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EVALUATING THE PERFORMANCE OF EARTH-AIR HEAT EXCHANGERS COUPLED TO A GALVANIZED RECTANGULAR PRISM UNDER DIFFERENT INSTALLATION DEPTHS

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Abstract. *Earth-air heat exchangers (EAHEs) stand among sustainable alternatives for heating and cooling buildings. Such systems consist of one or more ducts buried at a certain depth and a ventilation system, which forces the air to flow inside the ducts, exchanging heat with the surrounding soil and entering the buildings at a milder temperature. Based on the literature, we decided to analyze EAHE composed of ducts coupled to galvanized structures with high thermal conductivity. In particular, this work considers the ducts enveloped by a rectangular prism (block) then we perform different numerical simulations to study the system performance when the installation depth varies. Here, we adopt climate and geotechnical data from the southern Brazilian city of Viamão. For the EAHE simulations, we employed a validated version of the so-called GAEA model, where the soil temperatures are estimated numerically in two dimensions, using the Finite Element Method. To evaluate EAHE performance, we determine the soil thermal potential (P_s), the EAHE thermal potential (P_t), and the EAHE efficiency (θ). Therefore, this article aims to evaluate how the depth of the block affects P_s, P_t, and θ. From the preliminary results, we have that coupling a duct to a galvanized block increases the system efficiency by about 30% compared to simulations without it. Placing the installation at 3.5 m, we estimated that Ps and Pt reach annual RMS values of approximately 4°C and 3.8°C, respectively.*

Keywords: *Earth-air heat exchanger (EAHE), Thermal Potential, Renewable energy, GAEA model*

1. INTRODUCTION

The planet is facing climate changes that can be associated with human activities. Hence, there is a worldwide concern to develop sustainable alternatives that minimize the environmental impacts caused, for instance, by the rampant electricity consumption. According to Mimouni *et al.* (2014) and Rodrigues *et al.* (2018), the electricity spent on air conditioning systems represents a significant part of daily energy consumption in developed and developing countries. This work explores a sustainable alternative based on the Earth-air heat exchangers (EAHE), which are systems designed to use the constant temperature of the underground soil for heating or cooling the air of a building (Agrawal *et al.*, 2019). The EAHE can work with low-power fans; hence, they demand little energy, and one can recover the installation costs with energy savings. EAHE can also be coupled to other air conditioning systems, further reducing their energy consumption as they pre-heat (or cool) a place (Brum, 2016). Figure 1 presents a typical two-dimensional scheme of EAHE.

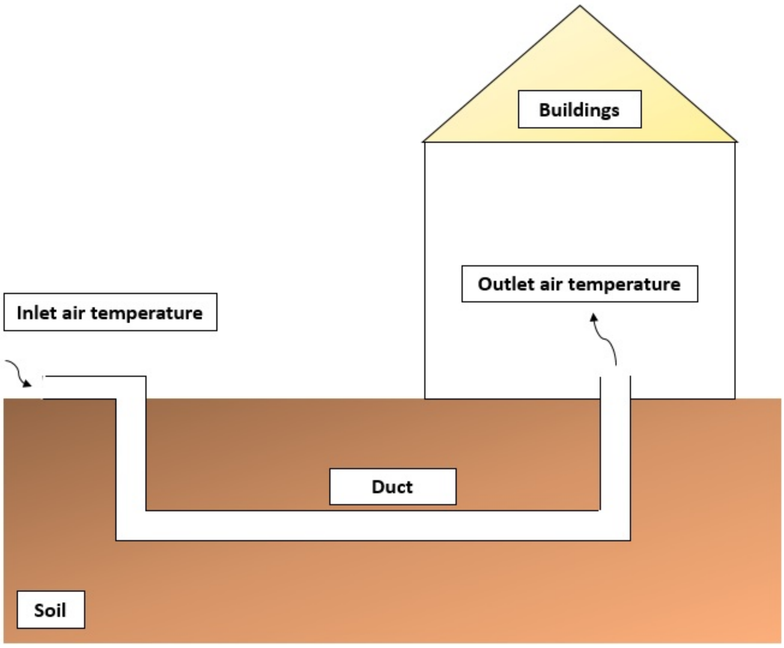

Figure 1. A typical EAHE scheme.

In the following, we describe some relevant references for this research. For the EAHE simulations, we adopted the GAEA model from Benkert *et al.* (1997). It is an analytical model that allows faster simulations and provides the air temperature along the duct by estimating heat transfer coefficients for the heat flow between the air, the duct walls, and the surrounding soil. A more recent comparison among GAEA and other analytical models is given by Papakostas *et al.* (2019). To validate the model, we compared its results with the experimental data from Vaz *et al.* (2011), where the author investigated an EAHE installation in the Southern Brazilian city of *Viamão*. The results were also verified, comparing them with the work of Domingues *et al.* (2021), where the authors made a parametric study of EAHE, considering the characteristics of three different places in the Southern Brazilian city of *Rio Grande*. Overall, these two last references point out a significant thermal potential for EAHE devices in the Brazilian state of *Rio Grande do Sul*.

Inspired by the work of Hassanzadeh *et al.* (2018), we decided to investigate how to couple the ducts to galvanized structures, aiming to increase the thermal conductivity of the area around the duct and maximize the soil and EAHE thermal potentials. Hassanzadeh *et al.* (2018) integrated galvanized bridges (fins) to the ducts and analyzed how the heat transfer rates between the ducts and the ground increased, considering three different soils, with different thermal conductivities. The recent works of Olivera (2022) and Pastor (2022) also accessed variations of the methodology from Hassanzadeh *et al.* (2018). Pastor (2022) surrounded the duct by a galvanized block coupled with at most four galvanized fins. From the results, the EAHE thermal potential increased by using only one vertical fin, and the annual efficiency reached more than 90%. Olivera (2022) carried out a parametric study, verifying that it is possible to reduce the size of the installation by almost half, keeping the annual efficiency above 70%.

Based on the data from (Vaz *et al.*, 2011), this article simulates EAHE considering the soil and climate of the Brazilian city of *Viamão*. Moreover, we coupled the ducts to a galvanized block (rectangular prism) with a cross-sectional area of 3m^2 to increase the heat transfer around them. This work aims to study how the EAHE thermal potentials and their annual efficiency vary with the installation depth.

2. METHODOLOGY

Figure 2 gives a cross-sectional view of the computational domain adopted in this work. Here, z_0 is the depth of the duct center (which is also the center of the block). For the duct geometry, we used similar parameters described in Vaz *et al.* (2011); hence, the duct length and diameter are, respectively, L = 25.77 m and D = 0.11 m. The block is a rectangular prism that envelops the duct. The block dimensions are S_h, S_v and L. As for the soil dimensions, they are based on references like Brum (2016).

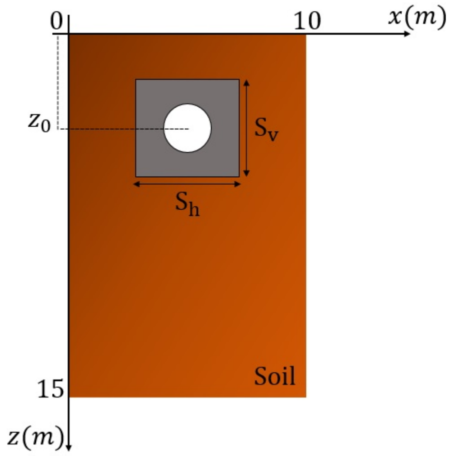

Figure 2. Cross-sectional view of the system: soil, block and duct.

To better understand the results of this paper, it is necessary to give some general definitions. The thermal potential of the soil (P_s) is the difference between the soil temperature (T_s) and the air temperature (T_a) in the duct inlet. Hence,

$$P_s(t) = T_s(t) - T_a(t). \tag{1}$$

It is worth noting that we are also considering T_a as the air temperature at the soil surface.

The EAHE thermal potential (P_E) is the difference between the air temperatures at the duct outlet (T_{out}) and the inlet (T_a), that is,

$$P_E(t) = T_{out}(t) - T_a(t). \tag{2}$$

The EAHE annual efficiency is computed using the following equation:

$$\theta_a = \frac{\sqrt{\int_0^{365} P_E(t)^2 dt}}{\sqrt{\int_0^{365} P_s(t)^2 dt}}. \tag{3}$$

2.1 GAEA Model

To simulate the heat exchanges in the duct, we used the GAEA model, detailed in Benkert *et al.* (1997), and implemented it in Matlab software (version R2019a). We describe the model algorithm using the following equations.

First, we estimate the Nusselt number by the equation

$$Nu_D = 0.0214 \times (Re_D^{0.8} - 100) \times Pr^{0.4}, \tag{4}$$

where Re_D and Pr are, respectively, the Reynolds and Prandtl numbers. The heat transfer coefficient on the inner surface of the duct is given by

$$h = \frac{\lambda_a \times Nu_D}{D}, \tag{5}$$

where λ_a is the thermal conductivity of the air, and D is the duct diameter. Hence, we compute the heat transfer coefficient (by length) between the air stream and the walls of the duct, using the equation

$$U_L = \pi\ D\ h. \tag{6}$$

The conductance ratio of heat transfer from air to duct and duct to ground can be calculated from

$$U^* = 2\pi \frac{\lambda_s}{U_L ln\left(\frac{2z_0}{D} + \sqrt{(\frac{2z_0}{D})^2 - 1}\right)}, \tag{7}$$

where z_0 is the duct center depth and λ_s is the thermal conductivity of the soil.

Now, we divide the duct length L into several segments of size Δx, making it possible to know the temperature in each segment iteratively, using a repeating structure. As in Benkert *et al.* (1997), we divided L by a hundred. Henceforth, for each segment, the soil temperature at the duct wall is calculated by

$$T_{c,w}^k = \frac{U^* T_s + T_{a,i}^k}{U^* + 1}. \tag{8}$$

Here, $T_{a,i}^k$ is the air temperature at the k-th segment inlet, and T_s is the ground temperature. The temperatures at the outlets of each segment is given by

$$T_{a,o}^k = T_{a,i}^k \frac{\Delta x U_L (T_{c,w}^k - T_{a,i}^k)}{\dot{m}\, c_{p,a}}, \tag{9}$$

where $\dot{m}$ and $c_{p,a}$ are, respectively, the mass flow rate and the specific heat of the air. The algorithm comes to an end after finding the outlet temperature in the last segment of the duct, which is also the duct outlet.

2.2 Numerical methodology to find the soil temperature

To use the GAEA model, one needs to obtain the soil temperatures not influenced by the duct presence. As in (Pastor, 2022; Olivera, 2022), the soil temperature was numerically computed in a two-dimensional way, adopting computational domains similar to the one shown in Fig. 2, excluding the duct. Thus, we estimated the soil temperature throughout the year by calculating the function $T_s = T(x, z, t)$, satisfying the energy conservation equation

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho\, c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad \text{in} \quad \Omega \times (0, \tau_0]. \tag{10}$$

Here, x and z represent the spatial coordinates and t the time. The spatial domain, Ω, is shown in Fig. 2 and is composed of the soil and the galvanized block. The total simulation period, τ_0, is one year and two months, but we discard the first two months to avoid numerical influences from the initial condition. The model must satisfy the following boundary conditions

$$\begin{cases} T = T_a \quad \text{em} \quad z = 0\,\text{m}, \\ \frac{\partial T}{\partial x} = 0°\text{C}/m \quad \text{em} \quad x = 0\,\text{m} \quad \text{e} \quad x = 10\,\text{m}, \\ \frac{\partial T}{\partial z} = 0\,°\text{C}/m \quad \text{em} \quad z = 15\,\text{m}. \end{cases} \tag{11}$$

We modeled the air temperature in *Viamão*, T_a, using the experimental data of Vaz *et al.* (2011). More specifically,

$$T_a(t) = 20.49 + 5.66 \sin\left(\frac{2\pi}{365} t - 5.30\right). \tag{12}$$

Table 1 gives the thermophysical properties of the air, soil, and galvanized material. We extracted the first two from Vaz *et al.* (2011), while the last is from Hassanzadeh *et al.* (2018).

Table 1. Thermophysical properties

	Density ρ (kg/m^3)	Specific heat c_p (J/kgK)	Thermal conductivity λ (W/mK)	Dynamic viscosity μ (kg/ms)
Air	1.16	1,010	0.0242	1.789×10^{-5}
Soil	1,800	1,780	2.1	-
Galvanized material	7,800	446	52	-

We adopted the same initial condition from (Domingues *et al.*, 2021)

$$T = T_0(z) = 20.49 - 5.66 \sin(5.30 + 0.39z)\, e^{-0.39z} \; at\; t = 0s. \tag{13}$$

It is based on a one-dimensional analytical model from Ozgener *et al.* (2013) and considers the data from Vaz *et al.* (2011), fitted by least squares.

We solved the equations numerically, using Galerkin's finite element method (Hughes, 1987) for the spatial discretization. For the time discretization, we used finite differences, more specifically, the implicit first-order Euler method (Özisik, 1993). Since we adopted finite elements, the condition of continuity of flow between the soil and the galvanized material is naturally absorbed in the variational formulation of the problem.

2.3 Galvanized block

We adopted a rectangular region (block) around the duct with high thermal conductivity, keeping the rest of the domain with the thermal conductivity of the soil. Figure 3 presents the main geometric aspects of the block.

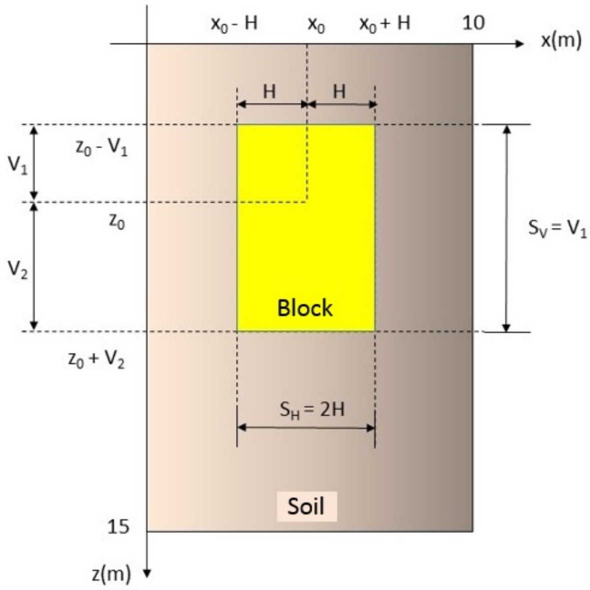

Figure 3. Geometric definitions of the galvanized block .

The block configuration is based on the following.

- The block is similar to the rectangular domain.
- The block is centered in the horizontal direction.
- H ranges from 0 to 5 m; hence, S_H can range from 0 to 10 m.
- The vertical variation follows the proportion:

$$S_V = \frac{15V_1}{z_0}.$$

  Thus, within the variation limits of V_1, between 0 m and z_0, S_V varies from 0 to 15 m. We note that V_2 depends on V_1, that is, $V_2 = S_V - V_1$. Therefore, V_2 can only vary between 0 and 15 m - z_0.

- The block and the domain have proportional areas. To ensure this, it is assumed that

$$S_H = \frac{2S_V}{3}.$$

  Thus, there are two limiting cases: (a) S_V = 0 m implies S_H = 0 m, and the block converges to a point (the center of the duct); (b) S_V = 15 m implies S_H = 10 m, and the block occupies the entire computational domain. In short, cases (a) and (b) represent extremes where the entire domain is composed, respectively, of soil or galvanized material.

- The area of the domain is again the constant A_c =150 m^2, while the area of the block is $A_b = S_H \times S_V$. Thus, the area fraction between the block and domain areas is given by

$$\psi = \frac{A_b}{A_c} 100\% = \frac{S_H \times S_V}{1.5}\%.$$

2.4 Mesh generation and tests

We generated our meshes using the software GMSH[1]. We made independence tests after adopting a time interval of $\Delta t = 1,800$s, which is the same as in the reference Domingues *et al.* (2021). The analysis compared vectors with the temperature solutions over a year, at the point $(x,\ z) = (5,\ 1.6)$ m. More specifically, we computed the maximum value of the difference (in absolute values) between two successive annual solution vectors. Table 2 presents the last conclusive data from the mesh tests. Based on the results and the literature, we considered it sufficient to adopt a regular mesh with a minimum of 2,017 nodes and 3,935 triangular elements.

[1] Available online on https://gmsh.info/

Table 2. Final data from the mesh tests

Nodes	Element	Simulation time (min)	Comparison
1,097	2,137	2.6	
1,396	2,722	3.4	1.80×10^{-3}
1,657	3,230	4.2	6.94×10^{-4}
2,017	3,935	5.5	2.41×10^{-4}

3. RESULTS

3.1 Model Validation

We validated the model by comparing its results with the experimental data from Vaz *et al.* (2011). A similar approach was taken to validate the model of Domingues *et al.* (2021). Figure 4 presents a comparison among the following: (1) the results of the daily (discrete) averages of temperature at the outlet of the experimental EAHE of Vaz *et al.* (2011); (2) the least-squares fitted curve of the same data; (3) results with the model of Domingues *et al.* (2021); (4) results with the model from this work.

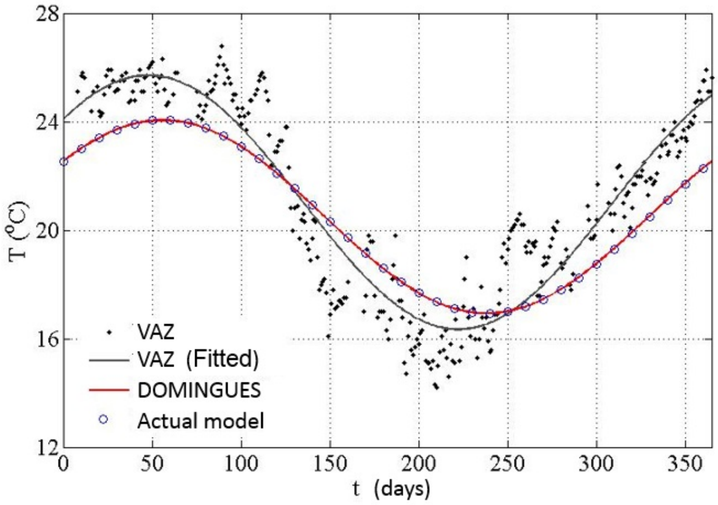

Figure 4. Comparison of the results from the current model with others from the literature.

We can see from Fig. 4 that the current model gives results approximately equal to the model from Domingues *et al.* (2021). Compared with the fitted results of Vaz *et al.* (2011), we obtained a Pearson correlation coefficient of 0.89; moreover, the annual RMS difference was approximately 1.45°C. We concluded that the current model is valid and provides accurate results, highly correlated to the experimental ones.

3.2 Results with the galvanized block

The galvanized block can help increase the thermal conductivity of the area surrounding the duct; the aim is to improve the efficiency and thermal potentials of the EAHE. Figure 5 shows that we can meet such objectives. It presents EAHE simulations for the depth of 1.6 m in two cases: (a) without the presence of a galvanized block; (b) with a block of 3 m^2 of cross-sectional area.

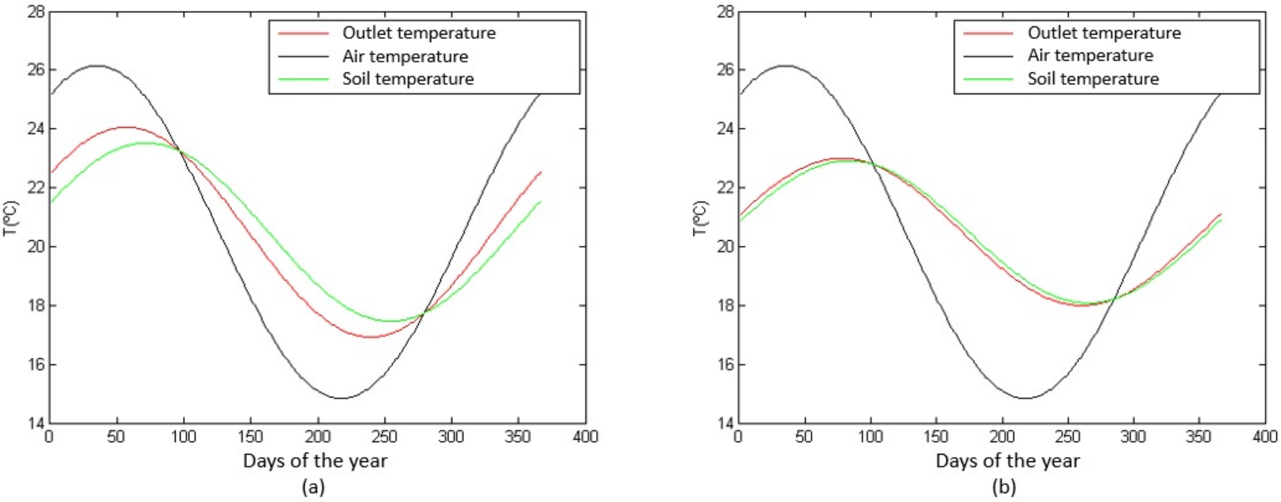

Figure 5. Comparison between the results obtained without a galvanized block (a) and with the galvanized block (b).

We can notice that the efficiency of the system increases significantly. While in (a) it is only 73 %, in (b) it reaches 95 %. In addition, the thermal potentials also increase. For a depth of 1.6 m, without the block, we have 2.59°C of soil potential and 1.9°C of EAHE potential. On the other hand, the soil and EAHE potentials for the same depth using the block are 3.09° C and 2.95°C, respectively. From such results, one can observe some of the advantages of the galvanized block, as the block increases the thermal conductivity of the region around the duct, it is possible to take advantage of all or practically all the thermal potential of the soil. We continued this research by accessing the use of the block at different depths.

3.3 Block simulations at different depths

The simulations considered five different installation depths to find which one gives the higher thermal potentials. For all cases, we kept a block area of $3m^2$. Table 3 displays the results.

Table 3. Simulation results involving depth variation

	1.6 m	2 m	2.5	3 m	3.5 m
Soil thermal potential	3.09	3.38	3.65	3.85	4.00
EAHE thermal potential	2.95	3.22	3.47	3.66	3.80

We can see that the thermal potentials increase as the depth increases, reaching 4°C of soil thermal potential and 3.8°C of EAHE potential for a depth of 3.5 m. In addition, it is possible to highlight that the annual efficiency of the system remained constant, around 95%, in all simulations involving the coupling of the galvanized block. These results are important because it is possible to realize that even at smaller depths, the potentials achieved are significant.This means that if the digging conditions are not so good, the system will work in the same way.

4. CONCLUSIONS

The EAHE is a promising technology to aid in obtaining thermal comfort but consuming less electrical energy. Such devices use a renewable energy source for their operation, contributing to environmental issues. In this study, we simulated EAHE installations based on the characteristics of a southern Brazilian city. We accessed the coupling of a galvanized block to the ducts, aiming to increase the thermal potential of the surrounding soil. We made different tests to conclude the best installation depth (using blocks with a cross-sectional area of $3m^2$) that maximizes the soil and EAHE thermal potentials. We can highlight that the depth interferes significantly in the process, and we obtained the best results for a depth of 3.5 m. Besides, coupling the block increases the annual efficiency of the system, which reaches a value close to 95% and helps to increase the EAHE thermal potential.

5. ACKNOWLEDGEMENTS

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