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Comparing analytical and numerical simulation models for Earth-air heat exchangers

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Abstract. In subtropical regions, like the South of Brazil, the air and soil temperatures follow phase shifted periodical patterns with large amplitude variations along the year. This means that the Earth has great potential to be used as a renewable heat source or sink for buildings, in the winter or summer, respectively. The Earth-Air Heat Exchangers (EAHE) are devices that take advantage of this phenomenon. They employ buried ducts, where the air is blown by low power fans (or by a passive method of natural convection) to exchange heat with the soil, and leave their outlets at milder temperatures. The present study presents a comparison among four different simulation models for EAHE. It takes into account experimental data available from an experimental installation in the South Brazilian city of Viamão. Two of the models are one dimensional and analytical, the other two are three dimensional and numerical. We evaluate their overall accuracy, complexity, computational performances, among other advantages/disadvantages.

Keywords: Earth-Air Heat Exchangers, Simulation models, Computational performances.

1 Introduction

Over the years, several research efforts try to understand and reduce global warming and the harmful effects that it causes to the environment. Despite a growing awareness of climate change, emissions of greenhouse gases continue to increase sharply [1]. One of the sources of these gases is the burning of fossil fuels to generate electricity. Today, society has developed an enormous dependence on electricity to carry out daily activities, with the thermal comfort of homes consuming a large part of it [2]. Therefore, there is a great concern in obtaining sustainable solutions, minimizing energy consumption, since the global demand tends to increase. This scenario highlights the need for investments in alternative energy resources, mainly from renewable sources, as is the case, for example, of solar, wind, hydroelectric, and geothermal [3].

In this context, Earth-Air Heat Exchangers (EAHE) are useful, since these systems consist of ducts buried at a certain depth, where the air flows and is cooled in the summer or heated in the winter, for example, reducing conventional energy consumption [4]. Due to the high thermal inertia of the soil, external temperature variations are progressively smoothed along with the depth. Therefore, the soil can be considered as a large thermal reservoir, whose temperature remains milder and more stable than the temperature of the outside air throughout the year, with the temperature of the air at the outlet of the pipe different from the inlet due to the heat exchanges that occur with the soil [5][6]. In Fig. 1 there is a schematic drawing of the EAHE system.

Several experimental and analytical studies have been conducted under various climatic conditions around the world. For example, Al-Ajmi et al. [7] developed a theoretical model to assess the thermal performance of EAHE in the arid climate of the Sahara, reducing energy demand by 30% in the summer. Kumar et al. [8] proposed a numerical model to predict the performance and energy conservation potential of an EAHE coupled to a building without air conditioning, where the cooling potential provided $19kW$ of heat exchange rate.

Thus, the present work shows a comparison between four different simulation models for EAHE, taking into account experimental data from an installation in the city of Viamão, in southern Brazil. Two of the models are one-dimensional and analytical, while the other two are three-dimensional and numerical. The models are evaluated by their accuracy, complexity, computational performance, among other advantages/disadvantages.

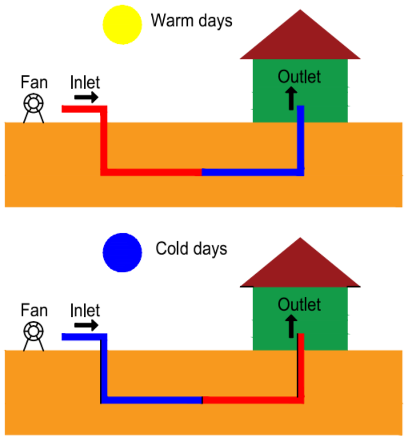

Figure 1. Typical EAHE scheme.

2 Analytical Model for EAHE

As seen in Bisoniya [9] and De Paepe and Janssens [10], if the duct wall contact with the ground is considered perfect and the ground conductivity is sufficiently high, compared to the surface resistance, then the wall temperature inside the pipe can be considered constant. This is a simplifying hypothesis used to make the analytical model for EAHE. The efficiency of EAHE is expressed by eq. (1), where NTU is a dimensionless quantity, Number of Transfer Units (NTU). Hence,

$$\varepsilon = 1 - e^{-NTU}. \tag{1}$$

Here, NTU is:

$$NTU = \frac{h\,A_s}{\dot{m}_a\,c_{p,a}}, \tag{2}$$

where h is the convective heat transfer coefficient, A_s is the surface area of the duct, $\dot{m}_a$ is the mass flow of air, and $c_{p,a}$ is the specific heat of the air. In a circular duct of diameter D, the coefficient h is given by:

$$h = \frac{Nu\,\kappa_a}{D}, \tag{3}$$

where Nu is the number of Nusselt and κ_a is the thermal conductivity of the air. The former can be estimated by different formulas obtained in the literature, considering a turbulent air flow in a duct with smooth walls, as seen in Bisoniya [9], Incropera et al. [11], Bejan [12], among other references.

On the other hand, the EAHE efficiency can be also defined by:

$$\varepsilon = \frac{T_a^o - T_a^i}{T_s - T_a^i}, \tag{4}$$

where T_a^o and T_a^i are, respectively, the air temperatures at the outlet and inlet of the duct, while T_s is the soil temperature, in the vicinity of the duct walls. Therefore, one can find an analytical model to describe the air temperatures at the EAHE outlet, i.e.:

$$T_a^o = T_a^i + \varepsilon(T_s - T_a^i), \tag{5}$$

where is computed ε by the formula given in the eq. (1).

To validate the analytical model, its results were compared with the experimental data from Vaz [13], considering an EAHE installation in the south Brazilian city of Viamão and the results from a numerical model (called Simplified Model), introduced by Brum et al. [14], which has been used in other works like Brum et al. [15].

The simulations considered a duct with $0.11\ m$ of diameter, $25.77\ m$ of length and mass flow of air $\dot{m}_a \approx 0.0364\ kg/s$. Regarding the physical conditions for the local soil and air, 1 summarizes them according to Vaz [13].

Table 1. Thermophysical properties for the air and the soil.

	Density	Thermal conductivity	Specific heat	Dynamic viscosity
	$\rho(kg\,m^{-3})$	$\kappa(W\,m^{-1}K^{-1})$	$c_p(J\,kg^{-1}K^{-1})$	$\mu(kg\,m^{-1}\,s^{-1})$
Air	1.16	0.0242	1010	1.798×10^{-5}
Soil	1800	2.1	1780	-

Using the algorithm proposed in Brum et al. [16], the local temperatures of the air and soil (this one at the depth of $z = 1.6\ m$, where the duct was buried) were fitted by least squares. They are given, respectively, by the following functions:

$$T_a^i(t) = 20.49 + 5.66\, sin\left(\frac{2\pi}{365}t - 5.30\right), \quad (6)$$

$$T_s(t) = 20.49 + 3.03\, sin\left(\frac{2\pi}{365}t - 5.92\right). \quad (7)$$

Here, the temperature values are in ^oC and the time t in $days$. Therefore, considering the thermophysical properties of the soil and air, presented in Table 1, more the functions given in the eq.(6) and eq.(7), it is obtained from eq. (8) the following function to describe the temperature at the outlet of the EAHE:

$$T_a^o(t) = 20.49 + 0.23\sin\left(\frac{2\pi}{365}t - 5.30\right) + 2.92\sin\left(\frac{2\pi}{365}t - 5.92\right). \quad (8)$$

3 GAEA model for Earth-Air Heat Exchangers

The GAEA (Graphic design of geothermal heat exchangers) model computes the air temperature in a duct estimating differently the heat transfer coefficients for the heat flow between air, duct wall and earth, from material coefficients, flow properties and geometric parameters. This work describes the main algorith for the model, more details can be find in Papakostas and Martinopoulos [17] and Benkert et al. [18].

The first step is to compute the Nusselt number for the air flow in the duct, that is:

$$Nu = 0.0214(Re^{0.8} - 100)Pr^{0.4}, \quad (9)$$

where Re is the Reynolds number and Pr the Prandtl number. In eq. (10), there is the coefficient of heat transfer by length of the pipe wall between the bulk air and the wall:

$$U_L = \pi D\, h, \quad (10)$$

being h the convective heat transfer coefficient, defined in eq. (3). The conductivity of heat transfer from the soil surface to the pipe and the air flow to the pipe wall is defined by:

$$U^* = 2\pi \frac{\kappa_s}{U_L ln\left(\frac{2z_0}{D_0} + \sqrt{(\frac{2z_0}{D})^2 - 1}\right)}, \tag{11}$$

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

The GAEA continues by dividing the duct in 100 segments, of size Δx, where corrected soil temperatures on the pipe walls are find from:

$$T^k_{c,w} = \frac{U^* T_s + T^k_{a,i}}{U^* + 1}, \tag{12}$$

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

$$T^k_{a,o} = T^k_{a,i} \frac{\Delta x U_L (T^k_{c,w} - T^k_{a,i})}{\dot{m}_a c_{p,a}}. \tag{13}$$

The algorithm ends by determining the air temperature at the outlet of the last segment, which is also the outlet of the duct.

The validation of the GAEA model was in accordance with the experimental data from Vaz [13], as well as in the analytical model previously presented. Assuming that the soil is homogeneous and that the thermal diffusivity is constant, in addition to the air temperature being provided by eq.(6), over time t, one can model the soil temperature (^oC) from sine based functions, as in [19]:

$$T_s(t, z) = 20.49 + 5.66 \sin\left(\frac{2\pi}{365} t - 5.3 - \gamma z\right) e^{-\gamma z}, \tag{14}$$

with $\gamma = \sqrt{\frac{\pi}{365 \times 24 \times 3600\alpha}}$, time t in days and z in meters. Therefore, the temperature at the exit of the EAHE, adjusted by the least squares method, is given by:

$$T_{GAEA}(t) = 20.50 + 3.56 \sin\left(\frac{2\pi t}{365} + 0.60\right). \tag{15}$$

4 Numerical Models for EAHE

Based on the experimental data of Vaz [13], Brum et al. [14] and Hermes et al. [20] developed mathematical models solved numerically using the Fluent software, which is based on the finite volume method. In both models, heat conduction in the ground is described by the energy conservation equation:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\alpha_s \frac{\partial T}{\partial x_i}\right), \tag{16}$$

which gives the temperature values T, at any time t and any spatial position x_i, assuming that the thermal diffusivity of the soil α_s is known. As for the air flow in the ducts, it is assumed to be incompressible and turbulent. It is governed by the average conservation equations of mass, momentum and energy:

$$\frac{\partial \overline{v}_i}{\partial x_i} = 0, \tag{17}$$

$$\frac{\partial \overline{v}_i}{\partial t} + \frac{\partial (\overline{v}_i \overline{v}_j)}{\partial x_j} = -\frac{1}{\overline{\rho}_a} \frac{\partial \overline{p}}{\partial x_j} \delta_{ij} + \frac{\partial}{\partial x_j}\left[\nu_a \left(\frac{\partial \overline{v}_i}{\partial x_j} + \frac{\partial \overline{v}_j}{\partial x_i} - \overline{v'}_i \overline{v'}_j\right)\right], \tag{18}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_i}(\overline{v}_i \overline{T}) = \frac{\partial}{\partial x_i}\left(\alpha_a \frac{\partial \overline{T}}{\partial x_i} - \overline{v'}_i \overline{T'}\right). \tag{19}$$

Here, υ, p, ν_a and α_a are, respectively, the velocity, static pressure, kinematic viscosity and thermal diffusivity of the air. Finally, δ_{ij} is the Kronecker delta.

In Brum et al. [14] although the numerical model is called a Simplified Model, this is a very complete three-dimensional model which can describe most of the physics for a general EAHE system, adopting simple or complex geometries. To model its turbulence, the Reynolds Stress Model (RSM), available in the FLUENT software, was used. Such a model solves the problem of closure by calculating the Navier-Stokes average, solving transport equations for Reynolds stresses, together with an equation for the dissipation rate [21].

In the modeling proposed by Hermes et al. [20], to solve the closure problem, it was employed the RANS $\kappa - \varepsilon$ model, which is based on the solution of two transport equations for turbulent variables, one for turbulent kinetic energy k and the other for the dissipation rate of turbulent kinetic energy ε [22] [23] [24]. Regarding the boundary conditions, the bottom and the sides can be supposed adiabatic, because the horizontal temperature gradients far from the ducts are negligible, and the same is true for the vertical ones at a depth of $15\ m$. The initial temperature of the simulation domain was 18.70^oC, which was the local mean temperature of the soil.

5 Results and discussions

As done in the references like Brum et al. [25], Brum et al. [26], Ramalho et al. [27], Brum et al. [15], Hermes et al. [20], all numerical and experimental results were fitted by sine based functions using the least squares method. Thus, the following temporal functions (t in days):

$$T_V(t) = 21.02 - 4.68\,sin\left(\frac{2\pi}{365}t - 2.43\right), \tag{20}$$

$$T_B(t) = 19.17 + 3.78\,sin\left(\frac{2\pi}{365}t + 0.53\right), \tag{21}$$

$$T_H(t) = 19.86 - 3.99\,sin\left(\frac{2\pi}{365}t - 2.41\right), \tag{22}$$

represent the temperature (in ^oC) for the results of Vaz [13], Brum et al. [14] and Hermes et al. [20], respectively. In Fig. 2, it is possible to compare the experimental and adjusted data of Vaz [13] with the data obtained through the numerical model presented in Brum et al. [14] and Hermes et al. [20], in addition to the analytical models described in eq. (8) and eq. (15).

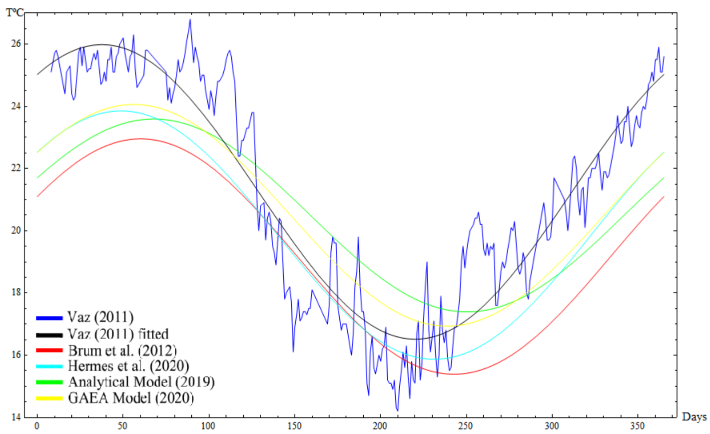

Figure 2. Comparison among experimental and simulated results.

The analytical and numerical results follow close to the experimental data. On the other hand, once the adjusted functions are known, the error in the models can be estimated. Therefore, the annual difference of the mean square root (RMS) between the adjusted experimental data values and the numerical and analytical models is described by:

$$e = \sqrt{\frac{\int_0^{365}[T_V(t) - T_M(t)]^2 dt}{365}}, \tag{23}$$

where $T_M(t)$ is the model's air outlet temperature.

The annual mean square error obtained between the experimental data of Vaz [13] and the numerical model of Brum et al. [14] was 2.40^oC, while in relation to the model proposed by Hermes et al. [20] it was 1.58^oC. Through the Fig. 2 it can be seen that among the numerical models the curve with the data from the Hermes et al. [20] is closer to the experimental data.

Regarding the results obtained in the calculation of the mean quadratic error for the analytical models, the GAEA model presented a lower value, 1.45^oC, while the other analytical model presented an error of 1.96^oC. Here, according to Fig. 2, it is possible to notice the curve of the GAEA model closest to the experimental values.

Thus, despite its simplicity, the GAEA analytical model provides more accurate results (in the sense of root mean square) than both numerical models when compared to experimental results. It is worth mentioning that the analytical models need for modeling the soil temperature, which can be determined numerically. Numerical models, on the other hand, require more complex elements, and take more than 6 hours to simulate the problem. This shows that the analytical models are very suitable for making first estimates about the use of EAHE in a location.

6 Conclusions

This work presents two analytical models and two numerical models for earth-air hat exchangers. It can be observed that the analytical models have greater simplicity in relation to the numerical ones, being easy to implement and low computational cost. However, it should be noted that analytical models have limitations, for example, they cannot model complex geometries as can be done by numerical models.

On the other hand, comparing with the experimental data, it is observed that the average annual square root of the error of the GAEA model is relatively smaller than that presented by the other analytical model and by the numerical models. While the errors of the numerical models were 2.40^oC and 1.58^oC, respectively, the analytical model showed an error of 1.96^oC and the GAEA model, 1.45^oC. Therefore, for simple geometries, the GAEA model has similar precision with the compared numerical models, or even more precise in the metric of root mean square. Thus, the GAEA model is an important tool for developing initial estimates of the potential of EAHE installations in a given location.

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