26th International Congress of Mechanical Engineering
COBEM 2021
November 22-26, 2021, Virtual Congress, Brazil

# COB-2021-1446
# ACCESSING THE THERMAL PERFORMANCE OF EARTH-AIR HEAT EXCHANGERS BY ADDING GALVANIZED BRIDGES TO THE SOIL

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***Abstract.*** *Due to the thermal inertia of the ground, it can be warmer or colder than the environment. Earth-air heat exchangers (EAHE) take advantage of that by connecting a building ventilation system to one or more buried ducts. The research of EAHE is valuable because they employ a renewable thermal source, and they can work with little electrical energy. Regarding the heating and cooling capacities of EAHE, they depend on many factors like local climate, duct design, and soil properties. This paper aims to evaluate the thermal performance of EAHE after coupling the ducts with galvanized bridges. The idea is to increase the overall heat exchange, as the bridges have a thermal conductivity much higher than the soil around them. This work considers the scenario of the south Brazilian city of Viamão, which has a subtropical climate. The simulations use the 1D GAEA model for EAHE after validating it with experimental data. As the model depends on estimating the soil temperatures without the ducts, this work computes them by solving the heat transfer equations in 2D with finite element methods. The methodology allows considering the soil, the galvanized bridges, and dynamic boundary conditions, varying along the year. The results show that the thermal potential of EAHE improves by equipping the ducts with the bridges. This paper adopts some types of vertical bridges, and it studies how changing their position can enhance the thermal potential and efficiency of EAHE. Important results presented during the research show that the thermal potential of the soil increases with depth, but its relative gains decrease, therefore, it is recommended a depth of at most 3.6 m for the installation of an EAHE system.Also in this study, it is possible to see that the coupling of galvanized bridges close to the exchanger duct generates an increase in the efficiency of the system.*

***Keywords:*** *Earth-air heat exchangers (EAHE), Thermal potential, Numerical simulations, GAEA, Galvanized bridges*

## 1. INTRODUCTION

Most of the energy used worldwide comes from fossil fuels such as coal, oil, and natural gas. The consumption of these fuels is faster than their regeneration, which is why they are considered non-renewable. Besides, their transport and storage have negative environmental impacts, hence, it is necessary to find alternative, efficient, non-polluting, and renewable sources.

The sun originates virtually every source of energy on Earth. This energy reaches the Earth's surface directly or by diffusion. The earth's crust acts as a large inertial reserve for this energy, with alternating cycles of storage and supply of heat to the environment. In the daily cycle, the Earth's surface gains heat during the day and loses it at night; similarly, in the annual cycle, the Earth's surface gains heat in hot periods and loses in cold periods (Vaz, 2011; Brum, 2016).

Among the most popular and increasingly accepted proposals for capturing this thermal energy from the soil, are the Earth-air heat exchangers (EAHE). The EAHE consists of one or more buried ducts, where the ambient air is forced to flow (for instance, by using fans). As the air exchanges heat with the soil, it is heated or cooled inside the ducts. After that, it enters a building where it mixes with the indoor air. The basic scheme of the EAHE can be seen in Fig. 1.

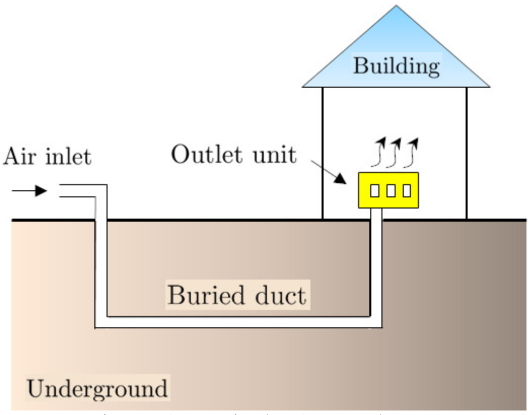


Figure 1: Typical EAHE scheme.

Articles like Agrawal *et al.* (2019); Bordoloi *et al.* (2018) cover the state of the art of EAHE, while one can discover many references on the Brazilian research by reading (Domingues *et al.*, 2021). Many works in the literature focus on modeling the phenomenon of heat transfer, which is established between the air, the duct and the ground, looking for the best efficiency for the system that depends on the optimization of its geometric characteristics and the physical environment. One-dimensional models of heat exchangers are treated in Benkert *et al.* (1997), Bisoniya (2015) and Nóbrega *et al.* (2020). Benkert *et al.* (1997) presents a model, called the GAEA model for EAHE, which will be worked on later in this research. Bisoniya (2015) presents important results on the geometry of the pipe used for the installation of an EAHE; the authors conclude that a duct with a longer length, followed by a smaller diameter can be used to increase the thermal potential. Nóbrega *et al.* (2020) presents the first simulations of a heat exchanger in the south Brazilian city of Pelotas, finding good prospects for a possible installation of the system. Exploring the same Brazilian region, Hermes *et al.* (2020) present numerical simulations of a 3D model for EAHE in the city of Rio Grande. The authors chose three places in the city and concluded that saturated soils present the best results for the installation of the system.

The differences among various approaches to model EAHE lie in several aspects of the system, like: (1) daily cycle and annual temperature cycle; (2) characteristics and thermal properties of the soil; (3) type of ground cover; (4) variation of air humidity in the ducts and in the soil; (5) interference of the heat transmission process in the ground around the ducts. Among the main parameters that affect the performance of EAHE, one can cite the air flow speed; the quantity and depth of ducts; their diameter, length, and, material.

This article aims to evaluate the thermal performance of EAHE after coupling galvanized bridges to the ducts, following the methodology presented in Hassanzadeh *et al.* (2018). The main idea is to improve the heat transfer rate between the ducts and the soil, as the bridges have a much higher thermal conductivity. After preliminary simulation tests using a bridge configuration shown in Hassanzadehet al. (2018), adapted to the reality of the city of Viamão, in southern Brazil, this was adopted for simulations with the exchanger and significantly increased the thermal potential of the EAHE. In addition, the performance of the EAHE was also evaluated by varying the depth of the pipeline.

## 2. METHODOLOGY

The simulations were performed under the conditions of the city of Viamão ($30^o$ 04' 51"S; $51^o$ 01' 24" W), a humid subtropical climate, located in the state of Rio Grande do Sul. Information on local soil properties can be found in the work of Vaz (2011), which reports data from an experimental EAHE installation in that city.

This work, inspired by Hassanzadeh *et al.* (2018), simulates EAHE systems with a configuration where the duct is surrounded by a box coupled to a vertical bridge, both galvanized and with high thermal conductivity, aiming to improve the system performance. Fig. 2 presents a 2D schematic of the computational domain. In the same figure, $z_0$ is the depth of the duct center, $b_0 = 18$ cm is the size of the box (which has a square cross sectional area), $S_v = 1$ m and $S_h$ =1 cm represent, respectively the vertical and horizontal (thickness) sizes of the bridge. For the duct geometry, we used the parameters described in Vaz (2011), in which the length and diameter of the duct have values of 25.77 m and 0.11 m, respectively. The average air speed in the ducts is of 3.3m/s, also like Vaz (2011).

From the references of Vaz (2011) and Hassanzadeh *et al.* (2018), we obtained the thermophysical properties of the soil and air in Viamão, and of the galvanized materials. Their values are provided in Tab. 1.

### 2.1 Model Problem

To simulate the EAHE, we adopted the GAEA model (Graphic design of geothermal heat exchangers), first described in Benkert *et al.* (1997) and later cited in Papakostas *et al.* (2019) and Domingues *et al.* (2021). The model was imple-

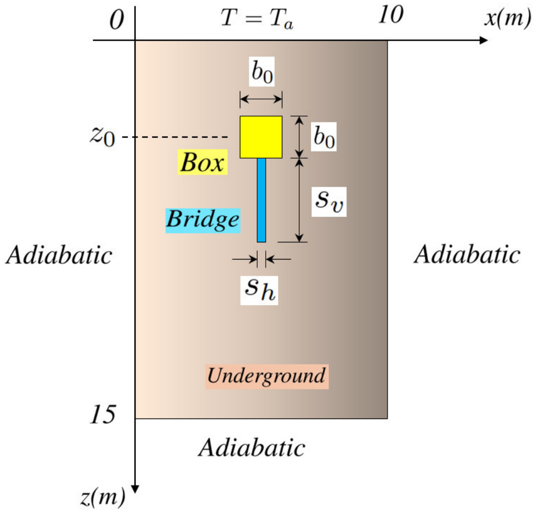


Figure 2: Computational domain definitions

Table 1: Thermophysical properties.

| | Density $\rho$ (kg/m$^3$) | Specific heat $c_p$ (J/kgK) | Thermal conductivity $\lambda$ (W/mK) | Dynamic viscosity $\mu$ (kg/ms) |
|---|---|---|---|---|
| Soil | 1800 | 1780 | 2.1 | - |
| Galvanized parts | 7800 | 446 | 52 | - |
| Air | 1.16 | 1010 | 0.0242 | $1.789\times10^{-5}$ |

mented in Matlab software (versionR2019a) and its main algorithm can be understood through the following equations. The same software was also used in pre-processing and post-processing stages.

The next equation shows the Nusselt number of air flowing in a duct:

$$Nu = 0.0214\,(Re_D^{0.8} - 100)\,Pr^{0.4}, \tag{1}$$

where $Re_D$ is the Reynolds number, and $Pr$ the Prandtl number. The following equation presents the heat transfer coefficient in (W m$^{-2}$K$^{-1}$) on the inner surface of the pipe:

$$h = \frac{\lambda_A\,Nu}{D_0}, \tag{2}$$

here, $\lambda_A$ is the thermal conductivity in (W m$^{-1}$ K$^{-1}$) of the air and $D_0$ is the diameter of the duct in (m). In the following equation, there is the coefficient of heat transfer by length of the pipe wall in (W m$^{-1}$ K$^{-1}$) between the bulk air and the wall:

$$U_L = \pi D_0 h. \tag{3}$$

The next equation is a dimensionless parameter for the ratio of the heat transfer modes:

$$U^* = 2\pi \frac{\lambda_s}{U_L ln\left(\frac{2z_0}{D_0} + \sqrt{(\frac{2z_0}{D_0})^2 - 1}\right)}, \tag{4}$$

where $z_0$ is the depth of the duct center in (m) and $\lambda_s$ the thermal conductivity in (W m$^{-1}$ K$^{-1}$) of the soil.

The GAEA continues by dividing the length $L_o$ of the duct in 100 segments, of size $\Delta x = L_o/100$, where corrected soil temperatures on the pipe walls are find from:

$$T^k_{c,w} = \frac{U^* T_s + T^k_{a,i}}{U^* + 1}, \tag{5}$$

in wich $T^k_{a,i}$ is the air temperature at the inlet of the segment $k$, while its values at the segment outlet is:

$$T^k_{a,o} = T^k_{a,i} \frac{\Delta x U_L (T^k_{c,w} - T^k_{a,i})}{\dot{m}\, c_{p,a}}, \tag{6}$$

where $\dot{m}$ and $c_{p,a}$ are, respectively, the mass flow in (kg s$^{-1}$) and specific heat in (J kg$^{-1}$ k$^{-1}$) of the air. The algorithm ends finding the air temperature at the outlet of the last segment, which is also the outlet of the duct.

The GAEA model, as shown in the equations above, requires the soil temperature not influenced by the pipeline, that is, as if the Earth's temperature in the pipeline wall depended only on heat transfer from the earth's surface to the deeper layers. Thus, the soil temperature was numerically estimated, in a two-dimensional way, adopting computational domains similar to that shown in Fig. 2. In the case where the box or the galvanized bridges are not present, the problem can be simulated assuming that these parts of the domain have the same thermophysical properties as the soil.

That said, the temperatures in the soil, box and bridges are estimated by solving the heat conservation equation that models the problem in two dimensions, ie,

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho\, c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad \text{in} \quad \Omega\times]0,\tau]. \tag{7}$$

Here, $T$ stands for the temperature in ($^o$C), $x$ and $z$ for the spatial coordinates (in m), and $t$ for the time (in s). The spatial domain (in m) $\Omega$ is $]0,10[\times]0,15[$ as shown in Fig. 2. The time period of simulations $\tau$ covers one year and two months, but the two first months are discarded, to avoid numerical influences from the initial condition (see more details in (Brum *et al.*, 2019)).

As indicated by Fig. 2, the model should satisfy the following boundary conditions

$$T = T_a \quad \text{at} \quad z = 0\,\text{m}, \tag{8}$$

$$\frac{\partial T}{\partial x} = 0\,^o\text{C}/m \quad \text{at} \quad x = 0\,\text{m} \quad \text{and} \quad x = 10\,\text{m}, \tag{9}$$

$$\frac{\partial T}{\partial z} = 0\,^o\text{C}/m \quad \text{at} \quad z = 15\,\text{m}. \tag{10}$$

Here, $T_a$ is the air temperature in the city of *Viamão*. The equation of air temperature in the respective city, adjusted by the least squares method from the results of Vaz (2011), is given by

$$T_a(t) = 20.49 + 5.66 \sin\left(\frac{2\pi}{365}t - 5.30\right). \tag{11}$$

As an initial condition, the soil temperature varies only in the direction $z$, according to the methodology of Ozgener *et al.* (2013). The equations were solved numerically using the Galerkin finite element method (Hughes, 1987) for the spatial discretization, and the first order implicit Euler finite difference method (Özisik, 1993) for the time discretization. It is important to highlight that in the finite element method, the continuity condition is absorbed in the variational formulation of the problem.

To avoid meshing significantly interfering with the final result, mesh independence tests were performed. Finally, after adopting a time step of $\Delta t = 1800$ s (half an hour) for the temporal discretization, as in Domingues *et al.* (2021), comparisons of the solution vectors of the temperatures along one year at the point $(x;\, z) = (5;\, 1,6)$ m were made, that is, at the position referring to the center of the duct and also of the box. Basically, at each simulation the maximum value of the modulus of the difference between two successive solution vectors was compared.

Tab. 2 summarizes the last conclusive data from the mesh tests. It presents the number of nodes and triangles used in each mesh, the approximate simulation times of the finite element code implemented in Matlab, and finally the comparison of the differences between successive solutions.

Table 2: Dados finais dos testes de malha

| Nodes | Elements | Time (min) | Comparison |
|---|---|---|---|
| 1097 | 2137 | 2.6 | |
| 1396 | 2722 | 3.4 | $1.80 \times 10^{-3}$ |
| 1657 | 3230 | 4.2 | $6.94 \times 10^{-4}$ |
| 2017 | 3935 | 5.5 | $2.41 \times 10^{-4}$ |

After the last result of Tab. 2, it was considered sufficient to adopt a mesh with 2017 nodes and 3935 triangles. After this study, it was standardized that when adopting different meshes for future simulations, these should contain 2000 or more nodes and/or 4000 or more elements.

## 3. RESULTS AND DISCUSSION

### 3.1 Model Validation

The validation of this model was compared with the experimental data of Vaz (2011), a methodology also used in Domingues *et al.* (2021), in which the validation of the GAEA model is made, relative to the same data, but calculating the temperature field in the soil through a 1D modeling. The Fig.3 presents a comparison between: (1) the results of the (discrete) daily averages of temperature at the exchanger outlet, as per Vaz (2011); (2) a least squares fitted curve of these same data; (3) the results of Domingues *et al.* (2021); (4) results present in this paper.

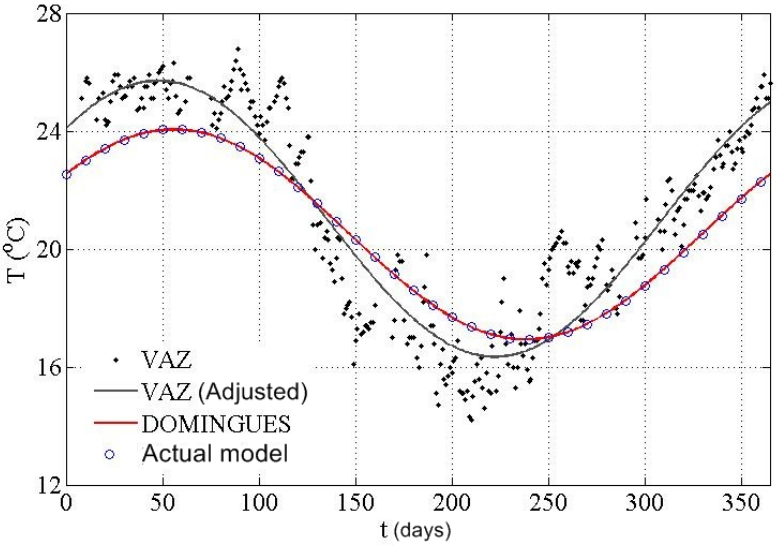
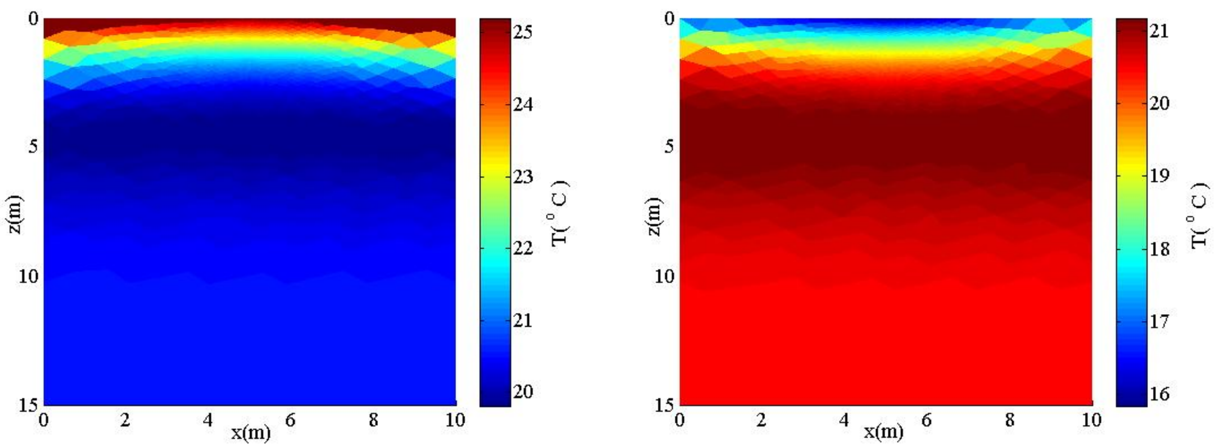



Figure 3: Comparison between results

As shown in Domingues *et al.* (2021), Pearson's correlation coefficient between her model results and the experimental data is 0.89. Further, the same reference estimated the annual RMS difference between the model and experimental values to be approximately $1.45°$C. Therefore, since the results of this work are approximately equal to those of Domingues *et al.* (2021), as shown in Fig.3, one can conclude the validity of the methodology used, which provides accurate results that are highly correlated to the experimental ones. Further, it can be seen that the methodology is computationally effective, as simulations can be performed in a few minutes (see Tab. 2).

To conclude this subsection, typical values for the soil temperature fields in summer and winter are shown in Fig. 4. In summer, the average daily air temperature is around $25°$C and the minimum soil temperature is around $20°$C. In winter, the air temperature decreases to almost $16°$C, while the maximum soil temperature is around $21°$C. In general, the maximum magnitude of the ground heat potential is a little above $5°$C.

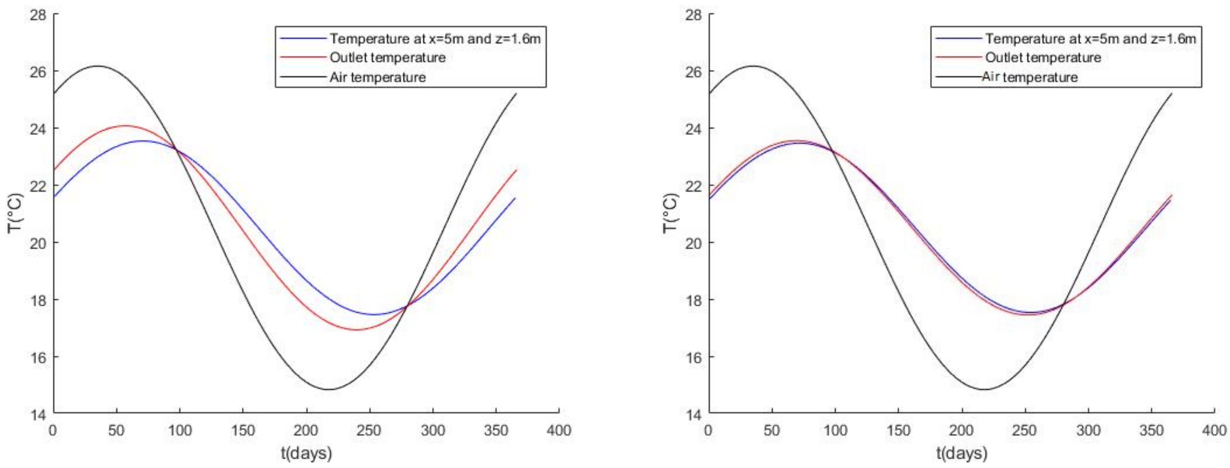



(a) Summer (b) winter

Figure 4: Simulated soil temperature fiels in summer (left) and winter (right)

### 3.2 EAHE Simulations

The first simulations were divided into two cases: (1) EAHE outlet temperature simulations without the galvanized bridges and (2) EAHE outlet temperature simulations with the galvanized bridges (both cases the burial depth of the ducts of 1.6 m (Vaz, 2011)). Fig. 5 presents these cases.




(a) Without galvanized bridges (b) With galvanizes bridges

Figure 5: Temperature comparisons among the air, soil at the depth of 1.6 m, and EAHE outlet; without (left) and with (right) galvanized bridges

You can see, in Fig. 5, some interesting points. Before, it is necessary to make clear to the reader important definitions. We call the difference between the soil and air temperatures as the "soil thermal potential"; in addition, the difference between the outlet system and air temperatures is called the "EAHE thermal potential". It is logical to perceive that the greater the efficiency of the EAHE system, the smaller will be the difference between the curves for the EAHE outlet temperatures and the soil ones.

Still in Fig. 5, it is possible to see a large increase in the efficiency of the EAHE after coupling the galvanized box and bridge assembly in the duct. From the same figure, it can be seen that the peaks of the magnitude of the thermal potential approach $4^o$C in summer and winter. The root mean square annual (RMS) of the potential has been estimated to be about $2.6^o$C.

In order to increase the thermal potential of the EAHE system, some tests were carried out varying the ducts depth, as done in other works (Brum *et al.*, 2012; Hermes *et al.*, 2020). The chosen depths were: 1.6, 2.6, 3.6, 4.6 and 5.6 m and the simulation results are presented in Table 3 and in Fig. 6 (In the figure, $T_a$ is the air temperature, $T$ is the soil temperature, and $T_s$ is the outlet temperature of the EAHE). It is noticed that the thermal potentials of the soil and of the EAHE increase with the depth, in which peaks of magnitude of more than $5^o$C are obtained at depths of 4.6 and 5.6 m. However, despite the improvement in thermal potential, the relative gains of the system decrease with depth. For example, the installation's annual gain by changing the depth from 4 to 5 m is less than 2%.

Table 3: Comparative on the annual root mean square (RMS) of the soil thermal potential at different depths.

| Depth(m) | RMS | Relative gain (in %) |
|---|---|---|
| 1.6 | 2.6481 | - |
| 2.6 | 3.4969 | 32.1 |
| 3.6 | 3.9753 | 13.7 |
| 4.6 | 4.2044 | 5.8 |
| 5.6 | 4.2762 | 1.7 |

## 4. CONCLUSION

It is possible to conclude that the set with the galvanized box and bridge contributes to increase the efficiency of the earth-air heat exchanger system. Furthermore, tests carried out varying the depth of the pipeline's burial showed that high depths can increase the thermal potential of the heat exchanger, reaching practically $5°$C, but the relative gains for such a situation do not favor the installation of these systems, since the greater the depth, the higher the installation costs. Therefore, an installation deeper than 3.6 m is not recommended.

Furthermore, it is possible to conclude that EAHE can be important devices to promote thermal comfort, without harming the environment, like many conventional cooling and heating systems.

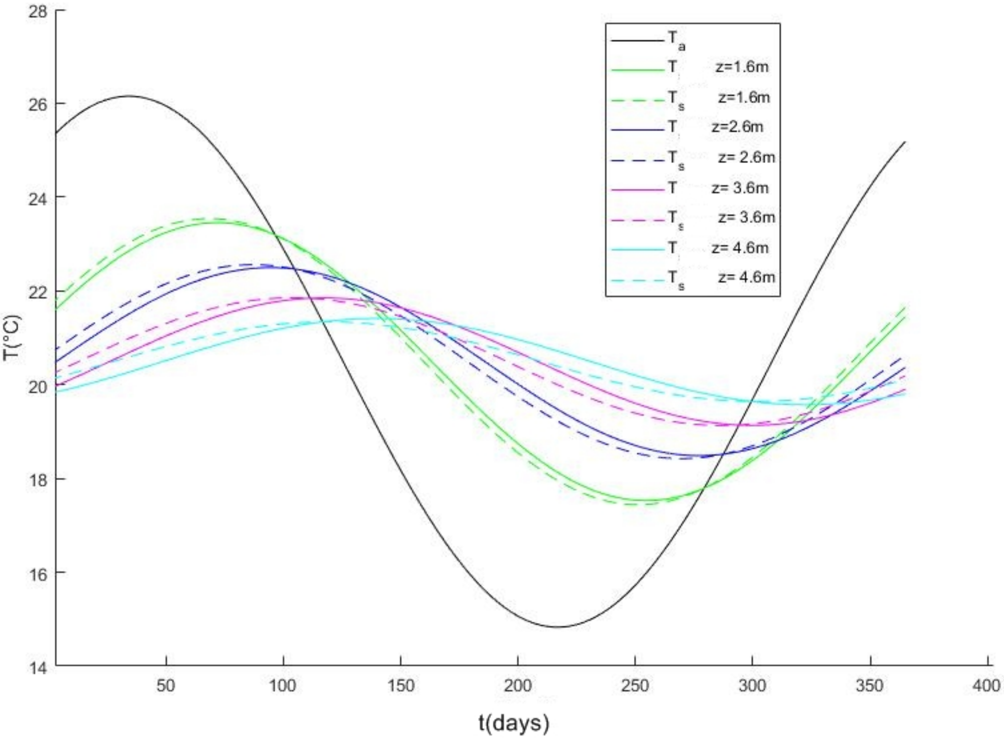



Figure 6: Comparative of the annual outlet temperatures placing the ducts at different depths

## 5. ACKNOWLEDGEMENTS

A. M. B. Domingues thanks her scholarships to the Fundação de Amparo à Pesquisa do Rio Grande do Sul (FAPERGS). R. S. Brum thanks the FAPERGS by the following grants: Edital $4/2019-$ARD: Processo 19/2551-0001345-0 and Edital $05/2019-$PqG: Processo 19/2551-0001964-5.

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