A FIRST STUDY ON EARTH-AIR HEAT EXCHANGER IN PELOTAS

ESTUDO INICIAL DE TROCADORES DE CALOR SOLO-AR EM PELOTAS

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Abstract: Earth-air heat exchangers (EAHE) represent a promising option to reduce the heating/cooling load of buildings. Unlike traditional air conditioning systems, the EAHE employ a renewable source of energy and they can work using low electric power. Basically, EAHE employ underground ducts where the air is blown to exchange heat with the ground. Since the superficial layers of the Earth are warmer than outside air in winter and cooler than it in summer, the soil can be used as a heat source or sink. Therefore, the air leaves the ducts at milder temperatures. Recent research has shown that the Brazilian south region, where prevails a subtropical climate, has a high potential for the use of EAHE. However, such references are still very limited. Hence, this work aims to analyze the thermal performance of EAHE considering the city of Pelotas, located in the south Brazilian state of Rio Grande do Sul. As a case study, we used in situ data, covering the soil geotechnical profiles from a site in the city, which were obtained by a standard penetration test (SPT). To make the computer simulations, we used an analytical model, which was previously tested and validated. The results point out good prospects for the installation of these devices in the city of Pelotas, taking advantage of its geological potential.

Keywords: Earth-air heat exchangers (TCSA). Simulation models. Geologic potential. Sustainability.

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**Resumo:** Os trocadores de calor solo-ar (TCSA) representam uma opção promissora para reduzir a carga de aquecimento/arrefecimento das edificações. Ao contrário dos sistemas tradicionais de ar condicionado, os TCSA empregam uma fonte renovável de energia e podem operar com pouca energia elétrica. Basicamente, os TCSA utilizam dutos subterrâneos, onde o ar circula a fim de trocar calor com o solo. Como as primeiras camadas do solo são mais quentes do que o ar externo no inverno e mais frias no verão, a crosta terrestre pode ser usada como fonte ou sumidouro de calor. Portanto, o ar sai dos dutos com temperaturas mais amenas. Pesquisas recentes mostraram que esses dispositivos podem funcionar adequadamente na região sul do Brasil, onde predomina um clima subtropical. No entanto, as referências existentes são limitadas. Este trabalho tem como objetivo analisar o desempenho térmico dos TCSA considerando a cidade de Pelotas, localizada no estado brasileiro do Rio Grande do Sul. Como estudo de caso, utilizamos dados “in situ” do perfil geotécnico do solo obtidos em um determinado local da cidade, através de testes de sondagem à percussão (SPT). Para fazer as simulações computacionais, foi testado e validado um modelo analítico. Os resultados apontam boas perspectivas para as instalações desses dispositivos na cidade de Pelotas, aproveitando seu potencial geológico.

**Palavras-chave:** Trocadores de calor solo-ar (TCSA). Modelagem e simulação. Potencial geológico. Sustentabilidade.
1 INTRODUCTION

As pointed out in (SILVA; PAULA, 2009), the global warming is a widespread climatic phenomenon. Among their causes, we find anthropogenic factors such as the greenhouse gas emissions from burning fossil fuels (mainly coal and oil products), the impacts of industries, refineries, engines, human caused fires, etc. In this scenario, a vital role is played by increasing energetic demands of growing populations and their needs of economic development (AGRAWAL; MISRA; AGRAWAL, 2020). Therefore, it is important to develop technologies based on clean and renewable energy sources.

Since the air and soil temperatures follow phase shifted periodical patterns along the year, devices like the earth-air heat exchangers (EAHE) take advantage of this phenomenon by using buried ducts, where the air is blown to use the soil as a heat source or sink. Hence, at the outlet of the ducts the air is cooled in the summer or heated in the winter. Besides, it is worthy to say that the EAHE can work using low powered fans, which reduces significantly the energy consumption with air conditioning.

A long review over the state of the art of EAHE can be find in (AGRAWAL et al., 2019). We note that several parameters influence the performance of EAHE, such as the airflow velocity, ducts design (and their quantity), soil characteristics, local climate and humidity, etc. Among other recent works, in (AGRAWAL; MISRA; AGRAWAL, 2020) the influences of the duct diameter, inlet air velocity, and soil moisture contents on the thermal performance of EAHE are analyzed experimentally. They found out how to obtain the same air temperature drops with smaller ducts by increasing the moisture in a wet soil. Using CFD models, several designs to use multiple ducts were studied in (BRUM et al., 2019), which complemented the previous work presented in (RODRIGUES et al., 2015). The authors found several relations among the geometric displacements of the ducts and the EAHE performance. As for the humidity, the reduction of its levels increases significantly the ventilation potential for EAHE, from the results in different cities of México given in (RODRÍGUEZ-VÁZQUEZ et al., 2020). Moreover, it is also worth to mention that EAHE can be coupled with other technologies, forming hybrid systems, such as the photovoltaic/thermal ones presented in (LI et al., 2019), just to cite a recent example.

Taking a particular look at the city of Pelotas, located in south of Brazil, there is an unfavorable picture, composed by the combination of great variations in the air temperature with other meteorological variables, such as, the relative high humidity, heavy rainfall, and intense winds (SILVA; LLOPART; BOIASKI, 2005). Hence, this leads the population to resort to traditional air conditioning systems. Nevertheless, works like (VAZ, 2011; BRUM et al., 2012; BRUM, 2013; BRUM et al., 2013; VAZ et al., 2014; RODRIGUES et al., 2018; HERMES et
show that this Brazilian region has a relatively high potential for the use of EAHE.

In light of these factors, this work presents a first case study to evaluate the installation of earth-air heat exchangers (EAHE) in Pelotas. However, instead of using complex numerical models, for a first approach we adopted an analytical, one dimensional, model as suggested by references like (PAPAKOSTAS; TSAMITROS; MARTINOPoulos, 2019; PAEPE; JANSSENS, 2003; BISONIYA, 2015).

In the rest of the paper, will be presented the model, which is tested and validated with the experimental data from (VAZ, 2011). To consider the reality of Pelotas, it will be used local weather reports and a geotechnical profile of the soil, obtained in-situ through standard penetration tests (SPT), which allows to estimate adequate thermo-physical properties. As shown ahead, the authors found a relatively high estimated potential for the installation of EAHE in the city.

2 ANALYTICAL MODEL FOR EAHE

In this work, is considered an EAHE composed by one straight duct, with a uniform cross-section, buried in the soil. It is also worth to note that the air is the only heat transporting fluid. To obtain a model for the heat exchange between the air and the duct walls, is assumed the following simplifying hypotheses.

- There is a perfect contact between the duct wall and the ground.
- The thermal resistance of the duct material is negligible, as its thickness is relatively small.
- The temperature of the wall inside the duct is constant and equal to the temperature of the soil around it.
- The surface temperature of the soil is equal to the ambient air temperature, which is also assumed equal to the inlet air temperature.
- The temperature on the duct surface is uniform in the axial direction.

Thus, as detailed in (BISONIYA, 2015; PAEPE; JANSSENS, 2003), the EAHE efficiency is given by:

$$\epsilon = 1 - e^{-NUT}.$$
Here, NUT is the number of transfer units, that is:

\[ NUT = \frac{h A_s}{m_a c_{p,a}}, \]  

(2)

where \( h \) is the convective heat transfer coefficient, \( A_s \) is the surface area of the duct, \( m_a \) 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:

\[ h = \frac{Nu \kappa_a}{D}, \]  

(3)

where \( Nu \) is the number of Nusselt and \( \kappa_a \) 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, 2015; BEJAN, 2013; INCROPERA et al., 2011), among other references.

For this work, is adopted:

\[ Nu = f \left( \frac{Re - 1000}{Pr^{1/3}} - 1 \right)^{1/4} \]  

(4)

Here, \( f \) is the friction factor for smooth ducts, while \( Re \) and \( Pr \) are, respectively, the Reynolds and Prandtl numbers. Their definitions are given as follows:

\[ f = \frac{1}{[0.79 \ln(Re) - 1.64]^2}, \]  

(5)

\[ Re = \frac{\rho_a v_a D}{\mu_a}, \]  

(6)

\[ Pr = \frac{\mu_a c_{p,a}}{\kappa_a}, \]  

(7)

where, \( \rho_a \) is the air density, \( v_a \) is the mean velocity of the air flowing in the duct and \( \mu_a \) is the dynamic viscosity of the air.

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

\[ \epsilon = \frac{T_o^a - T_i^a}{T_s - T_o^a}, \]  

(8)

where \( T_o^a \) and \( T_i^a \) 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.:

\[ T_o = T_i + \epsilon (T_s - T_i), \]  

(9)

where is computed \( \epsilon \) by the formula given in the Eq. (1).

3 VERIFICATION OF THE ANALYTICAL MODEL

To validate and verify the analytical model, this work compared its results with:

1. experimental data from (VAZ, 2011), considering an EAHE installation in the south Brazilian city of Viamão;

2. the results from a numerical model (called reduced model), introduced by (BRUM et al., 2012), which has been used in other works like (BRUM et al., 2019).

To reproduce the experiment of (VAZ, 2011), the simulations considered a duct with 0.11 m of diameter and 25.77 m of length, as illustrated by Fig. 1, which also gives the soil domain dimensions (in m), used in the numerical simulations.

Figure 1: Simulation Domain.

Source: Authors.

Is used the same mass flow of air, \( \dot{m}_a \approx 0.0364 \text{ kg/s} \), taken in (VAZ, 2011). Regarding the physical conditions for the local soil, as well as for the air, they are shown in Table 1:
Table 1: Thermophysical properties for the air and the soil.

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

Using the algorithm proposed in (BRUM et al., 2015), 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:

\[
T_a^i(t) = 20.49 + 5.66 \sin \left( \frac{2\pi}{365} t - 5.30 \right), \tag{10}
\]

\[
T_s(t) = 20.49 + 3.03 \sin \left( \frac{2\pi}{365} t - 5.92 \right). \tag{11}
\]

Here, the temperature values are in $^{\circ}C$ and the time $t$ in days.

Therefore, considering the thermo-physical properties of the soil and air, presented in Table 1, more the functions given in the equations (10) and (11), is obtained from Eq. (9) the following function to describe the temperature at the outlet of the EAHE:

\[
T_o^i(t) = 20.49 + 0.23 \sin \left( \frac{2\pi}{365} t - 5.30 \right) + 2.92 \sin \left( \frac{2\pi}{365} t - 5.92 \right). \tag{12}
\]

In Fig. 2, a comparison is made among the experimental data of (VAZ, 2011), the numerical data of (BRUM et al., 2012) and the results obtained with the Eq. (12).

As done in the references like (BRUM et al., 2019; RAMALHO et al., 2018; BRUM et al., 2016; HERMES et al., 2020; BRUM et al., 2016), all numerical and experimental results were fitted by sine based functions using the least squares method. Thus, the following temporal functions ($t$ in days):

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

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

represent the temperature (in $^{\circ}C$) for the results of (VAZ, 2011) and (BRUM et al., 2012), respectively.

From the Fig. 2, it is already possible to see that the analytical and numerical results follow close to the experimental data. On the other hand, once the fitted functions are known,
the error in the models can be estimated. Hence, the annual root mean square (RMS) difference between the values of the adjusted experimental data and the numerical model of (BRUM et al., 2012) is given by

$$\sqrt{\frac{1}{365} \int_0^{365} [T_V(t) - T_B(t)]^2 dt} = 2.40^\circ C. \hspace{1cm} (15)$$

As for the RMS difference between the adjusted experimental values and those provided by the analytical model is:

$$\sqrt{\frac{1}{365} \int_0^{365} [T_V(t) - T_o(t)]^2 dt} = 1.96^\circ C. \hspace{1cm} (16)$$

Thus, in spite of its simplicity, the analytical model gives more accurate results than the numerical model when compared to the experimental results. This shows that it is very suitable for making first estimates on the use of EAHE in a location.

4 RESULTS AND DISCUSSIONS IN PELOTAS

To analyze the use of EAHE in the city of Pelotas, is first assessed the properties of the local soil, as done in (RODRIGUES et al., 2018; HERMES et al., 2020). To make a
case study, is used data from a site called Trevo do Contorno, whose geographical coordinates are (31°45'24.8"S and 52°26'2.6"W). It were obtained with a local building company, called FUNDACON-Fundações e Construções, which performed there a Standard Penetration Test (SPT) in 2016. Such tests are made in-situ to obtain information on the properties of the soil, with minimum local disturbance (CAMARA; PEREIRA, 2005; NASEEM; S.M., 2016). The SPT report is valid up to depth of 4.3 m.

Thence, is verified that up to the depth of 4.30 m, the soil type of Trevo do Contorno is red sandy clay. To broaden the analysis, is have considered the limit cases of a homogeneous soil composed exclusively of clay or sand, whose thermo-physical properties are presented in Table 2.

|      | ρ (kg/m³) | κ (W/mK) | c_p (J/kgK) |
|------|-----------|-----------|-------------|
| Clay | 1600      | 0.25      | 890         |
| Sand | 1600      | 0.30      | 800         |

To estimate the annual temperature variations in Pelotas, is also used weather reports from 2016 given by the Estação Agroclimatológica de Pelotas⁵ (EAP), which is maintained by a partnership among the Embrapa⁶, UFPel⁷ and INMET⁸ (SANTOS, 2016). The geographic coordinates of EAP are 31°52'00"S and 52°21'24"W. It is worth to note that 2016 was a leap year, i.e., it had 366 days. Using again the methodology presented in (BRUM et al., 2015), is fitted the data by least squares, obtaining the following function

\[ T_a(t) = 17.90 - 6.34 \sin \left( \frac{2\pi}{366} t - 1.85 \right), \tag{17} \]

to describe the temperature (in °C) of the air, for each day \( t \) of the year. The Fig. 3 shows the daily averaged air temperatures in Pelotas in 2016, together with the adjusted curve.

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⁵Estação Agroclimatológica de Pelotas is an agroclimatological station in Pelotas.
⁶Embrapa is a Brazilian public agricultural research corporation.
⁷The Universidade Federal de Pelotas (UFPel) is a Brazilian federal university located in Pelotas.
⁸INMET is the meteorological institute of Brazil.
Using the methodology proposed by (OZGENER; OZGENER; TESTER, 2013), the soil temperature at a depth \( z \) (in m), for each day \( t \) (in days), can be estimated by the function:

\[
T_s(t, z) = 17.90 - 6.34 \sin \left( \frac{2\pi}{366} t - 1.85 - \gamma z \right) e^{-\gamma z},
\]  

(18)

where \( \gamma = \sqrt{\frac{24.3600 \alpha_s}{\pi}} \) and \( \alpha_s = \frac{k}{\rho c_p} \) is the thermal diffusivity of the soil, which can be calculated from the properties shown in Table 2.

Taking Eq. (18) in the limit cases of a homogeneous clayey and sandy soil, respectively, is obtained the following functions to describe the soil temperatures:

\[
T_{clay}(t, z) = 17.90 - 0.25 \sin \left( \frac{2\pi}{366} t - 5.08 \right),
\]  

(19)

\[
T_{sand}(t, z) = 17.90 - 0.39 \sin \left( \frac{2\pi}{366} t - 4.65 \right),
\]  

(20)

Finally, is estimated the outlet temperatures for EAHE in Pelotas by applying the equations (19), (20), (17), more the thermophysical properties given in Table 2, to the analytical model given by the Eq. (9). To simplify matters, is adopted the same values used in (VAZ, 2011) for the duct dimensions and the air mass flow.
For the limit cases of a clayey or sandy soil, the Figures 4 and 5 illustrate, respectively, the temperatures of the air entering the EAHE inlet and leaving its outlet. In both cases, it is possible to see the results supposing the ducts buried at the depths of 1, 2 and 3 m.

Figure 4: Inlet and outlet temperatures at three depths (clayey soil).

Source: Authors.
In general, the results from both limit cases follow close curves. From them, it is possible to estimate that an EAHE in Pelotas has the potential to reduce (in the peak of the summer) or increase (in the peak of the winter) the air temperatures in about $6^\circ C$ if the ducts are buried at a depth greater than or equal to $2m$.

5 CONCLUSIONS

This article began detailing an analytical model for EAHE, which was compared with a numerical one, taking into account data from an experimental installation in the south Brazilian city of Viamão. After computing the annual mean square differences between the results provided by the models and the experimental ones, it is found out that the analytical model is valid and more accurate than the numerical one, considering a benchmark case of an EAHE composed by a straight duct buried in an homogeneous soil.

After that, due to its simplicity, the model was chosen to make a first case study considering the city of Pelotas, which is also located in the south of Brazil. This was done taking into account the soil and air temperature profiles obtained from local sources. From the results, it is estimated that local EAHE have peak potentials to reduce or increase the air
temperatures in about 6°C. Combining these results with others from the references, it is clear that the Brazilian south region has high prospects with the use of EAHE systems.

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