

ENC-2020-0270

TOWARDS EARTH-AIR HEAT EXCHANGERS IN PELOTAS

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Abstract. *The earth-air heat exchangers (EAHE) are valuable tools for preheating (or pre-cooling) buildings, using little electric power. They work blowing air into buried ducts to exchange heat with the soil. Hence, they take advantage of the thermal energy accumulated in the Earth's surface layers, which is clean and renewable, helping the efforts to reduce the global warming effects and the depletion of the ozone layer. The article aims to study the feasibility and potential for the installation of EAHE in the south Brazilian city of Pelotas. The EAHE simulations use the analytical model GAEA, showing that it is accurate and computationally efficient, after the initial steps of validation and comparison with experimental data and results from other models available in the literature. This paper analyzes, from a thermal point of view, hypothetical installations at two local addresses, with geotechnical data estimated by Standard Penetration Tests (SPT). The authors evaluate how the depth and diameter of the ducts influence the thermal potential of EAHE. The best results occur by installing them at a depth of 2m and using a diameter of 0.05m.*

Keywords: *Earth-air heat exchanger (EAHE), GAEA model, Geothermal energy, Computer models, Sustainability.*

1. INTRODUCTION

Energy consumption has increased substantially with population growth, the desire of the population to raise their standard of living, and the rapid industrialization of countries (Kayaci and Demir, 2018). According to the forecast of the international organization, Energy Outlook, world energy consumption will increase by 45% between 2017 and 2045 (Li *et al.*, 2020).

With this in mind, researchers have been reflecting on new systems that modify the way energy is produced, delivered, and consumed, thus discovering sustainable ways to ensure comfort for the population. For such demand, it is vital to use economically and intelligently the existing renewable energy sources; these, in turn, can be used to generate electricity, heat, or produce liquid fuels for the transportation sector. Today, it is necessary to include them in countries' energy policies, as they contribute to the sustainability of the energy system (Da Costa and Prates, 2005).

According to Li *et al.* (2020), renewable energy production not only relieves the burden of energy scarcity but also contributes to building a cleaner and more ecological living environment. Thus, geothermal energy emerges a natural, unlimited, ecologically correct, and sustainable energy source (Wey and Yang, 2019).

As a device that uses geothermal energy, we have the earth-air heat exchanger (EAHE). It uses the soil directly to exchange heat with the air (Wey and Yang, 2019), serving as an alternative heating/cooling system, which does not require large amounts of electrical energy to operate (Ascione *et al.*, 2011).

Due to the high thermal inertia of the soil, the temperature variations progressively smooth with the depth (Estrada *et al.*, 2018). That said, an EAHE installation can use one or more pipes in its construction (Brum, 2016). It uses the soil as a source (or sink) heat, and the air as a means of heat transfer (Agrawal *et al.*, 2019), which is blown into the tubes to exchange heat with the surrounding soil, entering the buildings cooled or heated, depending on the time of year (Bisoniya, 2015). Figure 1 presents the operational example of an EAHE. On the left, one can observe what happens on

cold days, while on the right, what happens on hot days.

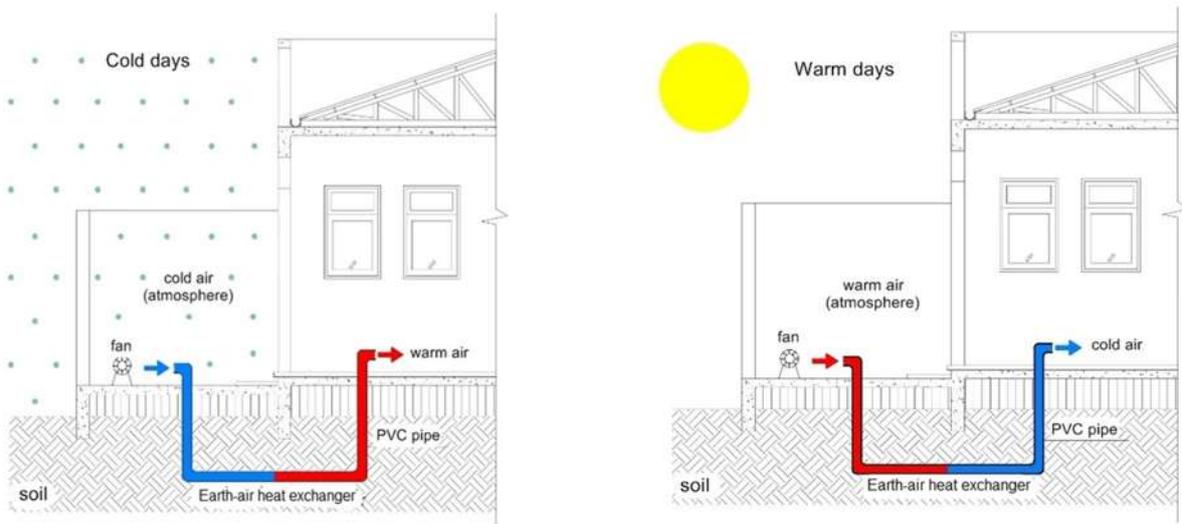


Figure 1. Image exemplifying an EAHE model.

Earth-air heat exchangers are studied by researchers around the world, in different ways and methodologies. Brum (2016) used the Constructual Theory to obtain better performances for EAHE systems. The research was able to determine the best spacing between the pipes, the appropriate geometric shape, and the days and months that guaranteed the highest thermal potentials, as well as their respective values. Estrada *et al.* (2018) designed an EAHE model based on latent heat transfer. Besides, their weather-dependent model was combined with actual meteorological data to show when a heat exchanger can become a good option in tropical climates, taking eight cities in Brazil as a case study.

A literature review on EAHE systems is presented in Agrawal *et al.* (2019), as well as recent significant developments to indicate emerging trends in the domain. In that work, one finds the differences between an EAHE and the ground source heat pumps (GSHP), which use a liquid as the heat transfer fluid and vertically installed pipes (that can reach 200 meters in length). Wey and Yang (2019) present a rectangular plane EAHE, where the pipe cross section is not cylindrical and the heat conduction modeling from the ground around the pipe is not in a cylindrical coordinate system.

Works regarding analytical models are also in development, as discussed in the following. Bisoniya (2015) uses a model based on the effectiveness and number of transfer units (NTU) to simulate EAHE in the city of Bhopal, India. The author discovers through a parametric study that an increase in duct length, followed by a decrease in air velocity and duct diameter, improve heat exchange performance. Papakostas *et al.* (2019) modified and validated models of EAHE based on the works of Benkert *et al.* (1997) and De Paepe and Janssens (2003). The authors chose them due to their simplicity of calculations and the presence of a few parameters. Nóbrega *et al.* (2020) used the model of De Paepe and Janssens (2003) to present the first simulations of EAHE in the city of Pelotas, located in the south Brazilian state of Rio Grande do Sul. The results showed heating and cooling local potentials of 6°C.

Among the novelties of this research, it is worth mentioning the union of an analytical model described in (Benkert *et al.*, 1997) validated through the experimental data of Vaz (2011), and a numerical code for soil temperatures, since the case study proposes simulations in heterogeneous soils, and analytical models usually treat the soil as being homogeneous (Bisoniya, 2015; De Paepe and Janssens, 2003). This paper considered the soil types found in two addresses in the city of Pelotas, to seek the best potentials as well as the best depths for the installation of an EAHE system in these locations.

2. METHODOLOGY

This work used the model described in Benkert *et al.* (1997), called GAEA (Graphic design of geothermal heat exchangers), implementing it in the Wolfram Mathematica language. The model validation used experimental data from Vaz (2011), and a comparison with the 3D model from Brum *et al.* (2012). After that, the study raised the soil thermal properties at two addresses in the Areal neighborhood of Pelotas. They are called here “Domingos de Almeida” and “Barão de Cotegipe” to represent the local street names of their addresses. The information about the soil types in these locations is from Standard Penetration Tests (SPT), granted by the company FUNDACON - *Fundações e Construções* for the year 2016, which was a leap year. The air temperature data were granted by BAP - Boletim Agroclimatológico de Pelotas (2020).

The following equation presents the Nusselt number of air flowing in a tube:

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

where Re_D is the Reynolds number, and Pr the Prandtl number. The next equation states the heat transfer coefficient [$W m^{-2} K^{-1}$] on the inner surface of the pipe:

$$h = \frac{\lambda_A \times Nu}{D_0}, \quad (2)$$

being λ_A the thermal conductivity [$W m^{-1} K^{-1}$] of the air in a pipe and D_0 the diameter of the EAHE pipe in [m]. In the following equation, there is the coefficient of heat transfer by length of the pipe wall [$W m^{-1} K^{-1}$] between the bulk air and the wall:

$$U_L = \pi D_0 h. \quad (3)$$

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

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

where z_0 is the depth of the duct center [m] and λ_s the thermal conductivity [$W m^{-1} K^{-1}$] of the soil.

Before proceeding, it is necessary to obtain the soil temperature, T_s , disregarding the duct presence. To cope with the multi-layered soil found in Pelotas, the authors developed an in-house finite differences code, within the Octave program language, to solve the energy conservation equation:

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial z^2}, \quad (5)$$

where $\alpha_s = \alpha_s(z)$ is the soil thermal diffusivity [$m^2 s^{-1}$], t is the time [s], and z is the depth [m]. For the boundary conditions, the soil is supposed adiabatic at $z=15m$, and T_s is equal to the air temperature at $z=0m$. Besides, the continuity conditions:

$$\lim_{z \rightarrow \zeta_k^-} \left(-\lambda_{s,i} \frac{\partial T}{\partial z} \right) = \lim_{z \rightarrow \zeta_k^+} \left(-\lambda_{s,j} \frac{\partial T}{\partial z} \right) \quad (6)$$

are imposed at the intersection points ζ_k between two layers with thermal conductivities $\lambda_{s,i}$ and $\lambda_{s,j}$. For the initial condition, T_s is approximated by the function:

$$T_0 = T_m + A \sin\left(\omega t + \phi - z \sqrt{\frac{\pi}{\tau \alpha_s}}\right) e^{z \sqrt{\frac{\pi}{\tau \alpha_s}}}. \quad (7)$$

Here, T_m , A , ω , and ϕ are, respectively, the average, amplitude, angular frequency, and phase of the air temperature, which are computed after fitting it (from local weather data) by least squares. The simulations cover a period τ of one year and $\bar{\alpha}_s$ is an average of the diffusivities along the multiple layers. A mesh independence test was performed, and it was adopted a time step of $1800s$ and divisions of the soil length in intervals of size $0.05m$. Finally, the numerical results were fitted by least squares to obtain $T_s(z)$ functions at the depths, z , of interest for the simulations.

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 found from:

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

here, $T_{a,i}^k$ is the air temperature at the inlet of the segment k , while its values at the segment outlet is:

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

where \dot{m} and $c_{p,a}$ are, respectively, the mass flow [$kg s^{-1}$] and specific heat [$J kg^{-1} K^{-1}$] 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.

2.1 Validation of the GAEA model

Vaz (2011) reports experimental data from an EAHE installation in the south Brazilian city of Viamão. Moreover, the work contains information on the local soil properties and air temperatures. The equations and parameters needed to validate the GAEA model, based on such data, are presented next. In the following equation, the air temperature [$^{\circ}C$] for Viamão is presented in a time t [days]:

$$T_A(t) = 20.49 + 5.66 \times \sin\left(\frac{2\pi}{365}t - 5.3\right). \quad (10)$$

The next equation exposes the soil temperature [$^{\circ}C$] in a time t [days] and depth z [m]:

$$T_S(t, z) = 20.49 + 5.66 \sin\left(\frac{2\pi}{365}t - 5.3 - \gamma z\right)e^{-\gamma z}, \quad (11)$$

where $\gamma = \sqrt{\frac{\pi}{365 \times 24 \times 3600 \alpha}}$.

The equations that follow show the results of the EAHE outlet temperatures adjusted via the least squares method for sine functions:

$$T_{GAEA}(t) = 20.50 + 3.56 \sin\left(\frac{2\pi t}{365} + 0.60\right), \quad (12)$$

$$T_V(t) = 21.02 - 4.68 \sin\left(\frac{2\pi t}{365} - 2.43\right), \quad (13)$$

$$T_B(t) = 19.17 + 3.78 \sin\left(\frac{2\pi t}{365} + 0.53\right), \quad (14)$$

where T_{GAEA} , T_V , and T_B represent the results obtained in the GAEA model, in the experimental data of Vaz (2011), and in the Simplified model of Brum *et al.* (2012), respectively.

Fig. 2 compares the EAHE outlet temperatures measured experimentally by Vaz (2011) with the results given by the models GAEA and Simplified:

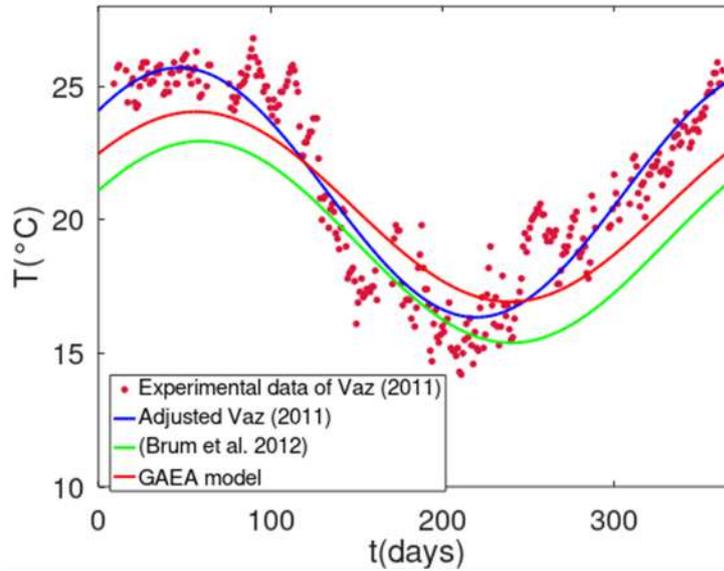


Figure 2. Comparison of the results of Vaz (2011), Brum *et al.* (2012) and the GAEA model.

Considering the Eq. (12)-(14), it is possible to estimate the difference between the experimental data and the model results. The Eq. (15) and Eq. (16) present the Root Mean Square (RMS) of the differences. The results below show that the GAEA model presents a lower error compared to the Simplified one. That said, one concludes that the GAEA model is a valid alternative to simulate EAHE:

$$\sqrt{\frac{\int_0^{365} (T_{Vaz}(t) - T_{GAEA}(t))^2 dt}{365}} = 1.45^{\circ}C, \quad (15)$$

$$\sqrt{\frac{\int_0^{365} (T_{Vaz}(t) - T_{Brum}(t))^2 dt}{365}} = 2.37^{\circ}C. \quad (16)$$

The following are the thermophysical properties and parameters used in the validation of the GAEA model. Here, ρ_s and $c(p, s)$ are, respectively, the density and specific heat of the soil.

Table 1. Thermophysical properties and parameters described in Vaz (2011).

Parameters	Values	Units
ρ_s	1800	[kg m ⁻³]
$c(p, s)$	1780	[J Kg ⁻¹ K ⁻¹]
λ_s	2.1	[W m ⁻¹ K ⁻¹]
L_0	25.77	[m]
D_0	0.11	[m]
z	1.6	[m]

3. RESULTS AND DISCUSSIONS

Figure 3 shows a map of the city of Pelotas and its neighborhoods; this paper analyses two sites located in the Areal one.

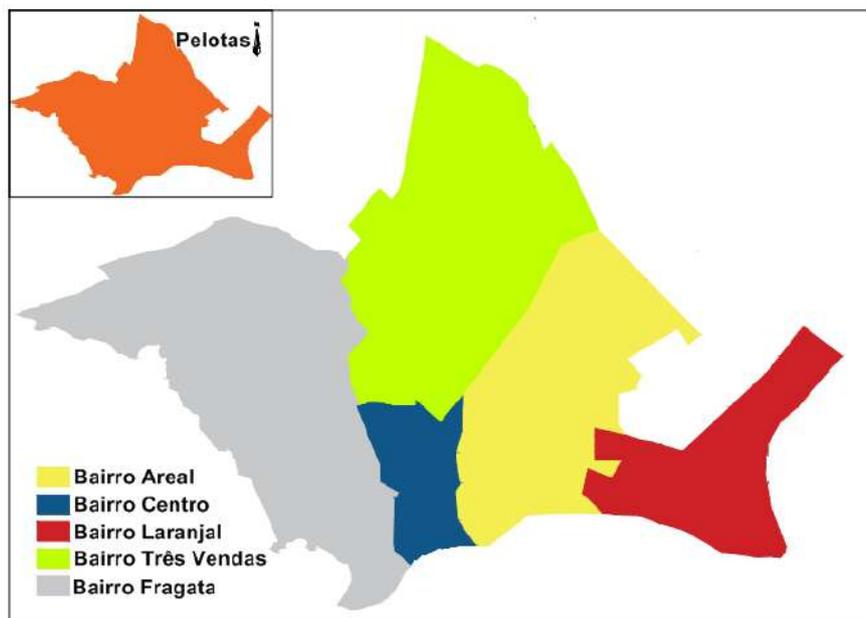


Figure 3. Map of Pelotas.

The next equation models the air in Pelotas during 2016, whose data were obtained through the BAP - Boletim Agroclimatológico de Pelotas (2020), and adjusted by sine functions.

$$T_A(t) = 17.80 + 6.29 \times \sin\left(\frac{2\pi}{366}t + 1.24\right). \quad (17)$$

As previously mentioned, the soil temperatures were found at different depths by a numerical code. It was developed on the Octave language to solve the conservation of energy equation in the soil by finite differences. After that, the numerical data were fitted by sinusoidal functions, using the Wolfram Mathematica software.

In Pelotas, one also finds soils of the type: Clay sand and Sandy clay. However, to simplify matters, the former was considered just sand and the latter as clay. Figure 4 presents the soil layers studied in Domingos de Almeida and Barão de Cotegipe, according to data from local SPT reports.

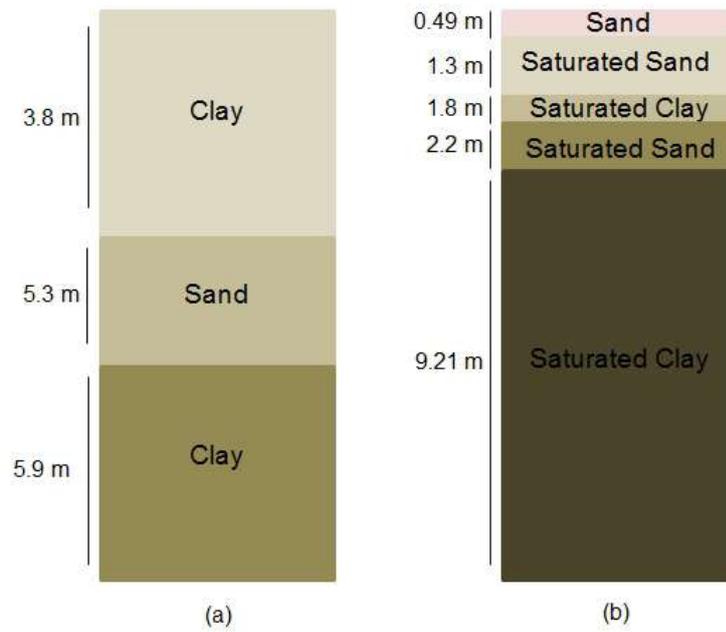


Figure 4. Soil layers located in the (a) Domingos de Almeida and (b) Barão de Cotegipe.

The following table shows the soil and air constants used in Pelotas.

Table 2. Physical indices used in Pelotas, according to Hermes *et al.* (2020).

	Density [kg m^{-3}]	Thermal conductivity [$\text{W m}^{-1} \text{K}^{-1}$]	Specific heat [$\text{J kg}^{-1} \text{K}^{-1}$]
Sand	1600	0.30	800
Clay	1600	0.25	890
Saturated Sand	2000	2.20	1480
Saturated Clay	2000	1.58	1550
Air	1.16	0.0242	1010

3.1 Areal - Domingos de Almeida

For Domingos de Almeida, five depths were analyzed, 1, 2, 3, 4 and 5 meters. Figure 5 shows the comparison of the temperatures of the EAHE outlet at the five depths with the air temperature.

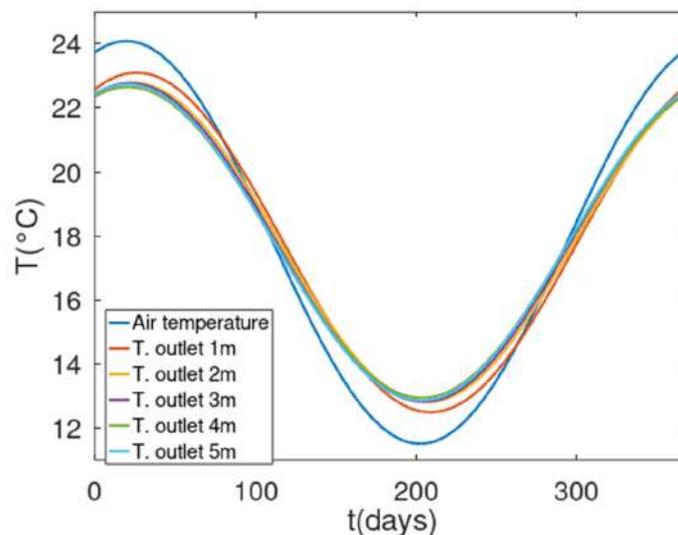


Figure 5. Temperatures found at the outlet of the EAHE to 1, 2, 3, 4 and 5 meters in Domingos de Almeida.

To obtain the above temperatures, the authors used the same parameters of pipe length, diameter, and air velocity adopted in Vaz (2011). In Fig. 5, notes that the temperatures at the outlet of the exchanger at the depths of 2, 3, 4 and 5 meters do not present significant differences, which indicates that an excavation up to 5 meters is not necessary to achieve good results. Besides, the EAHE do not perform well in this case. For example, the magnitude differences between the air temperature at the EAHE outlets are not higher than 1°C, which indicates that parameter changes, mainly in pipe length, diameter, and air velocity, could improve efficiency for the EAHE, as pointed out by Bisoniya (2015).

Brum (2016) suggested parameter variations to increase EAHE efficiency. This work used the same strategy, changing the diameter of the duct. Figure 6 shows the results using a diameter of 0.05m (the smallest usual market size). With the modification, the difference between the air temperature and the outlet ones after 1m increased by approximately 3°C. That is, placing the duct at only 1m, it is possible to find magnitude peaks in the thermal potential close to 3°C. At 2 and 3m, the differences are even higher, reaching values of 4°C.

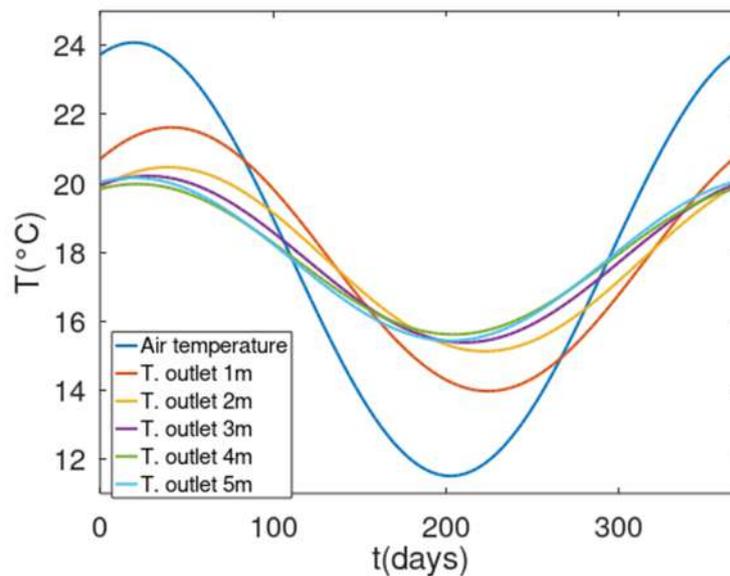


Figure 6. Temperatures found at the outlet of the EAHE to 1, 2, 3, 4 and 5 meters in Domingos de Almeida (Modification in pipe diameter).

3.2 Areal - Barão de Cotegipe

For the second site, two depths were analyzed. Figure 7 shows the comparison of the outlet temperatures at the two depths with the air temperature.

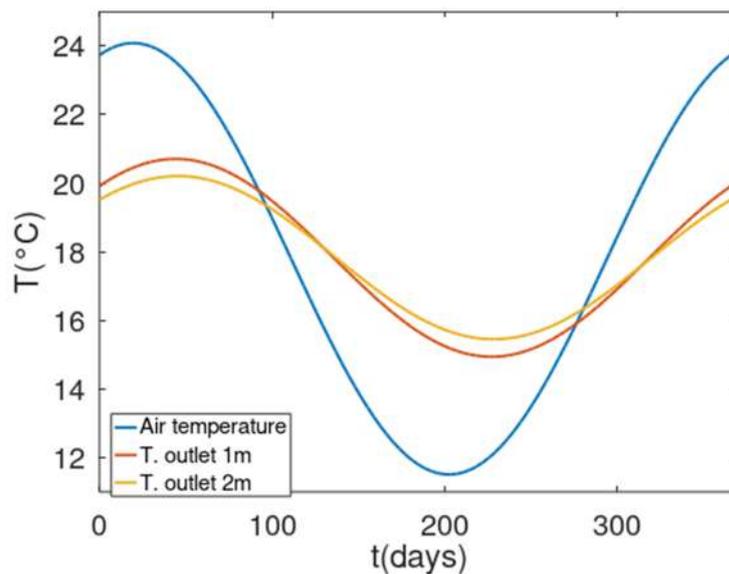


Figure 7. Temperatures found at the outlet of the EAHE to 1 and 2 meters in Barão de Cotegipe.

Note that although Vaz (2011) parameters are used, there is a considerable difference between the outlet temperatures of the exchanger and the air temperature in a saturated soil, a difference that goes from 4°C to 2 meters deep.

Although the exchanger performed well with the parameters of the literature (Vaz, 2011), it was decided to change the tube diameter again to 0.05 meters, while the other parameters remain constant as in Brum (2016).

Figure 8 presents expressive results. With the modification of the pipe diameter, the difference between the air temperature and outlet curves at 1 meter reached almost 4°C and at 2 meters the temperatures cooled/heated almost 6°C, these results that can be of great benefit for the installation of an efficient EAHE.

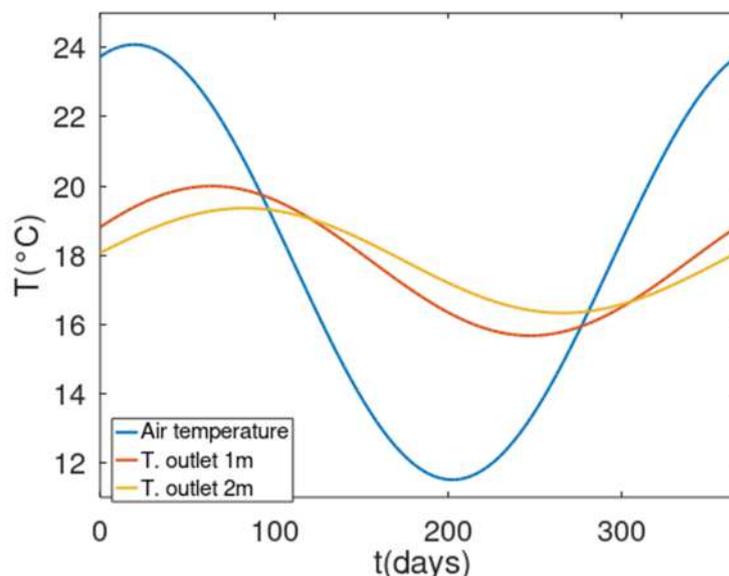


Figure 8. Temperatures found at the outlet of the EAHE to 1 and 2 meters in Barão de Cotegipe (Modification in pipe diameter).

4. CONCLUSION

In Pelotas, with the parameters arranged in Vaz (2011) for the dry soils, the curves of the outlet temperatures of the exchanger are extremely close to the curve of the air temperature, which indicates that, with these parameters, adequate thermal comfort would not be achieved. In view of the literature, it can be seen that an increase in pipe length, a decrease in air speed and diameter may be suitable alternatives for the increase of this comfort. Thus, the authors opted for the use of a parametric study, which yielded a heating and cooling potential of 6°C in Barão de Cotegipe.

In addition, the difference between the performance of saturated soils and dry soils is evident, and how saturated soils

have better results. Saturated soils, compared to dry soils, cause heat to be transferred at a higher rate, and also, it has a higher thermal energy storage capacity.

It is concluded that digging up to 5 meters deep to ensure good results is not necessary, since from the figures shown above, 5 meters resulted in curves similar to 2 meters, thus, 2 meters is considered the ideal depth for the installation of the EAHE in these specific locations.

5. ACKNOWLEDGEMENTS

The authors thank FUNDACON - Fundações e Construções and Boletim Agro climatológico de Pelotas, respectively, for granting the SPT surveys and the average air temperatures in the city of Pelotas. Ana Maria B. Domingues and Eduardo S. B. Nóbrega are grateful for their research grants, respectively, to the Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS) and to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). Ruth S. Brum thanks FAPERGS for the financial support with the Edital 4/2019-ARD: Process 19/2551-0001345-0 and Edital 05/2019-PqG: Process 19/2551-0001964-5.

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