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Compact buried pipes system analysis for indoor air conditioning

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HIGHLIGHTS

- ► The use of a compact buried pipe system for indoor air conditioning is studied.
- ► The compact buried pipe system is compared with the single layer configuration.
- ► The performance of the buried pipe system is simulated by a 1-D discrete model.
- ► The system is also studied performing a parametric analysis.
- ► The physical layout of the heat exchanger is described.

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ABSTRACT

Given the international state of affairs in what concerns the heating of buildings and the necessary reduction of costs in the heating and cooling energy consumption, it is imperative to study and develop passive methods of heat transfer including heat exchange through buried pipes. Common configurations of a heat exchanger usually consider one single layer of pipes requiring a large installation area. This major drawback can be overcome using a multiple layer configuration. This paper presents a study considering the use of a heat exchanger with a multiple layer configuration, namely, comparing it with a single layer of pipes and describing the major performance differences. A parametric analysis was also performed to better understand the effect of the main input parameters on the heat exchanger power output. It was concluded that the heat exchanger power increases with the layers depth until 3 m and that the more efficient distance between layers should be kept at 1.5 m. The heat exchanger layout is also described as well as the implementation of the numerical model and the corresponding application to a real case study.

1. Introduction

About 40% of the energy consumption in Europe is delivered to the building sector [1]. Current trend on building design and European legislations, like the EPBD recast of 2010 [2], are pushing buildings to low energy designs with the creation of the "near zero energy buildings" concept. More than 50% of this consumption could be reduced through energy efficiency measures, leading to a possible annual reduction of 400 millions of tons of CO_2 – nearly the total commitment of the EU to the Kyoto Protocol target. In light of this, it is clear that a major potential for the implementation of low energy consumption systems like earth-to-air heat exchangers (buried pipes) can be found in the household and service sectors.

A wide diversity of ground cooling/heating systems has been already used and applied [3], from closed to open system, and both analytical and discrete models have been studied and compared to predict the performance of buried pipe systems. For example, Santamouris et al. [4] compared eight different models to study their sensitivity to change the main operation parameters of an open horizontal earth-to-air heat exchanger.

The analysis of buried pipe systems must consider the study of the soil's thermal behaviour. It includes formulating the proper energy balance equations at the soil surface level [5] and developing the temperature profiles of the soil due such energy balance [6]. It was noted that the soil energy balance is affected by the type of cover, for example, grass covered or bare, and the humidity ratio [7,8]. A sophisticated model describing the complex mechanisms of

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Nomenclature

Roman symbols

A	area of heat transfer, soil surface (m^2)
C_p	thermal capacity (J kg^{-1} °C^{-1})
f	factor of moistness of the ground surface (%)
I_{sol}	total incident radiation on the horizontal (W m^{-2})
m_{ar}	mass flow rate of environment air through pipe (kg s^{-1})
Nu	Nusselt number
Pr	Prandtl number
Q	circulating air volume (m^3)
Q_{arm}	heat stored in the node (J)
Q_{cd}	heat for conduction in the surface of the ground (J)
Q_{cv}	heat for convection (J)
Q_{ev}	heat for evaporation (J)
Q_{re}	heat for incident radiation (J)
Q_{ri}	heat for incident radiation (J)
Re	Reynolds number
T_{amb}	exterior temperature (°C)
T_{in}	interior temperature (°C)
T_{out}	exterior temperature (°C)
T_{solo}	soil surface temperature (°C)
X	element size on the direction x
Y	element size on the direction y
Z	element size on the direction z
W_e	power of the fan (W)
COP	coefficient of performance
EER	energy efficiency ratio
IAQ	interior air quality
LNEC	Civil Engineer National Lab – Laboratório Nacional de Engenharia Civil
RCCTE	buildings thermal behaviour characteristics regulation

Greek symbols

ϕ_{ar}	relative air humidity (%)
α_{solo}	coefficient of absorption of the ground
α_{sup}	coefficient of convection in the surface of the ground (W m^{-1} °C^{-1})
ρ_{ar}	density of the air (kg m^{-3})
ρ_{solo}	density of the ground (kg m^{-3})
λ	mineral conductivity (W m^{-1} °C^{-1})

simultaneous heat and mass transfer occurring around an earth tube has also been developed and integrated into TRNSYS by Mihalakakou et al. [9].

In order to describe the performance of the buried pipes system theoretical and numerical models were developed. Frequent cases found on literature are discrete numerical models applied to earth-to-air heat exchangers with a single layer of pipes [3,10–12]. Another approach not so frequent is the analytical modelling of the heat exchanger [13,14]. Other features of this technology have already been studied, such as economic feasibility and integration into a building [15–17]. In the Middle Eastern Europe a similar technology on buried ducts cooling air into buildings is also being carried out. However, the major limitation for the implementation of this kind of ground-coupled heat exchanger is the area restrictions particularly in dense urban areas, where large buildings leave few spaces in the surroundings to install these systems. The major advance of the model described in this article is its capacity to considerably reduce the installation area of the system, while maintaining the high performance characteristics of this technology. The system under study consists of a compact multi-layer earth-to-air heat exchanger.

The exchanger consists of layers of horizontal tubes buried underground next to each other in each layer, in which air will flow from the outside into the building and will be cooled or heated while it crosses along the buried pipes in an open circuit. The system will be installed in a green area besides the building instead of beneath the building. However, horizontal exchangers have a serious disadvantage of requiring large horizontal area to install the pipes, thus, in this paper the effectiveness of a horizontal exchanger on two and three levels without saturating the soil's heat exchange capacity was explored. This system can be thought for retrofit and new buildings. However, for retrofit buildings some problems can arise up affecting the foundations. The implementation should take into account safety, economical and technical issues.

For performance analysis of the multiple layer heat exchangers it is important to bear in mind that the gap from the surface and between layers both need to be dimensioned, otherwise the pipes can saturate quickly the soil's thermal capacity, thereby reducing the overall system performance. Multiple layer horizontal heat exchangers have an advantage when compared to single layer heat exchangers because of the considerably reduced horizontal area needed for the system installation. However, the decreased area should not sacrifice significantly the heat exchanger performance. The analysis of both configurations performance will be studied in the present paper.

The approach followed in this paper starts with a description of the Portuguese soil as well as climatic factors, in order to establish their characteristics regarding the heat transfer capacity. Then, a physical model of a heat exchanger with two and three levels was developed with the corresponding boundary conditions and assumptions. Next, the most promising numerical models were analysed, namely, analytical and discrete (one and two-dimensional) with the corresponding validation. The one-dimensional model was selected as the best option to model this heat exchanger, under an accuracy and computational effort perspective. A parametric study was also carried out to check all the variables of the heat exchanger system and the corresponding optimal values for each parameter were obtained. Finally, the developed model was applied to a heat exchanger in a real case study in Portugal.

The systems were designed for cooling purposes where the target indoor temperature was 25 °C defined by the national Portuguese regulation, RCCTE [18]. During the winter season the soil is able to gather about 260 kWh of useful energy and deliver about 870 kWh during the summer season.

2. Main considerations

The soil properties are crucial to ease the heat transfer between the ground and the conditioned air supplied to the building, either for cooling or heating purposes. Both the internal and external characteristics of the ground, which have a part in the calculation of its thermal properties, were defined in the following sections. The mineral classification of the soil is addressed at a national Portuguese level and considered as the basis for the calculation of thermal conductivity and thermal capacity. The effect of porosity and soil moisture was studied, as well as other external factors (described below) that can influence the temperature along time.