AIR/GROUND HEAT EXCHANGERS FOR HEATING AND COOLING: DIMENSIONING GUIDELINES

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ABSTRACT

This paper deals with air-soil heat exchangers used for heating or cooling airflows used for ventilation of buildings. Basing on a previously published analytical solution concerning heat charge and discharge around an array of buried pipes, it is shown how convective air/pipe and diffusive pipe/soil heat exchange are combining, and how the characteristic exponential amplitude-dampening along the pipe is achieved. The main result consists in dimensioning guidelines, in terms of relations between airflow and pipe length necessary for complete dampening of yearly or daily amplitude. Latter guidelines are finally illustrated and validated with numerical simulation

KEYWORDS

passive heating and cooling, buried pipes, daily and seasonal heat storage

SYSTEM DESCRIPTION

As considered 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 it was shown that under Mid-European climates both these modes differ as well in terms of the effect that is to be striven for (yearly versus daily amplitude dampening), as of synergy with the rest of the ventilation system and with the building itself [1].

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:

- Winter preheating and summer cooling characterize as well by daily amplitude-dampening (the day/night meteorological extremes contracting around the daily average) as by yearly amplitude-dampening (the daily average approaching the yearly meteorological average).

- While yearly heat storage propagates approximately 3 m around the pipes, daily heat storage does so on approximately 15 cm. Daily amplitude-dampening hence always surpasses yearly amplitude-dampening, which requires a wider storage volume and is limited by more in depth heat diffusion.

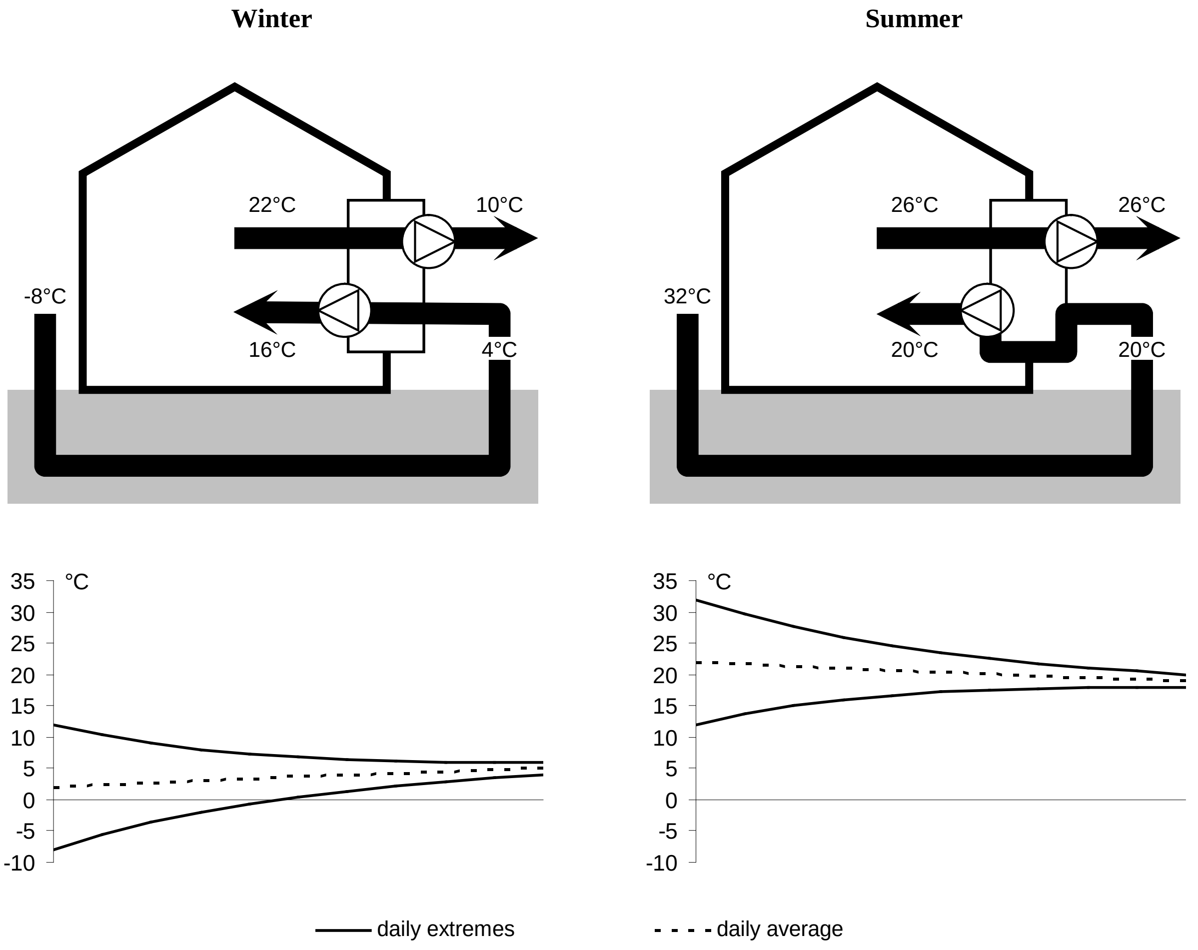


Fig. 1: System schematic with typical daily and yearly amplitude dampening along the pipe.

GOVERNING PRINCIPLES AND PARAMETERS

So as to establish appropriate dimensioning guidelines, we will start by characterizing the governing principles and their link to amplitude-dampening along the pipes. We therefore will 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 [2], which yields following main results.

Heat penetration depth

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 δ, which depends on the oscillation period:

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

In the case of a typical soil (conductivity: 1.9 W/K.m ; capacity : 1.9 MJ/K.m3), which will be taken as a reference, the daily heat oscillation hence extends on approximately 15 cm around the pipes, against 3 m for the yearly oscillation:

$$\delta_{day} \approx 15\,\mathrm{cm}$$

$$\delta_{year} \approx 3\,\mathrm{m}$$

Oscillation dampening

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

$$T_{in} = \theta_0 \sin(\omega t)$$

dampens exponentially along the pipe exchange surface *S*:

$$T_{out} = \theta_0 \exp\left(-\frac{Sh}{c\dot{m}}\right)\sin(\omega t)$$

Strictly speaking, and as for all type of diffusive heat storage, 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 storage may extend over its natural penetration depth δ, phase-shifting remains secondary, reason why it is ignored here.

The amplitude-dampening coefficient *h*, which will govern the dimensioning guidelines, basically results from serial linking between the convective exchange coefficient h_a (air/pipe) and a diffusive exchange coefficient h_s (pipe/soil):

$$h \approx \frac{h_a h_s}{h_a + h_s}$$

The diffusive exchange coefficient h_s relates to heat charge and discharge in a soil layer of thickness δ and can be approximated by the corresponding static conduction coefficient (fig. 2).The convective exchange coefficient h_a can be computed by way of a simplified form of the Gnielinski relation [3].

GEOMETRICAL LAYOUT

As comes out of preceding relations, guidelines for dimensioning of air-soil heat exchangers relate to careful examination of convective and diffusive heat exchange coefficients, which themselves depend on geometrical parameters:

- 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.m2 for velocities between 1 and 4 m/s.
- The diffusive heat exchange on 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 geometrical layouts, with quite different behaviours (fig. 2):

- The first case concerns an extensive geometry, made of pipes buried deep and apart from each other (or possibly a unique deep 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 radial mode (fig. 2, left). For both these frequencies, the diffusive coefficient takes values in the same order of magnitude as the convective coefficient, although more important in daily than in yearly mode. As a consequence, in such a geometry daily and yearly amplitude-dampening always go on par, although latter somewhat less effectively.
- The second case concerns a compact geometry, made of pipes buried close to the surface and to each other, with approximately 15 cm soil around each, so that the daily heat oscillation carried by the airflow may be charged and discharged in the soil in the same radial way as before (fig. 2, right). To the contrary, charge and discharge of the yearly heat oscillation saturates the immediate vicinity of the pipes and can hence only take place in plane mode, downwards into the ground. As a consequence, such geometry enables to reach daily amplitude-dampening with the same pipe length as before, but almost without dampening of the yearly amplitude.

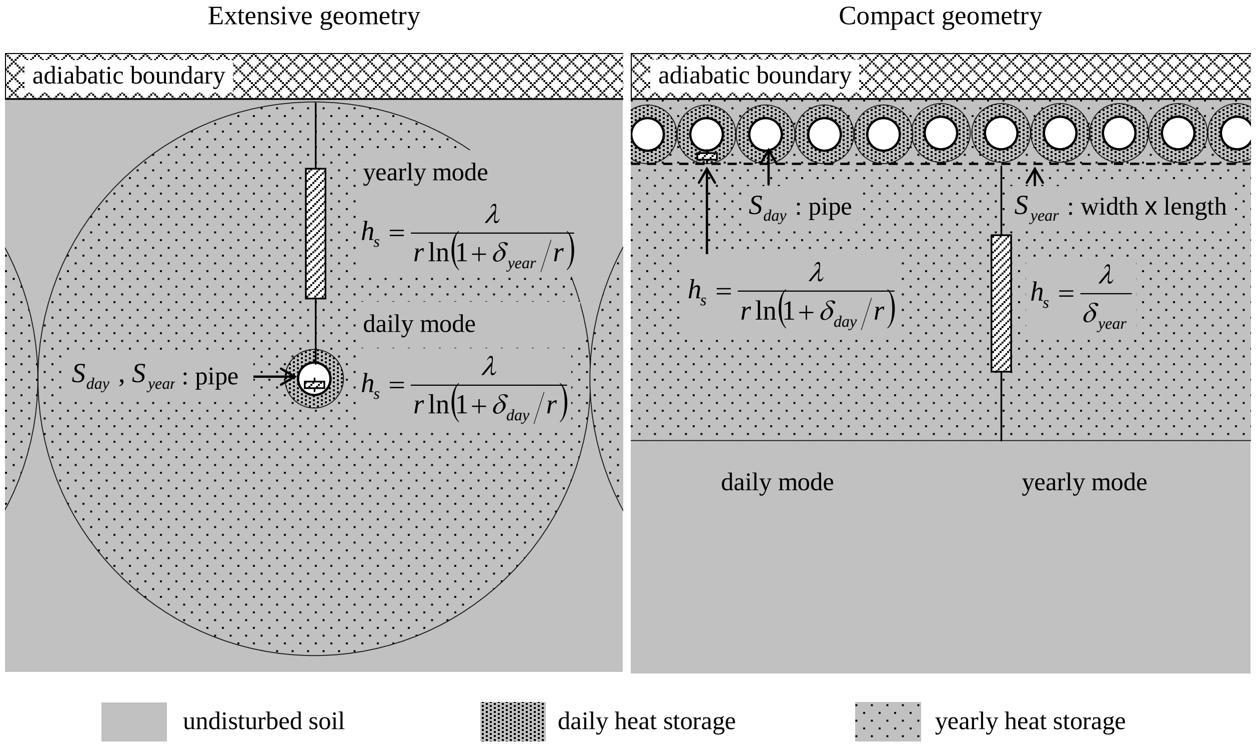
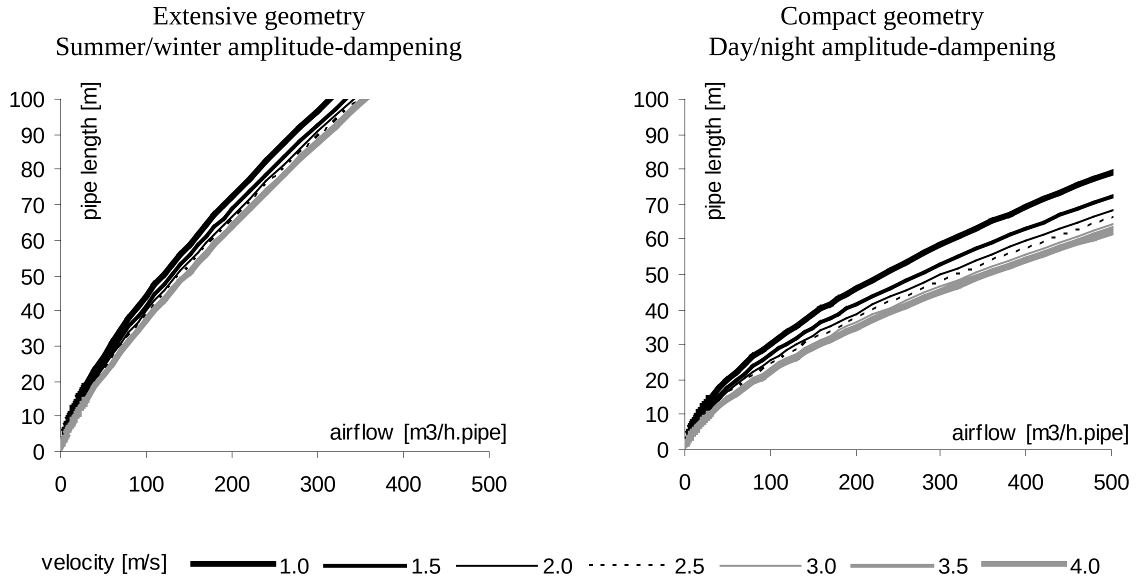


Fig. 2: Basic geometries and associated storage volumes

PIPE LENGTH

For both the above defined geometries it is now possible, via the exponential form of the temperature dampening, to give dimensioning rules in terms of necessary pipe length for “complete” amplitude-dampening, which we define as a residual amplitude of e^{-2} ~ 15%. The resulting guidelines are as follows (fig. 3):

- 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 dimensioning rule for complete amplitude-dampening is 30 m pipe per 100 m3/h airflow (fig. 3, left), for diameters yielding an air velocity in the 1 to 4 m/s range. As pointed out above, the daily amplitude will have vanished on approximately half that distance, with the same rules as hereafter.
- 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 15 cm soil around each. Typical required length is roughly 15 m per 100 m3/h airflow (fig.3, right), a relation which however isn't as linear anymore and slightly depends on the pipe diameter and associated air velocity.



Extensive geometry
Summer/winter amplitude-dampening

Compact geometry
Day/night amplitude-dampening

Fig. 3: Guidelines for dampening of daily or yearly amplitude

Note that preceding guidelines for pipe length concern residual amplitude of e^{-2}, but may be extrapolated by way of the exponential form of the temperature dampening. As an example, the guidelines for the compact configuration indicate that a 200 m3/h airflow in a 22 cm diameter pipe (~ 1.5 m/s) needs 55 m for complete daily dampening (fig. 3, right); a 20 m pipe hence would yield a residual amplitude of $e^{-2\cdot(20/55)} = 48\%$.

It should finally be stressed that the model on which these guidelines have been established does not take into account perturbation of the storage mechanism by thermal drive from 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 can however be investigated by way of numerical simulation.

VALIDATION

Validation as well as illustration of these behaviours and guidelines will now be given on hand of an extensively validated finite element numerical model for buried pipe systems [4], 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 within this study).

Both the considered configurations consist of a layer of 20 cm diameter pipes, each swept by a 200 m3/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. Superior border conditions are in both cases taken as adiabatic, whereas a sufficiently important soil layer is taken into account for the heat wave to expand as deep as necessary (adiabatic border conditions 15 m below pipes). The arrays are supposed to consist of a sufficient amount of pipes for lateral border effects to be negligible, so that the system may 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. 4, 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 residual yearly and daily amplitudes may be compared to the values given by the above dimensioning rules (fig. 4, bottom): a very good correlation is manifest in either case, theoretical guidelines only slightly overestimating the residual amplitudes given by numerical simulation

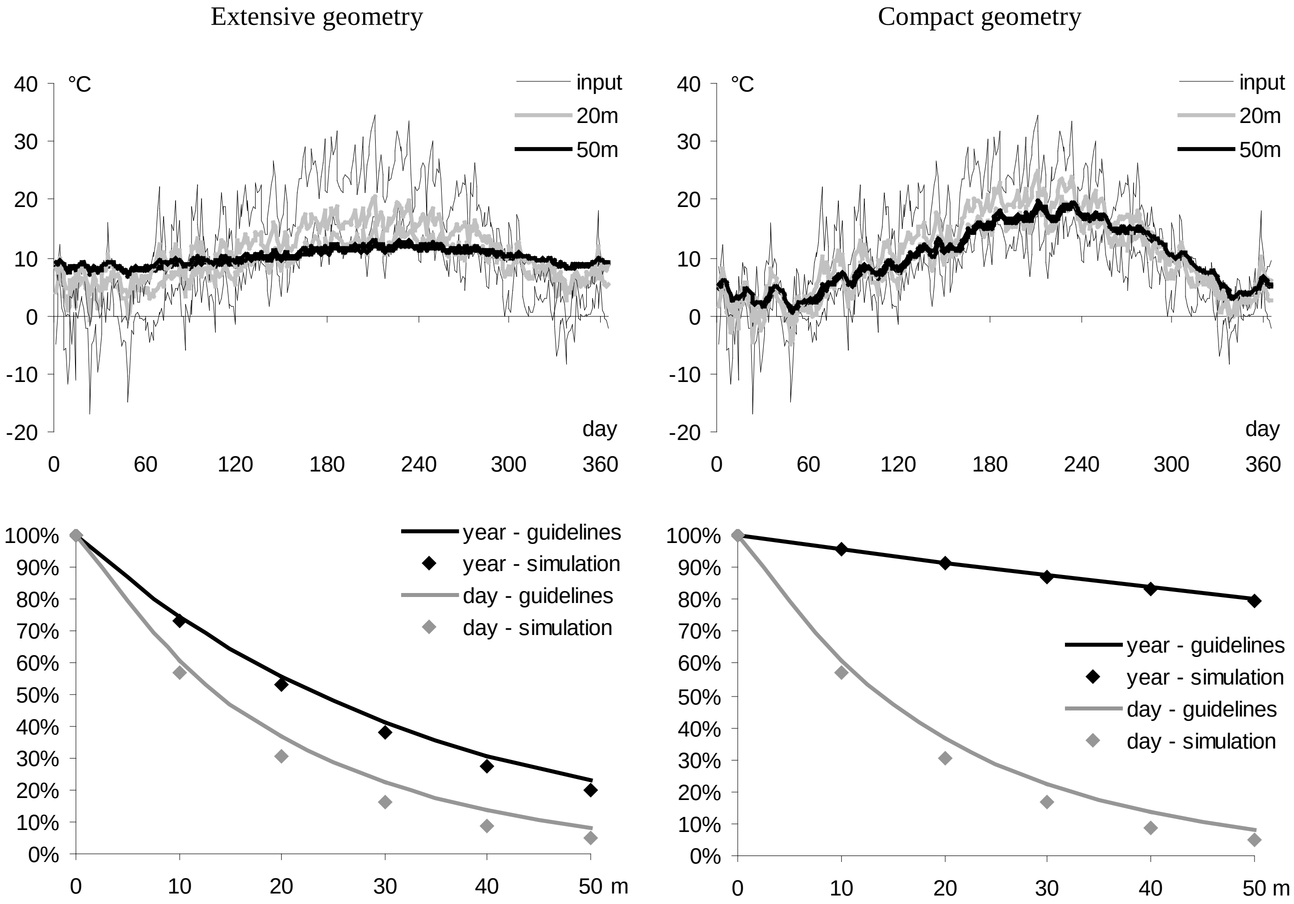


Fig. 4: Dynamic of daily minima and maxima (top) as well as resulting amplitude dampening (bottom).

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