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STUDY ABOUT THE SOIL TEMPERATURE STABILIZATION TIME IN AN EARTH-AIR HEAT EXCHANGER COMPUTATIONAL MODELING

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Abstract. *Earth-Air Heat Exchangers (EAHE) are equipment used to reduce electrical consumption usage by traditional air conditioning systems aiming to maintain thermal comfort in buildings. In this way, EAHE studies are developed with the purpose of improve constructive and operational parameters, and hence its performance. A widely used approach to this is the computational modeling. Therefore, the goal of the present work is to develop an investigation that allows the reduction of the time needed for the soil temperatures stabilization, without significant loss in thermal behavior of the EAHE. Nowadays, based on the literature, the numerical simulations of EAHE are performed during 2 years, being the first year used only to guarantee an adequate soil temperature distribution. From that, here numerical simulations adopting 1 year and 6 months, 1 year and 3 months and 1 year and 1 month were proposed in comparison with the one using 2 years. Results show a variation between 34.24 and 52.94% of reduction in processing time for a typical EAHE case with losses of accuracy in an order of only 0.69 to 3.38%.*

Keywords: *Earth-Air Heat Exchanger. Computational Modeling. Numerical Simulation. Finite Volume Method (FVM).*

1. INTRODUCTION

Comfort is an important factor to be considered on Civil Construction projects. Among its different categories, it is possible to highlight thermal comfort as being a big responsible for electrical energy consumption in buildings, through traditional air conditioning systems. In doing so, new technologies have been studied aiming to develop sustainable solutions. In view of these studies, Vaz et al. (2014) stands out Earth-Air Heat Exchangers (EAHE) usage throughout the employment of the soil as a thermal energy reservoir as a result of solar radiation, since the soil is one of the main sources of renewable energies (Sen, 2008).

Earth-Air Heat Exchangers are equipment installed with the intent of providing an improvement in the thermal condition of buildings, with less usage of electrical energy if compared with an air conditioner equipment. Its operation principal is simple: air is blown through buried ducts, being the surrounding soil responsible for carrying out thermal exchanges, making temperature at the exit of the ducts – located inside the building – milder. During hot seasons, the air temperature at the EAHE exit is expected to be colder than the inlet air, while during cold seasons the opposite may occur. This difference between outlet and inlet temperatures is called thermal potential (Rodrigues et al., 2015).

In the literature, one can find studies showing analytical (Belatrache et al., 2017; Zhengxuan et al., 2019) and numerical (Misra et al., 2013; Vaz et al., 2011; Rodrigues et al., 2015; Ahmed et al., 2016; Rodrigues et al., 2019) modeling of the EAHE and its operational parameters, as well as the constructive ones.

Regarding EAHE computational modeling is usually done with the employment of Computational Fluid Dynamics (CFD) and its validation is done throughout experimental temperature data obtained *in loco*, as performed in Vaz et al.

(2011). State of the art in terms of computational models used in EAHE behavior analysis includes a series of different validated approaches. In Vaz et al. (2011) it is proposed a 3D EAHE computational domain based on an experimental installation located at the city of Viamão, in the Brazilian state of Rio Grande do Sul. It was numerically solved with the aid of ANSYS Fluent software, with the Finite Volume Method (FVM) (Pantakar, 1980). On the other hand, in Brum et al. (2012), for its turn, it is possible to notice the proposition of a simplification of the computational domain. Its main contribution was to present a smaller computational model, when compared to the one provided by Vaz et al. (2011). After that, in Brum et al. (2013a) an even more compact domain was presented, being studied the employment of the reduced 3D model. Meanwhile, in Brum et al. (2013b) a study of a 2D model of the soil was carried out to simulate thermal diffusion in depth, enabling its usage in further EAHE simulations. From these proposed computational models, several works were performed, for instance Rodrigues et al. (2015) and Brum et al. (2019). All these studies used 2 years as duration of the whole simulation, being the first simulation year to certify proper soil temperature stratification, jeopardized due to initialization conditions. Therefore, only the second year of the simulation is effectively used for the soil or EAHE analysis.

In face of the exposed, the goal of the present work is to evaluate different soil temperature stabilization times for these computational models, aiming to decrease its total processing time without significant accuracy losses. To do so, the previously validated 2-year numerical simulation was taken as reference and 3 distinct cases were considered: 1 year and 6 months, 1 year and 3 months and 1 year and 1 month; being, respectively, the 6 months, 3 months and 1 month the soil temperature stabilization times which were tested. Firstly, only the soil study was carried out by means a 2D computational model to be able to evaluate its temperature profile; and in a second moment the air temperature variation at the EAHE exit of each case was compared to the reference as well. This investigation is justified since the reduction of processing time in computational modeling of transient problems is always recommended, especially for studies of geometric optimization when Exhaustive Search is employed, into which several simulations are needed for the analysis.

2. METHODOLOGY

2.1 Computational Modeling

In the present study, two computational domains, both discretized based on FVM, were used and numerically solved with the aid of ANSYS Fluent software. The domains can be checked in Fig. 1.
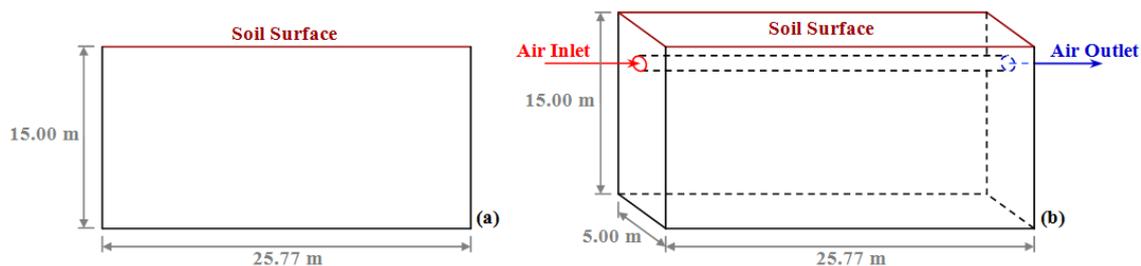

Figure 1. Computational domains for the city of Viamão/RS: (a) two-dimensional soil domain; and (b) EAHE three-dimensional domain.

The first model (Fig. 1a), two-dimensional, is used for the soil thermal behavior simulation, representing an idealized excerpt of the soil where the experimental EAHE of Vaz et al. (2011) was installed. To do so, it is prescribed the temperature variation of soil surface as a boundary condition at its top. This model allows a mere soil thermal diffusion analysis with only the energy conservation equation solution. It was already studied and validated by Brum et al. (2013b) for the simulation period of 2 years, albeit, for the sake of brevity, it will not be presented again in this paper. The domain consists in a rectangle of soil, with length of 25.77 m and height of 15.0 m, having in its superior line, temperature prescription with realistic data provided by ERA-Interim (Balsamo et al., 2013; Balsamo et al., 2015; Hermes et al., 2019; Vitoria et al., 2020). The other lines of computational domain were set as thermally insulated, that is, with null heat flux. Regarding thermal properties of the soil, experimental values obtained by Vaz et al. (2011) were adopted, being: $\rho = 1800 \text{ kg/m}^3$; $c_p = 1780 \text{ J/(kg. K)}$; and $\kappa = 2.1 \text{ W/(m. K)}$. In this case, an 1800 s time step was adopted, accordingly to Brum et al. (2013b).

As the second computational domain (see Fig. 1b), it concerns an EAHE modeling, representing a duct of the Vaz et al. (2011) installation. The length and height dimensions are taken equal to the 2D model, with the addition of a width of 5.0 m. The duct into which the air is blown is installed at the depth of 1.6 m and has a diameter of 110 mm. As a simplifying hypothesis, the wall of the duct influence was disregarded (Vaz et al., 2011; Rodrigues et al., 2015). For the EAHE simulations, as indicated in literature a 3600 s time step was used. Hence, in addition to the variation in the temperature of the soil surface (as in 2D model), the variation in the air temperature at the entrance of the EAHE (from ERA-Interim)

and its flow velocity (adopted of 3.3 m/s, as in Vaz et al. (2011)) were considered as boundary conditions, as well as the thermally insulated walls of the computational domain. More details about the 3D computational model, e.g. its verification and validation, can be found in Rodrigues et al. (2015).

It is important to explain that in 3D computational modeling the heat diffusion equation for the soil is solved in association with the time-averaged conservation equations of mass, momentum and energy for the airflow. The latter is a principle is used for compressible and incompressible flows, as presented in Versteeg and Malalasekera (2007). In an EAHE, the flow has no density changes throughout all the length and the period of the flow, characterizing itself to be incompressible. Since this assumption is possible, the conservation of mass can be reduced, being equal to:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

where: $\vec{v}$ is velocity vector of the air flow (m/s); and ∇ is the differential operator del – also known as nabla operator – using rectangular coordinates (R³ space).

In a second moment, regarding the momentum of the flow in the interior of the duct, it is considered that, since it is a forced convection process and there are no field forces, the classical quantity of motion equation can be reduced to:

$$\frac{\partial \overline{v_i}}{\partial t} + \frac{\partial (\overline{v_i v_j})}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial \overline{p}}{\partial x_j}\delta_{ij} + \frac{\partial}{\partial x_j}\left[v_a\left(\frac{\partial \overline{v_i}}{\partial x_j} + \frac{\partial \overline{v_j}}{\partial x_i}\right) + \overline{\tau_{ij}}\right] \tag{2}$$

where: ρ is density of the fluid, in this case the air (in kg/m³); p is the piezometric pressure (in N/m²); and $\overline{\tau_{ij}}$ is the viscous stress tensor related to superficial forces in an infinitesimal fluid element (in N/m²), being defined by:

$$\overline{\tau_{ij}} = v_t\left(\frac{\partial \overline{v_i}}{\partial x_j} + \frac{\partial \overline{v_j}}{\partial x_i}\right) - \frac{2}{3}\kappa\delta_{ij} \tag{3}$$

For flows that involves heat transfer, solving the energy equation is an important step to determine the proper diffusion over time of the thermal exchanges. The solution of this problem can be given by:

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_i}\left(\overline{v_i}\,\overline{T}\right) = \frac{\partial}{\partial x_i}\left(\alpha_a\frac{\partial \overline{T}}{\partial x_i} - q_i\right) \tag{4}$$

where T is temperature (in K) in a position of time and space; and q_i is the swirling flow of energy, expressed by:

$$q_i = \alpha_t\frac{\partial \overline{T}}{\partial x_i} \tag{5}$$

Considering that the flow is not laminar, it is necessary to model the turbulence in order to have accurate results. A broadly used method in engineering to this purpose is the Reynolds Average Navier-Stokes (RANS) κ-ε turbulence model proposed by Launder and Spalding (1974), which adds to the solution two additional transport equations, given by:

$$v_t = C_\mu\frac{\kappa^2}{\varepsilon} \tag{6}$$

$$\alpha_t = \frac{v_t}{Pr_t} \tag{7}$$

where C_μ is taken constant and equal to 0.09; Pr_t is the Prandtl number and is equal to 1; κ and ε are the turbulence kinetic energy and the turbulent dissipation, respectively, and they can be defined by:

$$\frac{\partial \kappa}{\partial t} + \overline{v}_j\frac{\partial \kappa}{\partial x_j} = \tau_{ij}\frac{\partial \overline{v_j}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(v + \frac{v_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial x_j}\right] - \varepsilon \tag{8}$$

$$\frac{\partial \varepsilon}{\partial t} + \overline{v}_j\frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(v + \frac{v_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{\varepsilon 1}\frac{\varepsilon}{\kappa}\tau_{ij}\frac{\partial \overline{v_j}}{\partial x_j} - C_{\varepsilon 2}\frac{\varepsilon^2}{\kappa} \tag{9}$$

being the value of the constants: $\sigma_\kappa = 1.0$; $\sigma_\kappa = 1.3$; $C_{\varepsilon 1} = 1.44$; and $C_{\varepsilon 2} = 1.92$.

Concerning the heat diffusion occurred in the soil region, is it possible to calculate its value using the equation defined by:

$$\nabla^2 T = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{10}$$

where α is the thermal diffusion of the material, in this case the soil (in m²/s).

2.2 Statistical Analysis

With the intent to compare the proposed cases with the reference, its results were submitted to statistical indicators aiming to evaluate air temperature variation at the EAHE outlet. The indicators used were select in accordance to those used on similar studies previously done (Madsen et al., 2005; Willmott et al., 2005; Hallak e Pereira Filho, 2011; Diagne et al., 2014; Samadianfard et al., 2018). In this way, the indicators were taken in conformity with (Wilks, 2019):

- Mean Error (ME): it is the simplest measure of error. Indicates the trend of the analyzed series to under or overestimate the reference series. A null ME indicates a perfect concordance between data. ME is given by:

$$\text{ME} = \frac{1}{n}\sum_{i=1}^{n}\left(T_i^{Est} - T_i^{Ref}\right) \tag{11}$$

where: T_i^{Est} is the temperature estimated by the computational model; T_i^{Ref} is the value of the reference temperature; and n is the sample size.

- Root Mean Squared Error (RMSE): it is a broadly used measure in data analysis. RMSE is always a positive value, indicating perfect concordance when its value is 0. It returns values in the same dimension as the analyzed variable, being defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_i^{Est} - T_i^{Ref}\right)^2} \tag{12}$$

- Pearson Correlation Coefficient (r): Pearson coefficient is a statistical indicator which varies between -1 and 1, indicating no linear correlation, in case of the former, and perfect linear correlation, in case of the latter. It is obtained by:

$$r = \frac{n\sum_{i=1}^{n}\left(T_i^{Est}\cdot T_i^{Ref}\right) - \left(\sum_{i=1}^{n}T_i^{Est}\right)\cdot\left(\sum_{i=1}^{n}T_i^{Ref}\right)}{\sqrt{n\sum_{i=1}^{n}(T_i^{Est})^2(T_i^{Est})^2}\cdot\sqrt{n\sum_{i=1}^{n}\left(T_i^{Ref}\right)^2\left(T_i^{Ref}\right)^2}} \tag{13}$$

- Mean Absolute Percentual Error (MAPE): MAPE is an indicator utilized for the concordance measure between data and it is given in percentage. Because of this, it is of easy understanding of the dataset behavior. It is calculated from:

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{T_i^{Ref} - T_i^{Est}}{T_i^{Ref}}\right| \tag{14}$$

Concerning the reference data used on the analysis, in both cases data obtained from 2-year duration numerical simulations with ERA-Interim as soil surface and air inlet temperature prescription. As previously stated, these methodologies are broadly discussed in the literature and, for the sake of brevity, they will not be represented.

3. Results and discussion

3.1 Two-dimensional model analysis

The investigation of the two-dimensional model consisted in the monitoring of 5 points in the soil computational domain (see Fig. 1a), corresponding to the depths of: 0.3 m, 0.5 m, 1.0 m, 2.0 m and 3.0 m. All points were placed at half the total length. The cases 1, 2 and 3 correspond to the time interval of 1 year and 6 months, 1 year and 3 months and 1 year and 1 month, respectively. Figure 2 shows the 2007 annual's soil temperature variation for the analyzed points, in comparison with the respective results for the numerical simulation performed during 2 years.
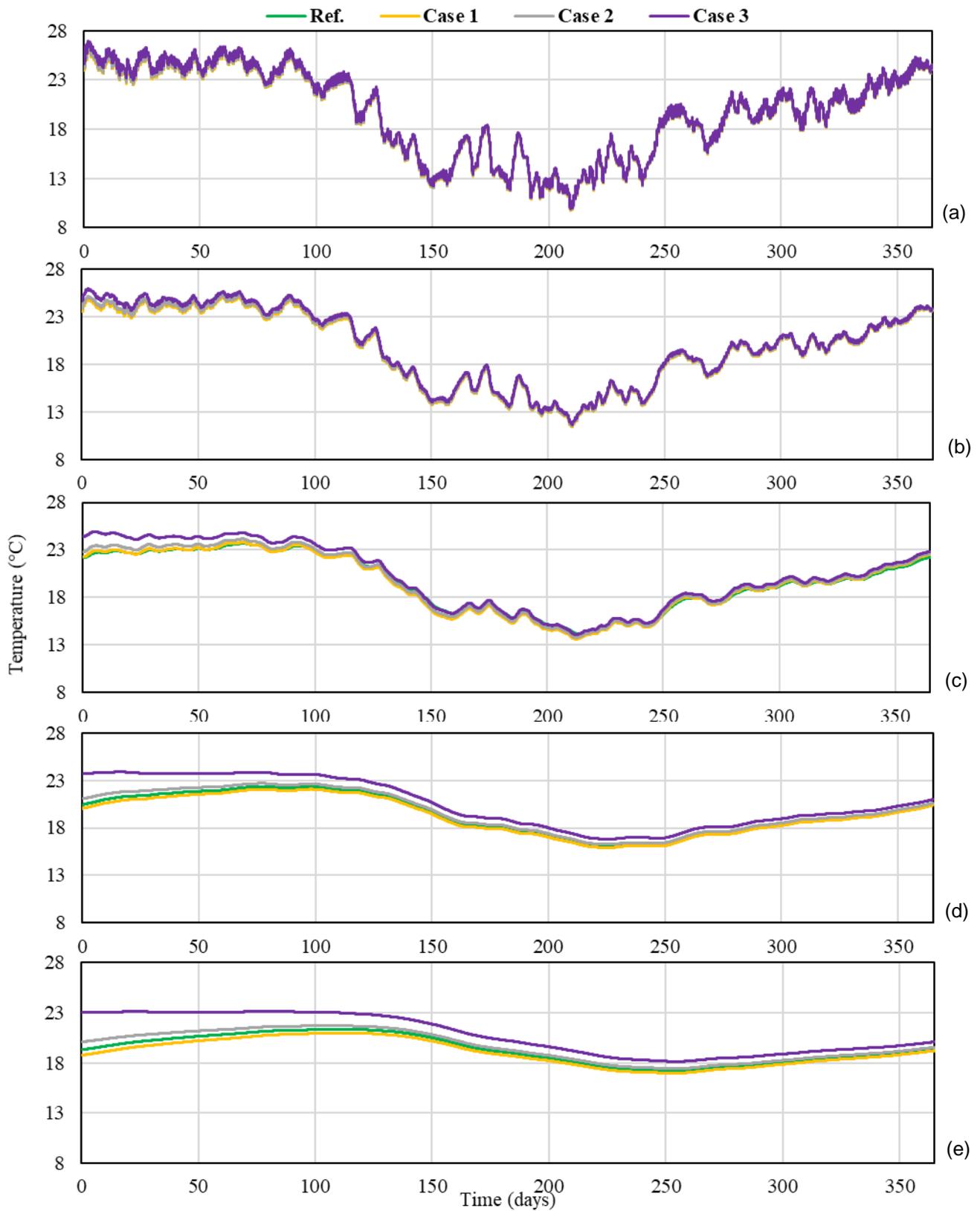
Figure 2. Annual soil temperature variation in city of Viamão for the depth of: (a) 0.3 m; (b) 0.5 m; (c) 1.0 m; (d) 2.0 m; and (e) 3.0 m.

In relation to the Fig. 2, one can note that to smaller depths, the initialization conditions may not interfere, since all series are represented practically overlapped over each other (see Fig. 2a and 2b). However, when deeper points are taken

into consideration, it is evident that greater differences may occur. To evaluate these losses, the statistical indicators are needed. Table 1 shows them when the 2-years simulation is taken as reference.

Table 1. Statistical indicators for the soil thermal behavior.

ME (°C)			
Depth (m)	Case 1	Case 2	Case 3
0.3	0.931	0.999	1.137
0.5	-0.555	-0.436	-0.205
1.0	-0.105	0.124	0.568
2.0	-1.471	-1.028	-0.200
3.0	-1.155	-0.537	0.564
RMSE (°C)			
Depth (m)	Case 1	Case 2	Case 3
0.3	1.527	1.562	1.628
0.5	1.005	0.920	0.784
1.0	0.650	0.622	0.841
2.0	1.552	1.106	0.680
3.0	1.276	0.765	1.094
r			
Depth (m)	Case 1	Case 2	Case 3
0.3	0.9999	0.9999	0.9997
0.5	0.9999	0.9999	0.9999
1.0	0.9978	0.9982	0.9950
2.0	0.9999	0.9990	0.9796
3.0	0.9986	0.9959	0.9465
MAPE (%)			
Depth (m)	Case 1	Case 2	Case 3
0.3	0.19	0.19	0.90
0.5	0.32	0.31	1.50
1.0	1.19	1.42	2.85
2.0	1.18	1.14	5.43
3.0	1.70	1.58	7.39

From Tab. 1 it is possible to infer that all proposed cases prove themselves to have a good agreement with the reference data. One can observe that RMSE values for all scenarios will vary from 0.622°C to 1.628°C. These results are within the expected error for the methodology adopted. However, case 3 presents an outcome with less accuracy when compared to cases 1 and 2 when deeper points are taken into consideration. MAPE shows that the difference compared to the reference data can reach 5.43% for the depth of 2.0 m and 7.39% for 3.0 m.

With regard to the processing time, all cases resulted in a significant reduction. Table 2 shows the comparison between cases as well the processing time. As expected, it is possible to infer that case 3 shows itself to be much faster to process than the other ones, however, as previously stated, the agreement with reference case is prejudiced. When compared with cases 1 and 2, it is possible to observe that processing time gains would not prove themselves to be profitable, since accuracy losses are much higher and the other cases have good reductions as well, reaching 49.55% for the case 1 and 59.85% for case 2, when compared to reference case processing time.

Table 2. Processing time comparison.

Case	Processing Time (s)	Processing Time (h)	Relative Difference (%)
Ref.	39600	11.0	-
1	19980	5.6	49.55
2	15900	4.4	59.85
3	11108	3.1	71.95

3.2 Three-dimensional model analysis

An EAHE installation was submitted to the same tests as the soil thermal behavior analysis, however here the comparison parameter was the air temperature at the exit of the duct. Figure 3 shows the EAHE annual outlet air temperature variation for Viamão also for the year of 2007.
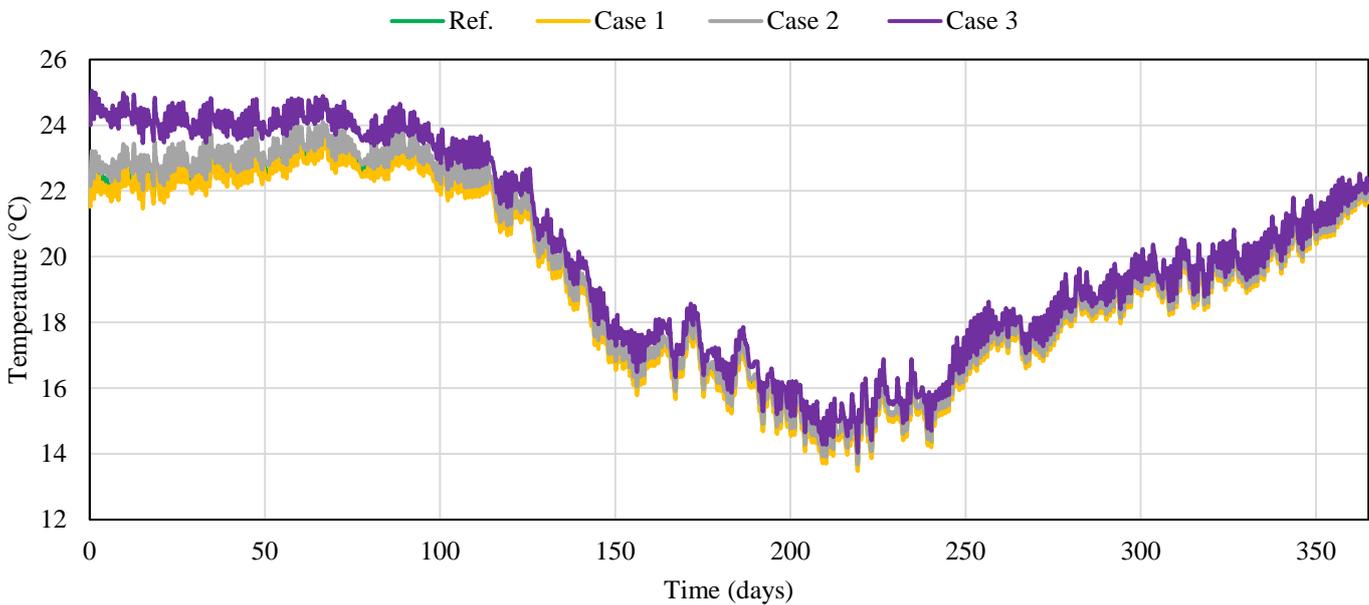
Figure 3. EAHE annual outlet air temperature variation.

From Fig. 3, it is possible to highlight the good agreement of cases 1 and 2, since they are almost overlapped with the reference data. Although, case 3 presents itself to have poor concordance with the reference from day 0 to almost day 100, spoiling its accuracy. Table 3 presents the statistical indicators between each proposed case and the reference case.

Table 3. Statistical indicators for the EAHE.

Indicator	Case 1	Case 2	Case 3
ME (°C)	-0.13	0.14	0.68
RMSE (°C)	0.14	0.17	0.81
r	0.9999	0.9997	0.9938
MAPE (%)	0.69	0.71	3.38

From Tab. 3, one can note that both ME and RMSE resulted in low values, varying between -0.13°C and 0.68°C and 0.14°C and 0.81°C, respectively. On the other hand, MAPE values are slightly better when compared to the ones for the 2D model comparison, varying from 0.69 to 3.38%. Cases 1 and 2 resulted in lower values for ME, RMSE and MAPE and a higher coefficient for Pearson Correlation, indicating almost perfect agreement between the cases and the reference

data. From that, it is able to reach a good level of concordance in air temperature at the exit of the EAHE for the proposed cases.

As in relation to processing time of the analyzed cases, Table 4 shows the values for each case. In face of this, one can infer that the adoption of the proposed method results in a significant gain in processing time, since the reductions reach values between near 34 and 53%

Table 4. Comparison among EAHE cases processing time.

Case	Processing Time (s)	Processing Time (h)	Relative Difference (%)
Ref.	106200	29.5	-
1	69840	19.4	34.24
2	59580	16.6	43.90
3	49980	13.9	52.94

Modeling future EAHEs according to the proposed case 3, however, despite the big reduction in terms of processing time, returns results with much bigger error, when the statistical indicators are compared among the other ones (see Table 3). As a result of that, processing gain of case 3 is not justifiable when compared to case 2, in face of the lack of accuracy in its results. Although, cases 1 and 2 presented significant gains, even in relation to the reference, already validated by literature, justifying their employment in EAHE studies. Between the two of them, it is highlighted the preference for the case 2, with 1 year and 3 months of simulation duration, since it has an improvement in processing time 9.66% bigger than case 1, when they are compared to the reference data, without any significant accuracy losses.

4. Final considerations

Based on previous works of Vaz et al. (2011), Brum et al. (2012), Brum et al. (2013a) and Brum et al. (2013b) the present article was developed having as main goal to reduce the time used for the soil temperature stabilization; both in numerical simulations only of the heat diffusion in the ground as well as in numerical simulations of EAHE devices. To do so, the 2 years numerical simulations usually employed were adopted as reference case, while cases with 1 year and 6 months, 1 year and 3 months and 1 year and 1 month were proposed.

Using statistical indicators, it was possible to conclude that the adoption of a 1 year and 3 months duration instead the 2-year duration of the simulation, traditionally used in similar studies, showed itself to be really fitted. For instance, regarding the EAHE numerical simulation, a considerable processing time reduction of near 50% was achieved associated with results presenting good agreement with those obtained by the validated and verified 2-year solution.

It is worth to mention that this decrease in processing time favors to perform investigations about EAHE geometric optimizations in which an elevated number of numerical simulations need to be done.

Further studies can be carried out to improve knowledge in the duration of simulations, such as: to evaluate the EAHE depth influence in the soil temperature stabilization time; and to expand this study for another locations, evaluating soil thermophysical properties influence in the soil temperature stabilization time.

5. ACKNOWLEDGEMENTS

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