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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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HIGHLIGHTS

- Overview of analytical models, numerical simulation, system integration and overall energy balance.
- Climate independent design guidelines for amplitude dampening of yearly or daily temperature oscillation.
- Highlighting of potentials and limits for preheating and cooling of buildings.
- Comparison with other passive cooling techniques.
- System integration (conflicts and synergies with other components) and derivation of overall 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.

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

1.2.1. Analytical models

Unlike a liquid heat storage medium, which can generally be fairly well described by means of two separate conductivity and

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Nomenclature

Latin letters

c	specific heat of air (J/K kg)
c_s	specific heat of soil (J/K kg)
h	overall heat transfer coefficient (air/soil) (W/K m^2)
h_a	convective heat transfer coefficient (air/pipe) (W/K m^2)
h_s	diffusive heat transfer coefficient (pipe/soil) (W/K m^2)
$\dot{m}$	total airflow rate (m^3/s)
$\dot{m}_0$	base airflow rate (standard ventilation) (m^3/s)
$\Delta\dot{m}$	additional airflow rate (over-ventilation) (m^3/s)
P_{ext}	gross heat gain, ventilation from outdoor (W)
P_{pipe}	gross heat gain, buried pipes (W)
P_{vent}	gross heat gain, ventilation system (W)
ΔP_{dif}	net heat loss by heat diffusion (W)
ΔP_{pipe}	net heat gain, buried pipes (W)
$\Delta P_{pipe+rec}$	net heat gain, combined buried pipes and heat recovery (W)
ΔP_{rec}	net heat gain, heat recovery (W)
ΔP_{vent}	net heat gain, ventilation system (W)
Pr	Prandtl number (–)
r	pipe radius (m)
Re	Reynolds number (–)
S	pipe exchange surface (m^2)
t	time (s)
T_{bld}	temperature of building (°C)
T_{ext}	temperature outdoor (°C)
T_{pipe}	temperature outlet of pipe (°C)
$T_{pipe+rec}$	temperature outlet of combined buried pipes and heat recovery (°C)
T_{rec}	temperature outlet of heat recovery (°C)
T_{vent}	temperature outlet of ventilation system (°C)

Greek letters

δ	heat penetration depth (m)
δ_{day}	heat penetration depth, daily oscillation (m)
δ_{year}	heat penetration depth, yearly oscillation (m)
η_{rec}	efficiency of heat recovery (–)
θ_{ext}	oscillation amplitude, outdoor (K)
λ_a	thermal conductivity of air (W/K m)
λ_s	thermal conductivity of soil (W/K m)
ρ_s	specific mass of soil (kg/m^3)
τ	oscillation period (s)
ω	oscillation frequency (rad/s)

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 [2–14]. 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 et 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 did not 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 neighboring pipes [19], but it also concerns deeply buried pipes and does not 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.

1.2.2. 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 [23–28]. 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 [29–32]. 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].

1.2.3. 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 [34–36].

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 min time step over an entire