Parameter analysis of Earth-air heat exchangers coupled to galvanized bridges

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Abstract. Due to the thermal inertia of the soil, it can be warmer or colder than the ambient air. Therefore, Earth-air heat exchangers (EAHE) connect the ventilation system of a building to buried ducts. Such research is valuable because EAHE use a renewable thermal source, and they consume little electricity. EAHE heating and cooling capacities depend on many factors, like the local climate, duct design, and soil properties. This study aims to evaluate the thermal performance of EAHE coupled to galvanized bridges with high thermal conductivity; the idea is to increase the overall heat exchange with the surrounding ground. This work analyses the settings of a subtropical climate, specifically, the southern Brazilian town of *Viamão*. The simulations use the validated 1D GAEA model, and they estimate the soil temperatures (without the ducts) by solving 2D heat transfer equations with finite element methods. The methodology considers the soil, galvanized bridges, and dynamic boundary conditions that vary throughout the year. As the thermal potential of EAHE improves with galvanized bridges, this article examines the reduction of the duct length, keeping high annual efficiency rates.

Keywords: Earth-air heat exchanger (EAHE), Galvanized bridges, GAEA model, Thermal performance.

1 Introduction

The greenhouse effect, which is considered a cause for climate change, makes us look for different possibilities of generating renewable and non-polluting energy. Besides, it is necessary to reduce electrical consumption and improve the efficiency of our technologies. Hence, the thermal comfort of building environments is a concerning theme because the usual air conditioning systems need high amounts of energy (Brum et al. [1], Brum [2]). Since the sun is an impressive energy source, we can explore it in many ways; one of them is the Earth-air heat exchangers (EAHE), which take advantage of the heat that our star emits and the planet stores on the superficial ground layers (Vaz [3]).

The flow of heat, which arises from the interaction between soil molecules, changes direction in daily and annual cycles. It flows to the soil during the day and towards the surface at night; a similar process occurs during summer and winter. Therefore, EAHE consist of one or more ducts buried horizontally or vertically; the air travels inside the ducts, exchanges heat with the soil, and enters the building environment at milder temperatures. Figure 1 shows a typical EAHE scheme.

Part of the EAHE research focuses on modeling the phenomenon of heat transfer, aiming to increase their thermal potential and efficiency. Domingues et al. [4] give a recent balance of the Brazilian studies in EAHE, while the articles by Agrawal et al. [5] and Bordoloi et al. [6] cover long reviews on the EAHE literature. Some of

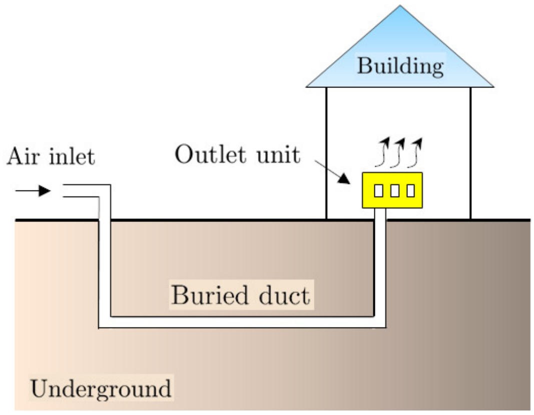

Figure 1. Typical EAHE scheme.

the main subjects in mathematical modeling regard: (1) the physical location of the installation, air temperatures, humidity, soil composition, compaction, solar radiation; (2) operational parameters, air velocity, installation depth, duct shape, and materials. Many works also investigate hybrid systems for air conditioning, combining EAHE to other technologies that may or may not use renewable energy.

Different references studied the effect of the duct material (especially using high thermal conductive ones); however, they have not shown significant improvements in the system thermal performance (Bansal et al. [7], Ascione et al. [8]). On the other hand, the radius and length of circular ducts, the installation depth, and the air velocity are four fundamental parameters to examine and develop parametric models, like Mihalakakou et al. [9], whose simulations showed significant agreement with experimental data.

In urbanized areas (particularly in large cities), a fundamental issue for the EAHE installation with horizontal ducts is the reduced space, but few works address it (Agrawal et al. [5]). For instance, Mathur et al. [10] proposed a spiral-shaped design to reduce construction space. They obtained satisfactory results compared to usual systems using straight horizontal ducts. Benrachi et al. [11] also considered spiral-shaped ducts from the EAHE system to reduce area requirements. In the same regard, Asgari et al. [12] assessed and compared the thermal performances of various duct arrangements using linear, spiral, and slinky types of horizontal EAHE.

Aiming to reduce the size of EAHE installations, this paper explores the idea proposed by Hassanzadeh et al. [13]; more specifically, we connect the ducts to galvanized bridges with high thermal conductivity. Since this method significantly improves the heat transfer rate between the ground and pipes, we show that their length can be reduced, keeping the system's annual thermal efficiency values above 70%.

2 Methodology

This work considers data from the south Brazilian town of *Viamão*, where Vaz [3] took several experimental measurements from a local EAHE installation. The place has a humid subtropical climate with slightly undulating soils; its geographic coordinates and altitude are (30°04'51"S, 51°01'24"W) and 111 m, respectively.

Replicating the conditions found in Vaz [3], we simulated a duct with diameter $D_0 = 0.11$ m, buried at a depth of $z_0 = 1.6$ m. We neglected the duct material properties, as done in many references (Brum et al. [14], Rodrigues et al. [15]). The novelty here is that we enclosed the duct with a box coupled to a vertical bridge, both of them galvanized and made of a high thermal conductivity material, exploring the ideas from Hassanzadeh et al. [13]. Moreover, we varied the duct length L_0, starting from 25.77 m (same value taken by Vaz [3]) and reducing it down to 10.77 m.

Figure 2 shows 2D views for the computational domain, including the duct, box, and bridge. In the $x - z$ plane view, $b_0 = 18$ cm is the size of the box; $S_v = 1$ m and $S_h = 1$ cm are, respectively, the vertical and horizontal sizes of the bridge. As we can see in the $y - z$ plane view, the bridge and box have the same length, L_0, of the duct. Moreover, the simulated portion of soil has a height of 15 m, a width of 10 m, and a varying length L_0.

To simulate the EAHE, we adopted the GAEA model (Graphische Auslegung von Erdwärme Austauschern) that Domingues et al. [4] validated against the experimental data of Vaz [3]. GAEA is a 1D model that computes the longitudinal variations in air temperatures along the ducts; to do so, it depends on estimates for the soil temperature without the duct presence. Since the air in the duct also influences the ground temperature around it, the model equations also evaluate this effect; however, due to space constraints, we ask the reader to consult references like (Domingues et al. [4], Benkert et al. [16], Papakostas et al. [17]) for more details.

Considering Fig. 2, the main variations in soil temperature occur in the x-z plane, and one can neglect them on

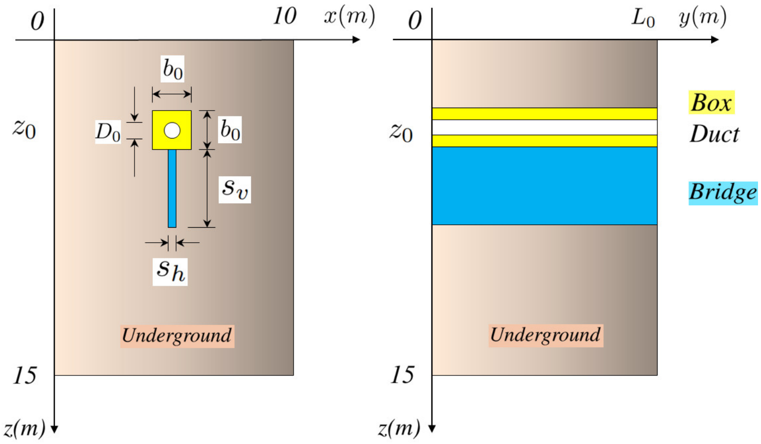

Figure 2. Schematic 2D views for the set duct, box, and bridge.

the y-z one. Therefore, to compute the temperatures in the ground, box, and bridge, we solved the heat conservation equation

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho\, c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad \text{in} \quad \Omega \times (0, \tau_0]. \tag{1}$$

Here, T stands for the temperature in (^{o}C) and t for the time (in s). The spatial domain is $\Omega = (0, 10) \times (0, 15)$ (dimensions in m), as in Fig. 2; the total time interval for simulations, τ_0, is of one year and two months. Table 1 defines the thermophysical properties; the values for air and soil are given by Vaz [3], the ones for the galvanized parts are from Hassanzadeh et al. [13].

Table 1. Thermophysical properties

	Density ρ (kg/m^3)	Specific heat c_p (J/kgK)	Thermal conductivity λ (W/mK)
Soil	1800	1780	2.1
Galvanized parts	7800	446	52
Air	1.16	1010	0.0242

The solution for eq. (1) is subject to the boundary conditions

$$T = T_a \quad \text{at} \quad z = 0\,\text{m}, \tag{2}$$

$$\frac{\partial T}{\partial x} = 0\,^o\text{C/m} \quad \text{at} \quad x = 0\,\text{m and } x = 10\,\text{m}, \tag{3}$$

$$\frac{\partial T}{\partial z} = 0\,^o\text{C/m} \quad \text{at} \quad z = 15\,\text{m}. \tag{4}$$

In eq. (2), T_a is the air temperature in *Viamão*. We can model it by

$$T_a(t) = 20.49 + 5.66 \sin\left(\frac{2\pi}{365} t - 5.30\right), \tag{5}$$

after fitting by least squares the daily average temperatures obtained by Vaz [3]. The initial condition is

$$T_{init}(z) = 20.49 - 5.66\sin(5.30 + 0.39z)e^{-0.39z}, \tag{6}$$

where we are supposing that the soil temperature is initially varying only in the z direction. Equation 6 follows the methodology from Ozgener et al. [18].

We solved the equations numerically, using the Galerkin finite element method (Hughes [19]) for spatial discretization. The time discretization used the first-order, implicit Euler, finite differences method (Özisik [20]). We conducted various refining tests before adopting meshes with about 4000 triangular elements, generating them in the GMSH software (version 4.8.8). As done by Domingues et al. [4], we employed discrete time intervals of 1800 seconds. The simulations used an in-house code; developed in the Matlab software (version R2012a)

As in Domingues et al. [4], we are computing the EAHE annual efficiency using the equation

$$\theta = \frac{\sqrt{\int_0^{365}(T_o - T_i)^2}}{\sqrt{\int_0^{365}(T_s - T_i)^2}}, \tag{7}$$

where T_o and T_i are, respectively, the temperatures at the duct outlet and inlet. Here, we assume $T_i = T_a$ from eq. (5). As for T_s, it is an estimate of the temperature at the point (5 m,1.6 m) on the $x - z$ plane, i.e., at the duct center (see Fig. 2).

It is worth adding the following remarks.

(a) To solve the initial and boundary values problem (IBVP), defined in eq. (1) to eq. (6), we are not considering the duct presence but only the soil, box, and bridge. The IBVP gives T_s, in eq. (7).

(b) Although the total interval of simulations τ_0 covers one year and two months, we discard the first two ones to avoid numerical influences by the initial condition (see more details in Brum et al. [14]). Hence, the final results presented in this paper represent a period of one year.

(c) In general, to keep consistency in the simulations, the time, t, is defined in seconds. For convenience, in pre and post-processing stages, we use least squares to fit all the temperature results by sine-based functions, where t is in days. Such is the case for the temperatures in eq. (5) and eq. (7).

3 Results

We begin comparing the annual results for the outlet temperatures, considering an EAHE duct buried at the depth $z_0 = 1.6$ m, similar to the experimental case of Vaz [3]. This simulation used a mesh based on the $x - z$ view from Fig. 2 and the same developed code. Since in Vaz [3], there was no box nor bridge, we just programmed these parts of the domain with the same thermophysical properties of the soil. The graphic on the left in Fig. 3 shows the adjusted air temperature of *Viamão* (see eq. (5)), the simulated soil temperature (without galvanized parts), and the outlet temperature.

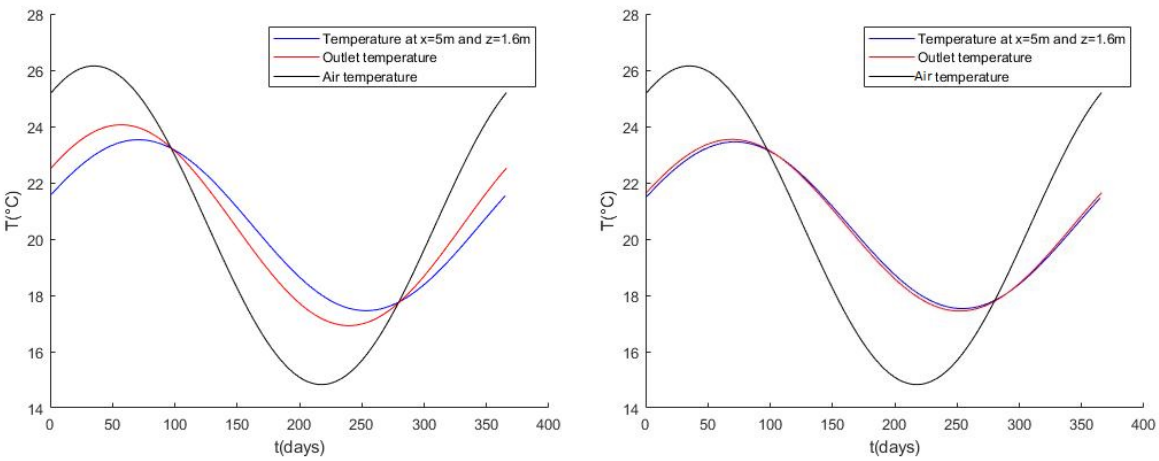

Figure 3. Comparative of the annual outlet temperatures without (left) and with (right) galvanized parts.

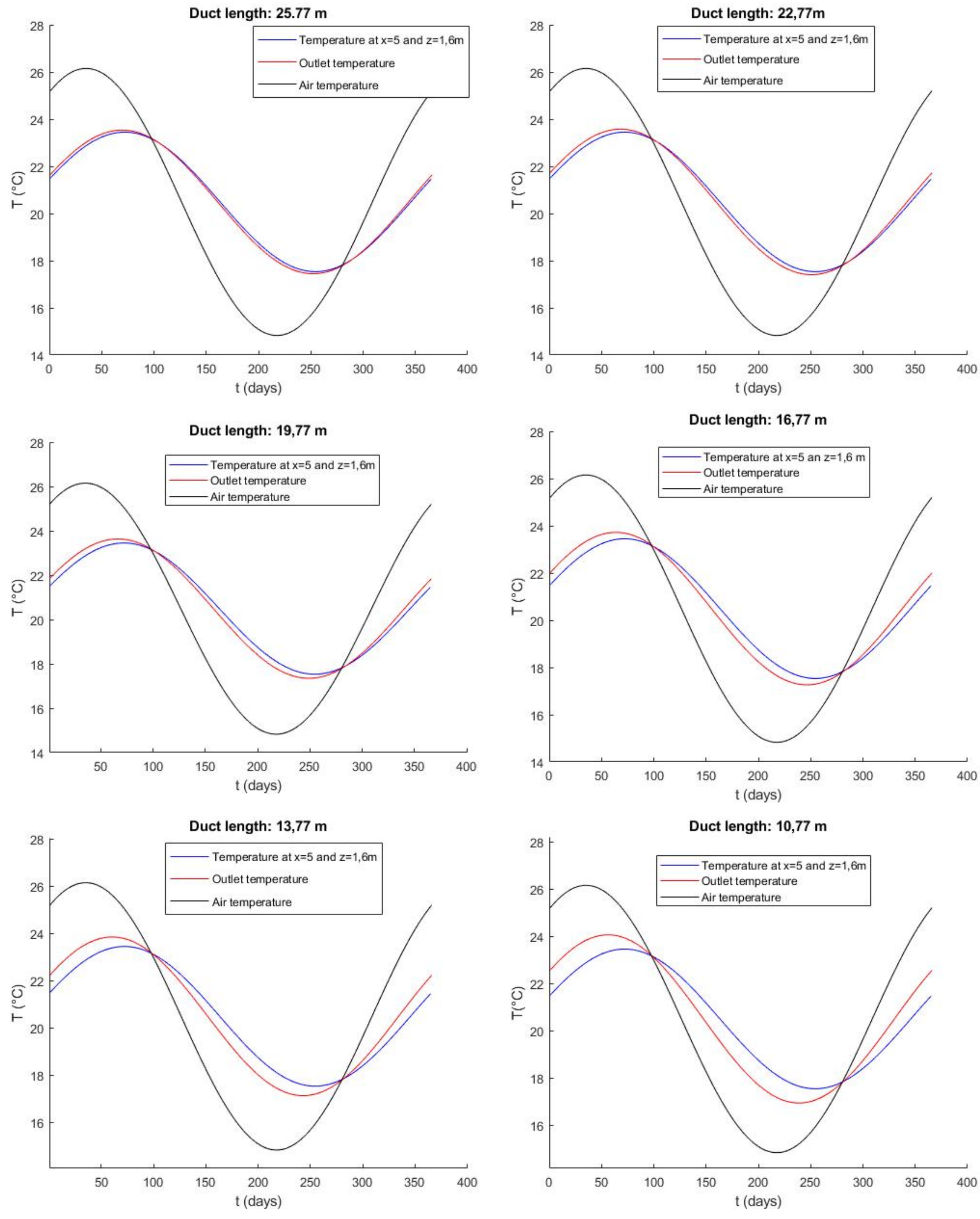

Figure 4. Comparison of annual outlet temperatures with ducts of different lengths

The results are very similar to the ones obtained by Domingues et al. [4], verifying the current methodology. Additionally, Fig. 3 shows that the outlet temperature curve lies between the air and soil ones. In this article, we distinguish the soil and EAHE thermal potentials. The former is the difference between the soil and air temperatures, while the latter is between the outlet and air ones. The higher the efficiency of the EAHE, the closer these two potentials are (see eq. (7)). As the graphic on the right in Fig. 3 shows, the insertion of the galvanized box and bridge hugely increases the EAHE efficiency compared to the results on the left. Besides, we note that the magnitude peaks of the thermal potential are close to 4^o C in summer and winter. In annual terms, the root mean square (RMS) of the thermal potential is approximately 2.6^o C (since the thermal potential is much smaller during spring and fall seasons).

Table 2 compares the EAHE annual thermal efficiency θ, varying the duct length L_0; the results show that reducing L_0 also reduces θ. We observe that the Vaz [3] installation had an annual efficiency close to 72% using a duct of 25.77 m. Adding the galvanized parts and using the same length, one can obtain $\theta \approx 95\%$. Moreover, we achieve efficiencies above 70% employing much smaller ducts, with L_0 varying between 10.77 and 13.77 m, reducing by almost half the installation size.

Table 2. Comparison between the length of the duct (Lo) and the annual thermal efficiency (θ).

Lo(m)	25.77	22.77	19.77	16.77	13.77	10.77
$\theta(\%)$	94.88	92.68	89.58	85.21	79.07	70.47

Figure 4 shows the variations in the outlet temperature as the duct lenght varies. It can be seen that the thermal efficiency decreases by reducing the length of the duct. Such results complement the ones from Table 2. The graphic corresponding to the length of 13.77 m is very similar to the first graphic of Fig. 3, where we had a duct without bridge and with a length of 25.77 m.

4 Conclusions

The EAHE annual thermal efficiency is increased significantly by coupling the ducts to a galvanized box and bridge set. Such methodology allowed obtaining efficiencies above 70% using much smaller ducts than a conventional installation. Therefore, EAHE systems can be improved, allowing us to reduce installation sizes in urbanized places where the spaces are limited.

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