18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0286
NUMERICAL ANALYSIS COMPARING THE THERMAL PERFORMANCE OF VERTICAL AND HORIZONTAL EARTH-AIR HEAT EXCHANGERS

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Abstract. *Earth-Air Heat Exchanger (EAHE) consist in buried ducts on the ground with air passing through it. The surface of the soil is a heat source and during the flow, the air is subjected to a heat transfer. Several numerical simulations have been performed with different geometric configurations. To evaluate the operation of each model, a verified and validated 3D finite volume analysis was developed using Fluent. Boundary conditions were set, such as the inlet velocity, temperature, and the soil and air properties. Operating conditions were evaluated in two different places, one with clayey soil and the other with saturated soil. The use of Horizontal EAHE, buried at different depths, was compared to Vertical EAHE operating with only one device or up to three in series. It was observed that Vertical EAHEs function properly and are viable for installations in places with limited physical space and that have saturated soil. However, the operation of Vertical EAHE for air heating (in cooler days of the year) presents some limitations related to the properties of the soil where it is installed, and different weather conditions.*

Keywords: *Earth-Air Heat Exchanger (EAHE), Thermal analysis, Vertical EAHE, Computational modeling.*

1. INTRODUCTION

Due to the current global increase of energy demand, it is necessary to develop and improve methods of harnessing energy from renewable sources to reduce the dependency on fossil fuels and its negative environmental effects (Lee et al., 2010). It has become a great concern to make engineering projects feasible, which consume as little electricity as possible to be adequate to requirements of energy audits recommended by local government entities. Renewable energy sources examples are the wind, solar, geothermal, hydropower, and biomass (Wu et al., 2010; Bordoloi et al., 2018).

Solar radiation is an ample energy supply of heat and light. The soil reserves this thermal energy, absorbing it on hot days and delivering it to the environment on cold days. Therefore, the temperature of the topsoil varies throughout the year, being hotter or colder than the ambient air in winter and summer, respectively (Ramadan, 2016). Systems that take advantage of this stored energy in the soil are capable not only to provide good efficiency, but also economic advantages. Thus, Earth-Air Heat Exchangers (EAHE) are sustainable and effective devices used to improve the thermal conditions of buildings by using the temperature gradient that is established between the soil and the ambient air during the year. As shown in Fig. 1, these devices are built with ducts buried in the ground, in which air is forced to pass through. The temperature of the air in the duct outlet increases or decreases by the transient heat transfer with the different layers of soil (Hermes et al., 2020)

There are different ways of duct disposal, such as horizontal and vertical (U-tube), and this configuration is called open loop EAHE since the inlet air comes from the external environment (see Fig. 1); while the entrance air belongs to the building it is a closed loop system (Bordoloi et al., 2018).

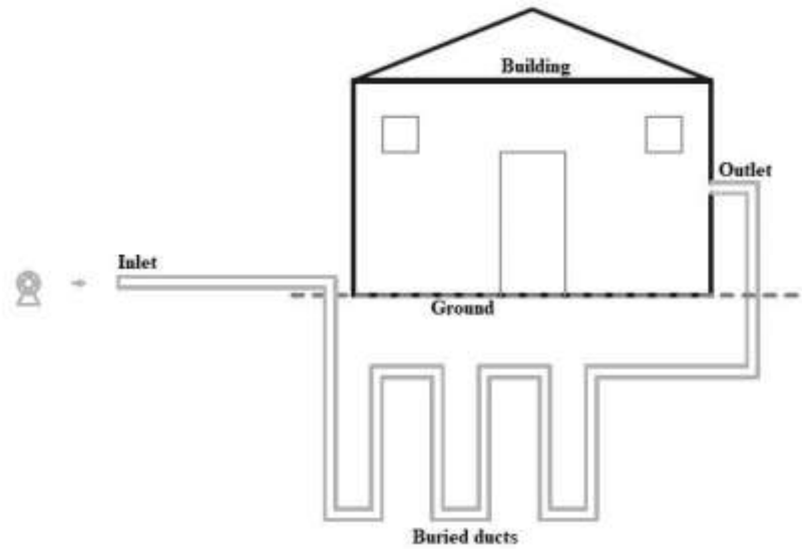

Figure 1. Schematic representation of a serial open loop of Vertical EAHE

In the literature, many EAHE studies use numerical methods to analyze in a reliable way the performance of these systems (e.g. Brum et al., 2012; Lee et al., 2010; Ramadan, 2016; Hermes et al., 2020). The reason behind it is that experimental setups of EAHEs are expensive, time-consuming, and limited in terms of analyzing different design options, justifying the employment of computational modeling. Nevertheless, some papers present only experimental results (such as Yu et al., 2019; Patel and Ramana, 2016); in other hand, there are studies that use experimental and numerical approaches (Vaz et al., 2011; Wu et al., 2010).

Regarding the numerical analysis, the Computational Fluid Dynamics (CFD) enables the behavior analysis of systems that involve fluid flow, heat transfer and other phenomena related to these processes (Versteeg and Malalasekera, 2007). It is an embracing methodology that includes many application possibilities, and among them are the EAHEs. In the present work, the software used to perform the simulations was ANSYS Fluent, which operates with finite volume analysis in order to model the fluid flow and the heat transfer in the EAHE. This software provides mesh flexibility, even when applied to complex geometries (Fluent Manual, 2008).

In urban areas the lack of physical space causes some problems in the implementation of Horizontal EAHEs. Moreover, this kind of duct layout is limited to structural projects under development, with the installation of ducts in parallel with the construction of the building. Besides that, the assembly of pipelines below the construction causes higher costs due to the necessary excavations, and maintenance (Wu et al., 2010; Patel and Ramana, 2016). Another concern is associated with the soil properties in the place of installation. For instance, coastal cities have saturated soil which compromises deeper drilling. In addition to that, the water table level near to the surface of the ground leads to almost constant temperatures thereafter (Liu et al., 2019; Hermes et al., 2020).

Taking into account these difficulties a possible solution is the adoption of a Vertical EAHE, since it takes up less space (both horizontally and vertically) than the Horizontal EAHEs. Concerning the installation of Vertical EAHEs, it can be adopted the same equipment which are widely used for installation of micropile foundations. Therefore, there is the possibility of employing manual equipment such as the hand auger and gasoline drills, for shallow perforations; or in the case of deeper perforations, it can be used rotary and percussion drilling machines. If the soil is cohesive, like clay, the drilling process does not need the coating tube; while for non-cohesive soil, e.g. the sand, the drilling is fully coated in the stretch along the ground to enforce the stability of the borehole (Brito, 1999; Gunaratne and Manjriker, 2014). In addition, the perforation diameter is typically between 100 and 300 mm; however, it is possible to achieve until 500 mm (Cintra et al., 2010; Gonçalves, 2010).

In this context, the current study proposes to computationally model and evaluate the performance of Vertical EAHEs running alone or up to three in series, with the premise of being easily buried in the ground and taking up less space. After that, temperatures in the duct outlet, will be compared to those obtained by the Horizontal EAHEs placed at different depths. It must be highlighted that as case of study two cities placed in the state of Rio Grande do Sul, which is located in the south of Brazil, were considered: Viamão and Rio Grande. For the first one, the soil has clayey characteristics (Vaz et al., 2011, Brum et al., 2013), and in the other one it is saturated and sandy, since the city is located in a coastal region (Hermes et al., 2020; Rodrigues et al., 2018).

2. MATERIAL AND METHODS

2.1 Soil and thermo-physical properties

This current study used data demonstrated in Brum et al. (2013) and Hermes et al. (2020). The first presents characteristics of the soil in Viamão; and the second in Rio Grande, more specifically the ground type in *Universidade Federal do Rio Grande* (FURG), which is the local federal university. Both studies provide information composed of results obtained by Standard Penetration Tests (SPT) bulletins, which give the sizes of soil layers, soil types and water table depth. Other data can be also given by SPT reports, such as the penetration resistance of the ground, however these data are not used for the EAHE numerical simulations.

Properties such as density, thermal conductivity, and specific heat were assumed as isotropic and homogeneous in the soil layers. In relation to the air its characteristics were considered the same way as in Brum et al. (2013); Lee et al. (2010); and Vaz et al. (2011), being constant values.

Figure 2 demonstrates the geotechnical profiles of Viamão and Rio Grande (FURG), until the depth of 15 m, and Table 1 the values that were assumed as the thermo-physical properties in simulations subsequently carried out.

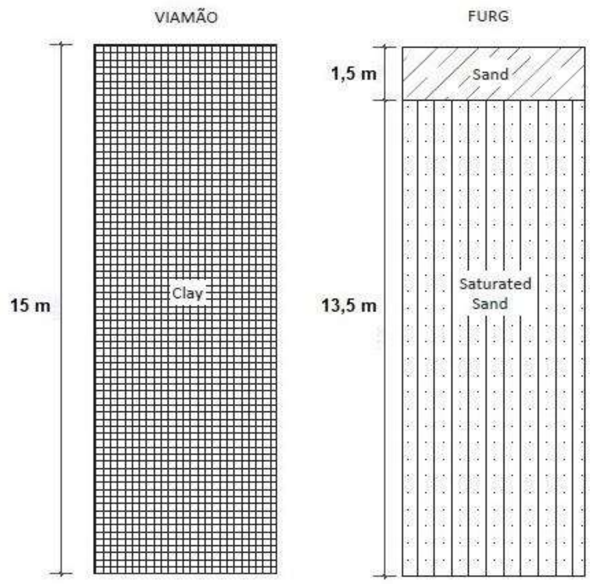

Figure 2. Geotechnical profiles of Viamão and Rio Grande (FURG).

Table 1. Thermo-physical properties for the different layers of soil and the air

Properties	Air	Sand	Saturated Sand	Clay
Density (kg/m³)	1.16	1600	2000	1800
Thermal Conductivity (W/m.K)	0.0242	0.30	2.20	2.10
Specific Heat (J/kg.K)	1010	800	1480	1780

For the air, it was necessary to put another property, the dynamic viscosity, and it was assumed to be equivalent to $1{,}798\times10^{-5}$ kg/(m.s).

2.2 Computational Domains

First, using the software Solid Edge a geometry was drawn, constituted of a parallelepiped which represents the soil with the following dimensions: Ls = 26.0 m, W = 5.0 m and H = 15.0 m, this soil domain was used for both Horizontal (Fig. 3) and Vertical EAHEs (Fig. 4) simulations. However, for the FURG case of study it was necessary to perform a split operation in order to separate the layers of soil (see Fig. 2). The ducts that represent the flow domain were inserted in this block, and it is important to be noted that for the Horizontal EAHEs the diameter d = 0,11 m was assumed, just the way it was considered in several Refs., such as Brum et al. (2013); and Hermes et al. (2020), and in the Vertical EAHEs cases this dimension was d = 0,05 m, due to practical constructive constraints.

With the soil characteristics of Viamão four different simulations has been developed. The first one was a Horizontal EAHE with the duct buried in a depth equivalent to 1.60 m, its results were used to validate the numerical model as it is subsequently presented in Section 2.5. The other three simulations were the U-tube EAHEs operating with only one device, two and three in serial to compare its thermal performances with the Horizontal EAHE buried at 3 m shown in Brum et al. (2013).

Regarding the simulations made for FURG, the Horizontal EAHEs were simulated at the depths of 0.5, 1.0, 1.5 and 2.0 m, being the obtained results compared with the U-tube EAHEs operating likewise that the devices in Viamão. In both case studies the coupled Vertical EAHEs were explored to attain similar results as the Horizontal EAHEs (adopted as reference).

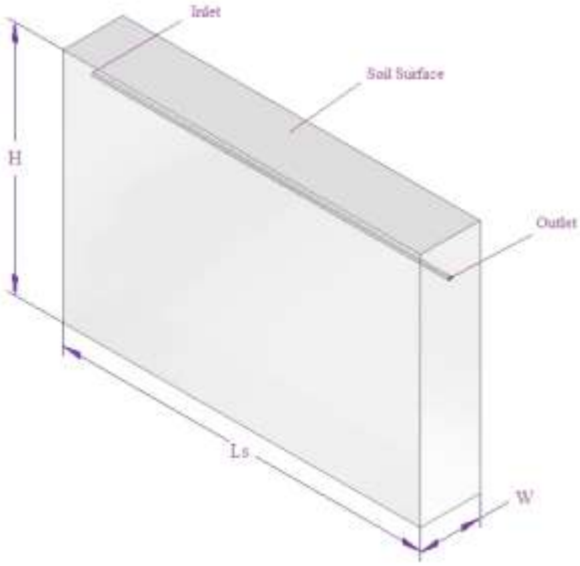

Figure 3. Domain representing the Horizontal EAHE.

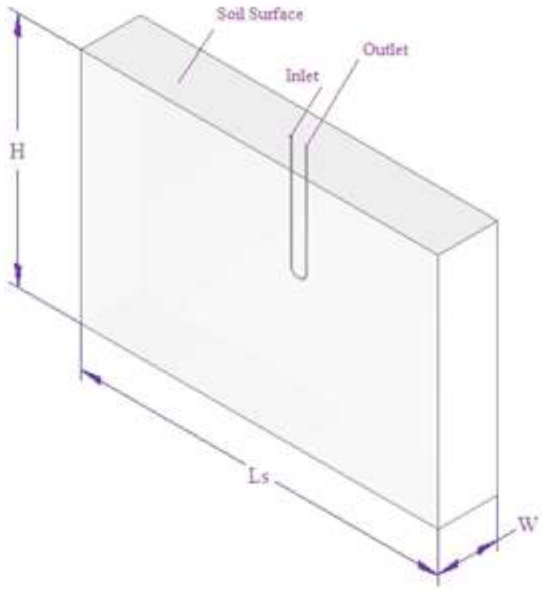

Figure 4. Domain representing the Vertical EAHE.

The geometries of the U-tubes and its dimensions are illustrated in Fig. 5, the height of the tubes is equal to 3.0 m in order to facilitate the installation of these devices in saturated soil regions. And it should be emphasized that the distance between the inlet and the outlet was chosen to diminish the influence of heat transfer from one stretch to other (Lee et al., 2010).

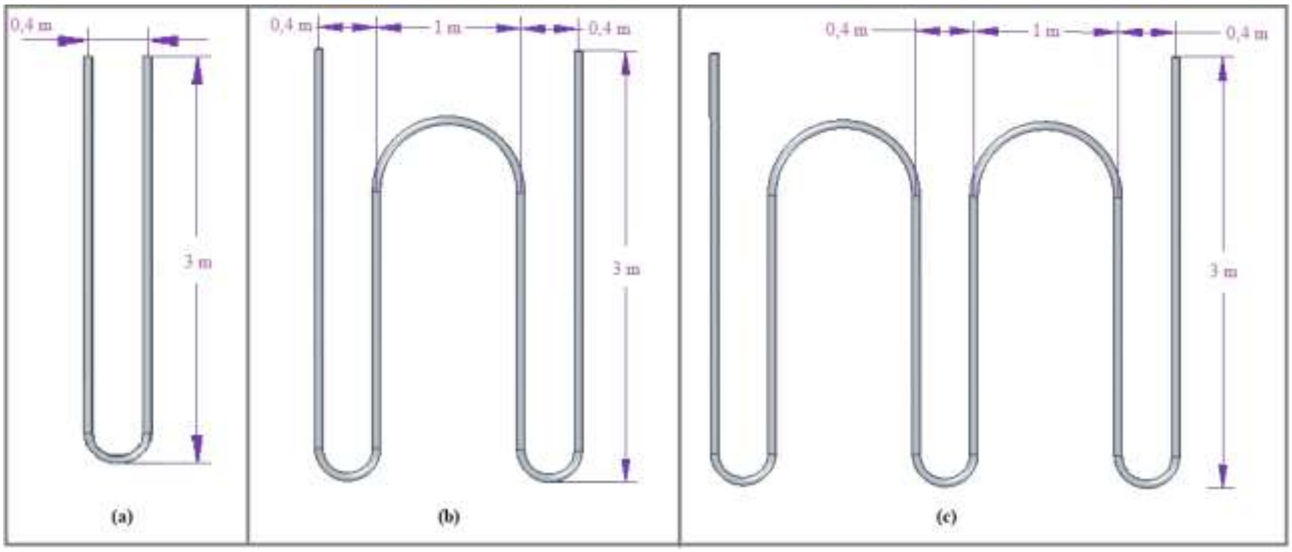

Figure 5. Flow domains of the simulated Vertical EAHEs.

Furthermore, the Meshing tool - available on ANSYS Workbench - was adopted for the spatial discretization (mesh generation). Tetrahedral elements were used to discretize all the simulated domains. Their sizes were equivalent to three times the diameter of the duct for the soil, and the diameter divided by three for the flow domain, as indicated in Rodrigues et al. (2015).

It is important to highlight that to avoid difficulties in mesh generation procedure, the duct thickness was not considered (and hence its properties). This simplification makes that the air flow occurs directly into a cylindrical drilling in soil, as already adopted in several references (Brum et al., 2013; Hermes et al., 2020; Rodrigues et al., 2018; Vaz et al., 2011). It can only be considered because of the small thickness of the ducts in these installations (Ascione et al., 2011).

2.3 Mathematical Model

The transient air flow in the ducts was considered as turbulent and incompressible, and so the governing equations that describe this kind of flow are the conservation of: mass (Eq. 1), momentum (Eq. 2), and energy (Eq. 3) (Bejan, 2013; Çengel and Cimbala, 2014;). The bar above the terms in the equations indicates that they are time averaging operators, and the apostrophe that they vary over time (fluctuate).

$$\frac{\partial \bar{v}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{v}_i}{\partial t} + \frac{\partial(\bar{v}_i \bar{v}_j)}{\partial x_j} = -\frac{1}{\overline{\rho_a}}\frac{\partial \bar{p}}{\partial x_i}\delta_{ij} + \frac{\partial}{\partial x_j}\left[\upsilon\left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i}\right) - \tau_{ij}\right] \tag{2}$$

$$\frac{\partial \bar{T}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{v}_j \bar{T}) = \frac{\partial}{\partial x_j}\left[\alpha_a \frac{\partial \bar{T}}{\partial x_i} - q_j\right] \tag{3}$$

where: v represents the velocity (m.s^{-1}), x is the cartesian coordinates, i.e., the displacement (m), t is the time (s), ρ the density (kg.m^{-3}), p the pressure (N.m^{-2}), δij the Kronecker delta, υ is the kinematic viscosity (m^2.s^{-1}), and T the temperature (K). The Reynolds stress tensor (τ) from Eq. (2) is described by:

$$\tau_{ij} = \bar{v}_i^{'} \bar{v}_j^{'} \tag{4}$$

Also, the q_j presented in Eq. (3) for the air can be modeled by:

$$q_j = \overline{v_i' T'} \tag{5}$$

Along with the earlier described equations, Eq. (6) describes the heat conduction in the soil, i.e., for soil the energy conservation equation is given by (Bergman et al., 2011):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\alpha_s \frac{\partial T}{\partial x_i}\right) \tag{6}$$

being α the soil thermal diffusivity ($m^2.s^{-1}$).

The implemented turbulence model in these problems was the Reynolds Average Navier-Stokes (RANS) k-ε, which is presented in Versteeg and Malalasekera (2007). These additional equations are related to the kinetic energy (k) and the turbulent dissipation (ε), that occur inside the velocity fluctuations and the dissipated energy. The terms of the Eqs. (4) and (5) are adapted for incompressible flow as in the Eqs. (7) and (8), and the eddy viscosity and diffusivity terms are represented by the Eqs. (9) and (10). Finally, the two additional transport equations are given by Eqs. (11) and (12).

$$\tau_{ij} = \upsilon_t \left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i}\right) - \frac{2}{3} k \delta_{ij} \tag{7}$$

$$q_j = \alpha_t \frac{\partial \bar{T}}{\partial x_j} \tag{8}$$

$$\upsilon_t = C_\mu \frac{k^2}{\varepsilon} \tag{9}$$

$$\alpha_t = \frac{\upsilon_t}{Pr_t} \tag{10}$$

$$\frac{\partial k}{\partial t} + \bar{v}_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial \bar{v}_j}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \varepsilon \tag{11}$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{v}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\upsilon + \frac{\upsilon_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial \bar{v}_i}{\partial x_j} - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \tag{12}$$

For the constants needed in K-ε model, the follow values were adopted (as in Hermes et. al, 2020): $C\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $Pr_t = 1$.

In Fluent, the transient and pressure-based solver was performed to attain the convergence of the simulations, the Upwind scheme promoted the control of the instabilities due to the advective terms, and the residuals were equivalent to 1×10^{-3} for all the involved equations except for the energy, which was 1×10^{-6}. The processing of all simulations was done with 17520 time steps with the size of 1 h (3600 s), this is equivalent to two simulated years. However, as shown in Brum et al. (2013), the first twelve months of simulation must be discarded because they are affected by initial established conditions. The obtained results were post-processed in Excel to measure daily temperature averages in the outlet surface of the EAHEs.

2.4 Boundary and initial conditions

The assumed inlet air velocity was equivalent to 3.3 $m.s^{-1}$, and the initial temperature of the simulation domain in all the cases was 18.6 °C (which is the average soil temperature). The inlet air and soil surface temperatures during the year of 2007 were set for Viamão as a function fitted from experimental data, as indicated in Vaz et al. (2011); while for Rio Grande these temperature variations were adopted as Hermes et al. (2020). In the second case, the realistic temperature values for the inlet air and for the surface of the soil among the year of 2016 were obtained with a project named ERA-Interim/LAND. This project is developed by the European Center for Medium-Range Weather Forecasts (ECMWF) and leads to accurate results, for this reason it is recommended by several Ref. besides Hermes et al. (2020) and Qin et al. (2016).

2.5 Validation and verification of the computational model

To validate the numerical methodology, a domain such as the one illustrated in Fig. 3 was simulated to compare its results with the numerical and experimental data published in Vaz et al. (2011). The boundary conditions were specified such as presented in Section 2.4, and the comparison between the results is demonstrated by Fig. 6.

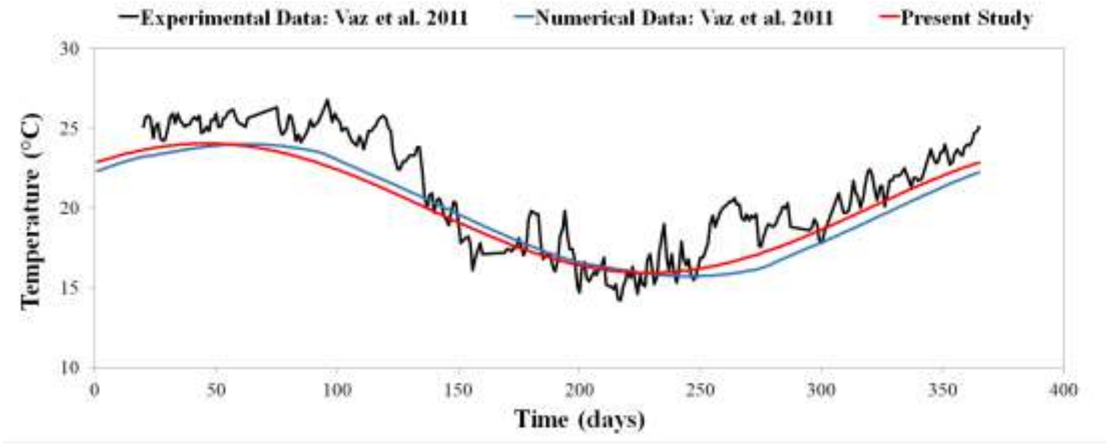

Figure 6. Validation of the numerical methodology.

From Fig. 6, one can note that the results of the present work are in good agreement with experimental and numerical results of Vaz et al. (2011), respectively, validating and verifying the computational model. The average value of the difference between the experimental and numerical results was approximately 2.4°C.

3. RESULTS AND DISCUSSION

3.1 Results in Viamão

Brum et al. (2013) showed that for a Horizontal EAHE installed at the clayey soil of Viamão (see Fig. 2), presents significant changes in thermal performance down to a depth equivalent to 3 m, after that the results remain stable. Thereupon, the current study pursued to simulate Vertical EAHEs to attain similar results to those established by the horizontal installation buried at 3 m.

Figure 7 illustrates the comparison of the Vertical EAHEs, operating with the association of one and up to three in series, with the Horizontal EAHE of Brum et al. (2013). The average temperature value at the inlet is also displayed and it is possible to monitor that the U-tube EAHEs achieve satisfactory performance for cooling, but for heating, in the coldest days of the year, it is less efficient.

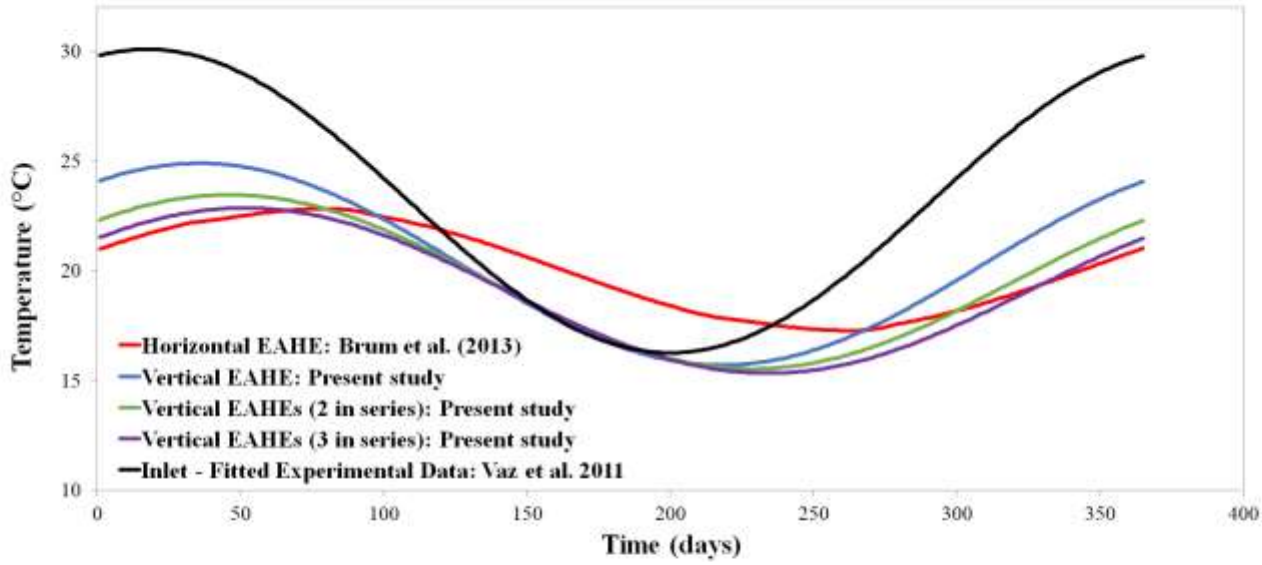

Figure 7. Comparison among outlet temperatures of Horizontal and Vertical EAHEs.

3.2 Results in Rio Grande (FURG)

Figure 8 displays the obtained results of Horizontal EAHEs simulations buried at different depths in Rio Grande City (see Fig. 2). These values were compared to the inlet air annual temperature variation. This preliminary analysis was performed aiming to identify an ideal installation depth for the Horizontal EAHE in Rio Grande, allowing subsequently the comparison of its results with those obtained for the Vertical EAHE installations.

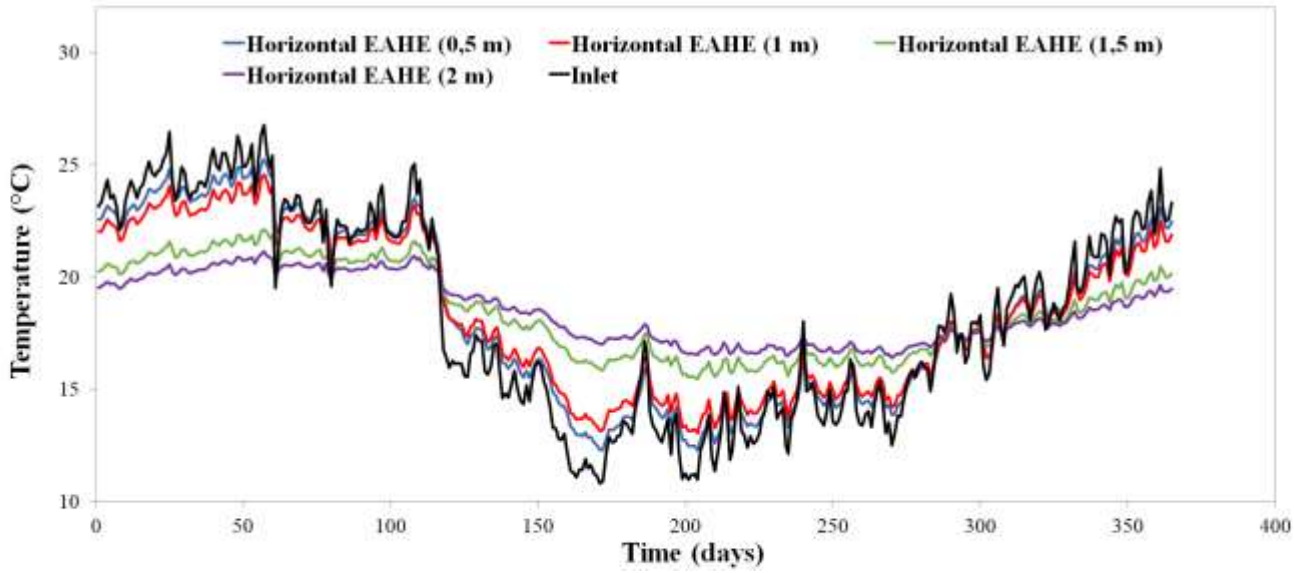

Figure 8. Distribution of the outlet temperatures in the simulated Horizontal EAHEs .

Thus, the best thermal performance of the Horizontal EAHEs was the achieved by the device buried at 2 m (see Fig. 6). Because of this, the result of the Horizontal EAHE installed at this depth was adopted as reference, being reproduced in Fig. 9 together with the results for the Vertical EAHEs.

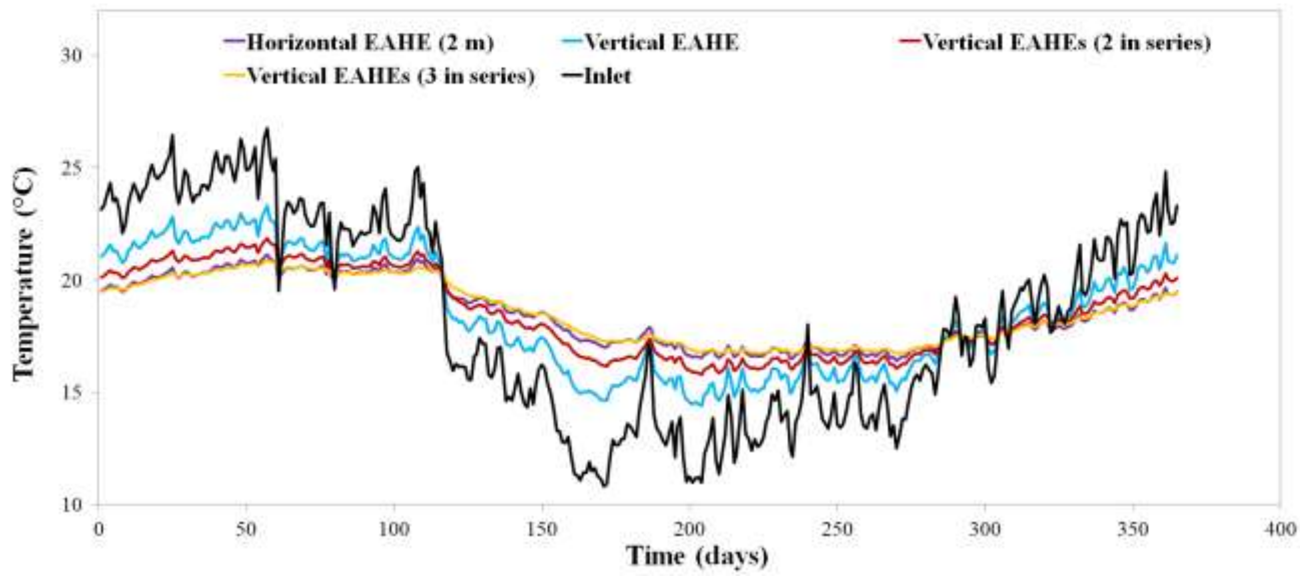

Figure 9. Air temperatures at the outlet of the Vertical EAHEs compared to the Horizontal EAHEs.

One can observe in Fig. 9 that the U-tube installations provide closer results to the Horizontal EAHE adopted as reference. This finding can be proved, since the Vertical EAHE operating with three in series presents practically the same results for the outlet temperature variation when compared to the Horizontal EAHE at 2 m of depth.

4. CONCLUSIONS

This research pursued to numerically evaluate the operation principle of Vertical EAHEs, being the purpose to compare its thermal performance with the often employed Horizontal EAHEs. To do so, a validated and verified computational model was used.

From the obtained results, the U-tube arrangements can be adequately used to replace the Horizontal EAHEs. However, in regions with clayey soil, during the winter period, these Vertical EAHEs do not present the same thermal performance, not even operating with two or three in series. Despite this, in saturated soil regions, such as the coastal cities, the Vertical EAHE layout presents thermal performance very similar to the Horizontal EAHE ones, in the hot and cold periods of the year.

Summarizing, the simulated Vertical EAHEs justify their advantages in relation to less use of physical space and easier installation, especially in regions where very deep excavations are not possible due to the conditions of the soil.

5. ACKNOWLEDGMENTS

The project was supported by FAPERGS (*Fundação de Amparo à Pesquisa do Rio Grande do Sul*), by the financial support (*Edital* 03/2019 - *Programa Institucional de Bolsas de Iniciação Científica e de Iniciação Tecnológica e Inovação* – PROBIC/PROBITI and *Edital* 02/2017 - *Pesquisador Gaúcho*, process 17/2551-0001-111-2). L. A. O Rocha, E. D. dos Santos and L. A. Isoldi also thank to CNPq (*Conselho Nacional de Desenvolvimento Científico e Tecnológico*, process 307791/2019-0, 306024/2017-9, and 306012/2017-0, respectively) for their research grants.

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