})(T_{\text{pipe}} - T_{\text{ex}}) \\
= (1 - \eta_{\text{rec}})P_{\text{pipe}} \]  

(14)

Hence, the more effective the heat recovery, the less effective the buried pipes, so that the pertinence of combining both systems must be examined carefully.

For illustration, the air-soil heat exchanger depicted in fig. 1 (winter situation) induces a gross temperature yield of 12 K (from -8 to 4 °C), before the air passes a heat recovery unit with 66% efficiency, yielding ventilation at 16 °C. In stand-alone mode, the heat recovery unit would bring about a direct temperature raise from -8 to 12 °C (66% of the -8 to 22 °C differential). The net gain due to the buried pipes hence only amounts to 16-12 °C = 4 K (which corresponds to 100-66 = 33% of the pipe output-input temperature differential, as pointed out in eq. 14). For comparison, a stand-alone heat recovery unit with state of the art 80% efficiency would bring about the same 16 °C as the combined buried pipe and low efficiency heat recovery.

5.3 Effect of heat diffusion from building

Another interference which has to be taken into account arises in the case of an air-soil heat exchanger buried below a building. The cold air that is driven through the soil during the winter will
induce an additional heat loss $\Delta P_{dif}$, which depends on the insulation below the building slab and the depth of the pipes. Of course, this additional heat loss will partially contribute to preheating of the airflow, but the net gain of this contribution will be limited by the heat recovery unit, as seen just above. In this case the net heat gain of the air-soil heat exchanger hence reduces to:

$$\Delta P_{pipe} = (1 - \eta_{rec})P_{pipe} - \Delta P_{dif}$$

(15)

Especially in the case of insufficient insulation below the slab (high $\Delta P_{dif}$), the net gain of the air-soil heat exchanger may become negative, actually corresponding to a net heat loss! Such has been observed and simulated for an air/water/soil heat exchanger located in Geneva [43]. The air is preheated by way of water loops which are connected to the air-handling unit, and which run at 45 cm depth below the entire area of a building with 3.5 cm slab insulation. Over the winter, the increased heat loss $\Delta P_{dif}$ (1.5 kWh/m$^2$) turns out more important than the heat gain by slight annual discharge of the soil, so that the global heat gain $P_{pipe}$ (1.9 kWh/m$^2$) actually results in an airflow 2.6°C above meteorological yearly average! However, taking into account the 48% efficiency of the heat recovery unit, the net contribution $\Delta P_{pipe}$ results in a net heat loss (0.5 kWh/m$^2$) as compared to the stand alone heat recovery unit.

The relationship between slab heat loss and net heat gain of a single pipe air/soil heat exchanger combined with heat recovery were also analyzed for the case of a Passivhaus building located in Mannheim [41], for which different geometrical layouts were analyzed (0.5 or 3 m depth, next or below the building). In this case, thanks to the 20 cm slab insulation, increased heat loss as compared to stand alone heat recovery remains in the range of 0.1 - 0.25 kWh/m$^2$, depending on the layout. With a 80% heat recovery efficiency, the resulting net heat gain $\Delta P_{pipe}$ of the system however remains limited to the range of 0.2 – 1.1 kWh/m$^2$. 
6 Conclusion

After a general review of the state of the art, potentials and constraints of air-soil heat exchangers for heating and cooling of buildings were analyzed, taking into account several aspects.

Based on the analytically resolved case of a constant airflow subject to sinusoidal temperature input, with explicit treatment of diffusive heat storage into the soil, we derived general climate independent design guidelines for dampening of the daily and/or the yearly temperature oscillation carried by the airflow. Two geometries were distinguished: i) pipes buried deep and apart from each other, for joint dampening of daily and yearly temperature oscillation; ii) pipes buried close to the surface and to each other, allowing for dampening of the daily amplitude but almost without effect on the yearly amplitude. For both these geometries, design rules in terms of necessary pipe length for “complete” amplitude-dampening were established.

Validation of the guidelines as well as illustration of these behaviors was given by means of an extensively validated finite element numerical model, yielding a very good correlation with the theoretical guidelines. The analytical solution was further integrated in a pre-design tool, which enables for easy and rapid calculation of the hourly temperature output over an entire year, taking into account all the frequencies embedded in the meteorological dynamic, and allowing for testing the effect of inter-pipe distance and soil characteristics. As a complement, we gave a few preliminary thoughts on perturbation of the storage mechanism by thermal drive from upper surface (ambient or building), as well as effects of transient airflow or latent heat exchanges, which can be investigated by way of numerical simulation.

In a second step, the constraints and potential of buried pipe systems are analyzed for the case of a typical Central European climate, for which the temperature differential between climate and comfort threshold induces a fundamental asymmetry between the preheating and cooling potentials.
In winter, preheating of the air requires dampening of the yearly meteorological oscillation, and is limited to the meteorological annual average of 10 °C. In this sense, the technique lacks competitiveness with heat recovery on exhaust air. In summer, dampening of the daily oscillation generally yields a temperature below the lower comfort threshold, so that the airflow may be increased to higher rates, for removal of excess building heat load. This is similar to night ventilation, the pipes mainly allowing for access to additional thermal mass. In this case it is however necessary to size the pipes consequently and to control overconsumption of electricity for the fans.

Finally it was shown that the net yield of an air-soil heat exchanger does not always correspond to its output-input temperature differential. If used as a support to a heat recovery unit on exhaust air, the net heat gain of the pipes is limited by the efficiency of the heat recovery, so that the pertinence of combining both systems must be examined carefully. Furthermore, if the pipes run underneath a building, with insufficient insulation in between, additional heat diffusion from the building may result in a net heat loss! If the system is designed for over-ventilation, as may be the case for cooling purposes, the net thermal gain related to the additional flow rate is proportional to the temperature differential between pipe outlet and building.

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References


   http://archive-ouverte.unige.ch/unige:147


http://archive-ouverte.unige.ch/unige:18029


http://archive-ouverte.unige.ch/unige:18031


http://archive-ouverte.unige.ch/unige:22557


http://archive-ouverte.unige.ch/unige:18062


http://archive-ouverte.unige.ch/unige:22622

Fig. 1: System schematic and typical temperature profile along the pipes.
Fig. 2: Convective heat transfer coefficient $h_a$ as a function of air velocity and pipe diameter.
Distant pipes (typically 3 m soil around each pipe)

Compact pipes (typically 20 cm soil around each pipe)

Fig. 3: Basic geometries and associated storage volumes.
Daily amplitude-dampening distant or compact pipes

Yearly amplitude-dampening distant pipes

Yearly amplitude-dampening compact pipes

Fig. 4: top: diffusive heat transfer coefficient $h_s$ as a function of pipe diameter; bottom: overall heat transfer coefficient $h$ as a function of air velocity and pipe diameter.
Fig. 5: Guidelines for residual amplitude of $e^{-2} \ (-15\%)$, total and zoom (top and bottom): pipe length as a function of airflow and pipe diameter, for air velocity between 1 m/s (upper dashed line) and 4 m/s (lower dashed line).
Fig. 6: Yearly amplitude dampening: pipe length increase as a function of available soil layer around the pipe (pipe diameter: 10 - 50 cm; air velocity: 1 - 4 m/s).
Fig. 7: Dynamic of daily minima and maxima (top) and resulting amplitude dampening (bottom).
Fig. 8: Dynamic of daily sensible and latent air-soil heat transfer. Positive/negative values correspond to soil charge/discharge (sensible heat), respectively condensation/evaporation (latent heat).
## Tab. 1: Degree hours below 0°C, distant and compact pipe configurations.

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>Distant (K.h)</th>
<th>Compact (K.h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2117</td>
<td>2117</td>
</tr>
<tr>
<td>10</td>
<td>219</td>
<td>1026</td>
</tr>
<tr>
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