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A STUDY OF SOME PHYSICAL PARAMETERS OF EARTH-AIR HEAT EXCHANGERS

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Abstract. *It is a constant concern of science and several governments across the planet to find ways to reduce the consumption of electricity and also to produce energy from renewable sources. Earth-Air Heat Exchangers (EAHE) are an option for indoor heating and cooling devices that use the thermal inertia property of the soil to ensure desired thermal comfort. In this sense, several works were developed to present the modeling of EAHE with a simple duct via numerical methods. Here, are presented the study of some physical parameters, such as the dimensions of the ducts, and how to optimize the performance of an EAHE from the variation of these parameters. In addition, a model for the transient modeling of temperature inside the ducts is presented. The models are developed analytically and numerically, delivering results in accordance with the experimental data. Finally, through Constructal Theory, the result for the efficient design of an EAHE is presented.*

Keywords: *Earth-Air Heat Exchangers (EAHE), Finite Differences, Thermal Comfort, Renewable Energy Devices*

1. INTRODUCTION

Society depends on electricity for everyday life, in all environments - homes, schools, shops, hospitals, etc. Due to the way electricity is produced in many countries around the world, there is a significant increase in the emission of greenhouse gases, essential agents in accelerating global warming (Rodríguez-Vázquez *et al.*, 2020). Because of this, science has sought renewable sources of energy, which do not contribute significantly to the deterioration of living conditions on the planet. It is also important to note that, in residential and commercial buildings, most of the electrical energy is consumed in order to obtain thermal comfort inside these buildings. As an alternative to the air conditioning systems normally found in existing buildings, there are earth-air heat exchangers (EAHE) (Bisoniya, 2015).

The EAHE is a system of ducts buried in the ground and its performance increases as the depth of burial increases too. This phenomena is due to the thermal inertia of soil. The burial depth of the ducts is also an important factor to the investment the build owner must do. Besides that, the EAHE is environmentally friendly and helps to decrease the energy consumption in buildings (Brum *et al.*, 2019a), and, thus, the coast of energy bill decreases too. Also, the EAHE system can contribute in reducing the greenhouse gas emissions, such as carbon dioxide, methane, chlorofluorocarbons (CFCs) (Singh and Tyagi, 2019).

In addition, one of the problems always present in the design of an EAHE is its optimization, in order to obtain the greatest possible energy gain and thus generate the largest volume of cooling or heating. To achieve this goal, based on the Constructal Law, developed by Bejan (1997), studies are carried out on the physical properties of the EAHE, such as its dimensions, the pressure inside it, etc. Lorente and Bejan (2005) describes the constructive law as the natural tendency to maximize flow.

Abadie *et al.* (2006) presented results of the comparison of the energy efficiency of an EAHE in some cities in southern Brazil. In this work, it is noticed that the energy advantages of EAHE are not universal, because even though all the cities analyzed belonged to the same climate zone, the results of energy gain were not significant for one of the cities under analysis. Vaz (2011) showed that the energy gain of an EAHE is higher under winter weather conditions, being, therefore, a good indoor heating system. In this work, it is shown that the energy gain in the summer is not satisfactory to achieve the thermal comfort of an indoor environment.

Brum *et al.* (2016) has already shown that using a design based on the Constructual law it is possible to increase the thermal potential of an EAHE at a rate between 7% and 25%. Such work presented the results taking into account the geometry configuration of the ducts of an EAHE and showed that it is possible to reduce between 230kWh and 810kWh the consumption of electrical energy in a residence.

In this sense, Brum *et al.* (2019a) has shown that it is more advantageous to use a network of multiple ducts instead of a single duct. The results obtained show that the energy gain of the duct network is higher than the energy gain of a simple duct while occupying less space. In addition, Brum *et al.* (2019b) presents the results of the study varying the internal geometry and the distribution of the ducts in the terrain.

Agrawal *et al.* (2019) presented results that show that the efficiency of an EAHE can be improved and the length of the ducts reduced with good thermal properties in the vicinity of the EAHE. In addition, the thermal properties of the soil can be improved by increasing its moisture ratio and its level of compaction.

The objective of this work is to present a model for stationary description of the variation of the enthalpy, from which a study on the variation of the diameter is developed to improve the thermal performance of an EAHE. In addition, it presents a model to determine the soil temperature based on the Least Squares method.

2. STEADY CASE ANALYSIS

A sketch of an EAHE is shown in Figure 1. In addition to the cylindrical duct, the system has a fan that blows inside the duct. As long as the fan motor is located outside the duct or its periphery, the position of the fan does not matter. To verify the first results, the geometry of the duct was not taken into account and the region of interest is its horizontal part whose length is L and diameter, D.

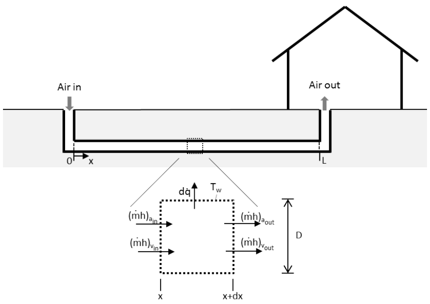


Figure 1. An EAHE system and model domain (Estrada *et al.*, 2018).

Considering the energy and mass conservation equations; the specific enthalpy of humid air $h_{ha} = c_{p,a}T + w(c_{p,v}T + L_v)$, where $c_{p,a}$ is the specific heat of the air dry, $c_{p,v}$ is the specific heat of the water vapor, w is the moisture, L_v latent heat of evaporation and T, the absolute temperature; obtains the equation to determine the diameter D as a function of the dimensionless enthalpy $\overline{h}$:

$$D = \frac{\ln(\overline{h}) m_a c_{p,ha}}{h_{cv}\pi L}, \tag{1}$$

$$\overline{h} = \frac{h - h_w}{h_{in} - h_w} = \exp\left(\frac{h_{cv}p}{m_a c_{p,ha}}x\right), \tag{2}$$

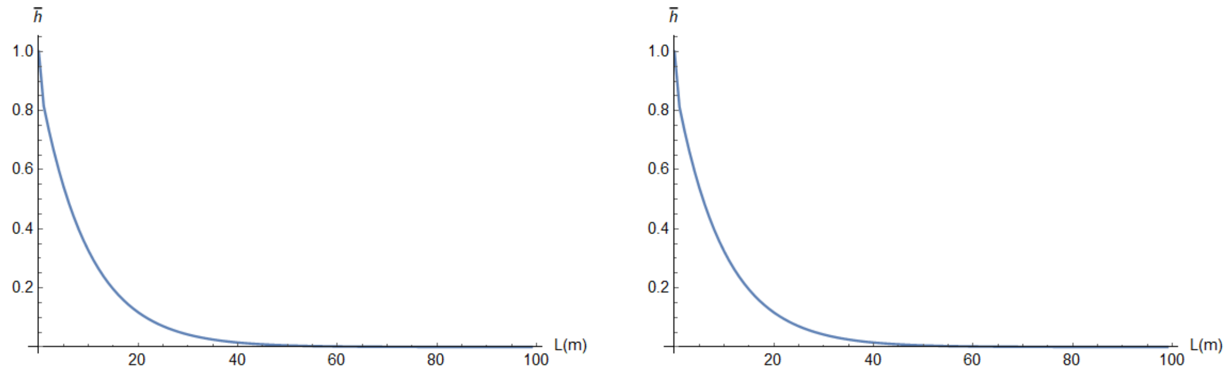
where h_{cv} is the convective heat transfer coefficient, m_a is the mass flow rate, $c_{p,ha} = c_{p,a} + wc_{p,v}$ is the specific heat of the humid air, p is the perimeter of the duct, h_w the enthalpy on the duct wall, h_{in}, the enthalpy at the inlet of the duct and h, the enthalpy at the point $x = L$ of the duct.

Using the values determined by the equation (2), it was found the values for the diameter in the equation (1). To determine the convective heat transfer coefficient, as in Estrada *et al.* (2018), was considered the dimensionless Nusselt number $Nu_D = 68.3$, with the internal diameter of the duct $D = 0.1m$.

2.1 Problem Verification

The preliminary results show the enthalpy inside the duct as a function of its length, as in the equation (2), and are shown in Figure 2. For these tests, two climatic situations were considered. The first one with temperature at the entrance of the duct $T_{in} = 27°C$ and relative humidity of the air $RH = 85\%$, according to the characteristics of a hot and humid climate. The second case corresponds to the climate of a hot and dry region, with $T_{in} = 27°C$ and $RH = 62\%$. In addition, for the first case, the soil temperature was considered $T_w = 23°C$ and for the second, $T_w = 19°C$. The mass flow rate of the modeled problem is $40g/s$. Also, to obtain these graphs, a discrete domain was considered, whose enthalpy is obtained from the enthalpy of the previous point.

From the results obtained, it is clear that for both types of climate, after 50m, the energy gain in relation to the length of the duct is almost zero. Thus, pipelines with longer lengths are not necessarily more effective.



(a) Enthalpy along the duct in hot and humid weather. (b) Enthalpy along the duct in hot and dry weather.

Figure 2. Enthalpy along the duct (Present work).

3. TIME-DEPENDENT PROBLEM

3.1 Problem Statement

Considerando, agora, o modoelo transiente, a equação de conservação de enrgia no interior de um EAHE é escrita como:

$$\frac{\rho_{ha}\pi D^2}{4}\frac{\partial h}{\partial t} = -m_a\frac{\partial h}{\partial x} + \frac{h_{cv}p}{c_{p,ha}}(h_w - h), \qquad 0 < x < L, \quad t > 0, \tag{3}$$

he equation (3) is subjected to the initial and boundary conditions:

$$h(x,0) = h_w, \tag{4}$$

$$h(0,t) = h_{in}. \tag{5}$$

To determine the initial condition (4), the equation that describes the soil temperature as a function of depth and time was considered:

$$T(z,t) = T_m + A_z \cdot \sin\left[\frac{2\pi}{P}(t - t_0) - \gamma z - \frac{\pi}{2}\right], \tag{6}$$

considering T_m the average surface temperature of the soil and t_0 the time interval necessary for the soil surface to reach T_m. In addition, A_z is the amplitude of the temperature wave to a depth of z, described by:

$$A_z = A_0 \cdot \exp\left(-\gamma z\right). \tag{7}$$

$$\gamma = \sqrt{\frac{\pi}{\alpha P}}, \tag{8}$$

where P is the period of oscillation, expressing one year in hours. The parameters T_m, A_0 and t_0 were extracted from the internet databases (**??**).

For modeling the equation (3), we used the approximation of derivatives by backwards differences, implying the following scheme, where $h_j^i = h(t_i, x_j)$:

$$\frac{\rho_{ha}\pi D^2}{4}\cdot\frac{h_j^i - h_j^{i-1}}{\Delta t} = -m_a\cdot\frac{h_j^i - h_{j-1}^i}{\Delta x} - \frac{h_{cv}p}{c_{p,ha}}\cdot h_j^i + \frac{h_{cv}p}{c_{p,ha}}\cdot h_w, \quad 0 < x_i < x_m = L, \quad 0 = t_1 < t_i < t_n, \tag{9}$$

such that i is the discretization of the domain in time and j in space.

3.2 Model Validation and Application

To validate the developed model, it was compared with the results obtained by Estrada *et al.* (2018). To perform the modeling, an EAHE with a simple duct with an internal diameter $D = 0.1m$, mass flow rate $40g/s$ and the number of Nusselt $Nu_D = 68.3$ was considered. The weather data was provided by INMET database. The results are ploted in Fig. 3. The results show a strong agreement between the present work and the work developed by Estrada *et al.* (2018).

The model presented in this section is applied to the geophysical characteristics and climatic data of 2019 in the city of Porto Alegre, capital of Rio Grande do Sul, in the south of Brazil. The results are shown in Fig. 4.

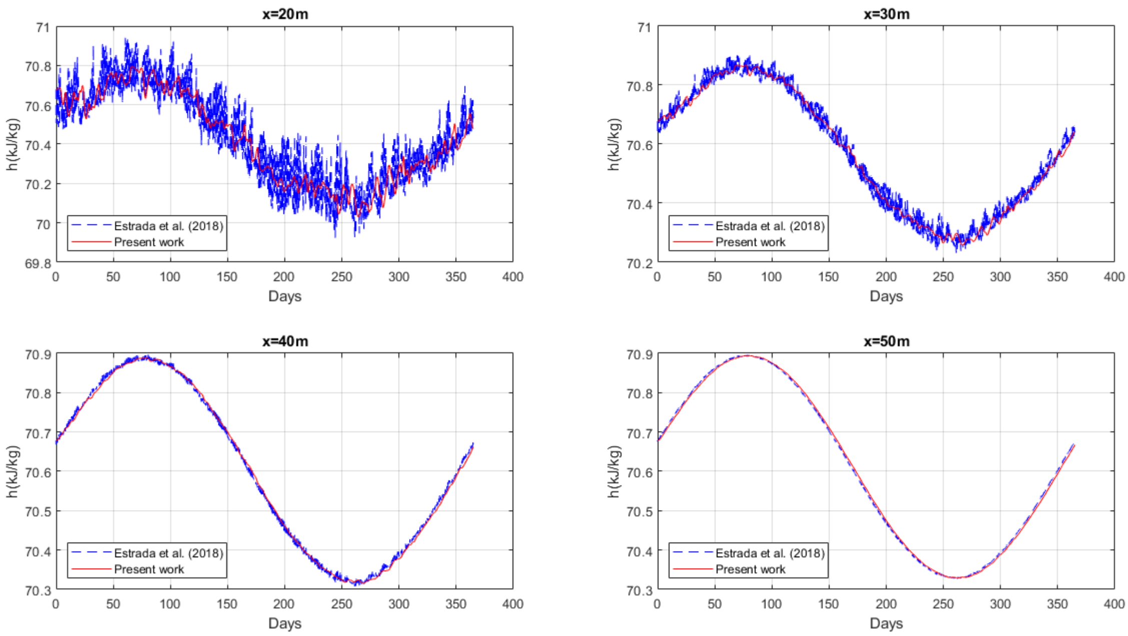


Figure 3. Comparison between the Estrada et al. (2018) and the present work for enthalpy over a year in different duct abscissa, Rio de Janeiro - Brazil.

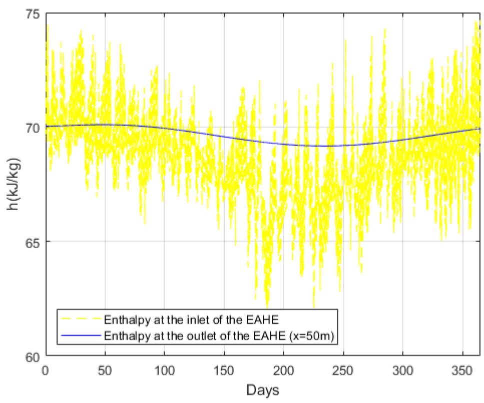


Figure 4. Enthalpy along the year of 2019 at the inlet and outlet of an EAHE in Porto Alegre, RS – Brazil.

The results show a significant difference between enthalpy at the entrance and exit of the EAHE over a full year. It is noticed that the difference is greater when it comes to winter, highlighting the potential of an EAHE as a good heater, in accordance with the studies of Vaz (2011). Furthermore, it is clear that Porto Alegre has favorable climatic characteristics for the installation of EAHE systems.

4. TEMPERATURE WITHIN AN EAHE

4.1 Model Validation

In this section, it is approached the modeling of temperature within an EAHE over a year. This modeling allows to analyze the behavior of the temperature inside the duct and its relationship with the average temperature of the external and internal environment of the building.

According to Vaz (2011), for the city of Viamão, the equations that model the temperature inside the duct, its wall and its outlet are, respectively:

$$T = 18.5847 + 5.71305 \sin\left[\frac{2\pi * d}{365} + 1.15533\right] \quad (10)$$

$$T_w = 18.7 + 3.2954 \sin\left(1.37 \times 10^{-2} - 5.8998\right), \quad (11)$$

$$T_{out} = \frac{h_{out} - w \cdot Lv}{c_{p,ha}}, \tag{12}$$

where d is the number of days that have passed since the beginning of the analysis.

To implement these equations, a C language program was developed. The specific heat of the dry air is equal to 1×10^{-2}, internal diameter of the duct, $11cm$, and air speed is $3.3m/s$. In Fig. 5, the comparison between the model developed in this work and two other models is presented, as well as the experimental data obtained by Vaz (2011).

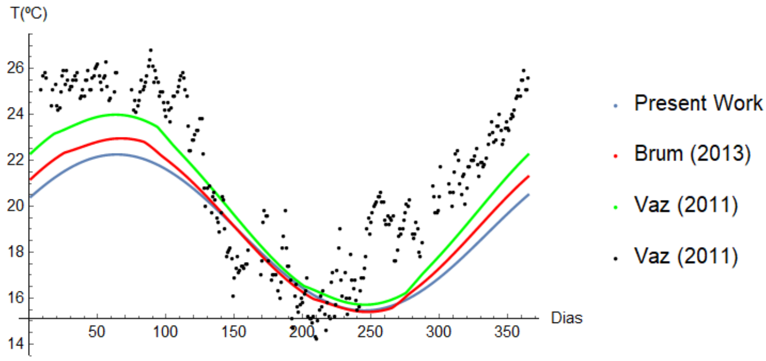


Figure 5. Temperature variation inside the duct throughout the year in the city of Viamão – RS, Brazil.

Table 1. Relative error between the experimental data, Vaz (2011) and the present work.

Day	Experimental data ($°C$)	Vaz (2011) (%)	Present work (%)
08	25.10	9.6097	17.2364
175	17.60	1.7458	0.3786
194	16.10	4.6053	3.7339
224	15.70	1.6463	0.1211
365	25.60	13.0696	19.9308

The results show that the model is consistent with the experimental data and the other models reproduced. It can be noted that the model developed here presents better results in relation to the work of Vaz (2011) in all seasons except the summer. It is also possible to use this model to analyze the temperature inside the buried duct in different depths of the soil. To do this, just adjust the parameters of the equations (10) and (11) to the depth in question.

In addition, it is possible to combine the results presented in Fig. 2 and Fig. 5 and present a complete transient model. Such a model will present the enthalpy variation inside the duct considering the temperature constant over a day. Each day, therefore, can be considered a contour line in the analysis between enthalpy and position.

4.2 Application of the model to Pelotas, RS – Brazil

The model validated in the previous section is now applied to climatic and geophysical conditions of Pelotas, a city in the south of Rio Grande do Sul, Brazil. Daily air temperature data during 2019 were obtained from the Pelotas Agro-climatological Station Bulletin. From these data, the parameters for the equations that model the temperature distribution were calculated. For grassy soil, the following equation was obtained:

$$T_{Grassy} = 20.4271 + 5.72985 \sin\left[\frac{2\pi}{365}t + 5.09989\right] \cdot \exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right), \tag{13}$$

where α is the thermal diffusivity of the soil.

The results of the proposed modeling in the equation (13) are presented in Fig. 6, in a comparison between three depths of the soil and the air temperature data.

For bare soil, the following equation was obtained:

$$T_{Bare} = 20.8137 - 7.28742 \sin\left[\frac{2\pi}{365}t - 8.13558\right] \cdot \exp\left(-z\sqrt{\frac{\pi}{365\alpha}}\right) \tag{14}$$

In Fig. 7 the graph of temperature behavior over a year at three different depths of bare soil is shown, modeled by Eq. (14), together with the average daily air temperature.

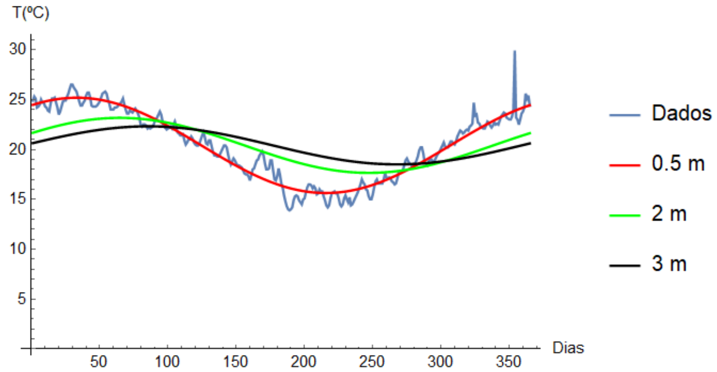


Figure 6. Grassy soil temperature at different depths in the city of Pelotas, RS – Brazil.

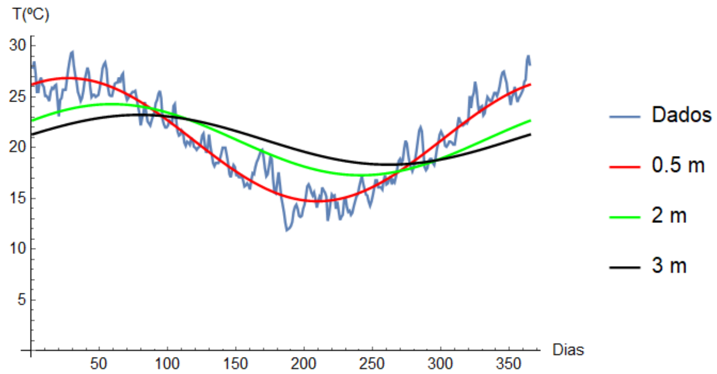


Figure 7. Temperature of bare soil at different depths in the city of Pelotas, RS – Brazil.

The results point to a significant difference between air temperature and soil temperature at $3m$ deep. This difference is greater when the most extreme temperatures, in summer and winter, are under analysis. In addition, in the milder seasons of the year, autumn and spring, the soil temperature and air temperature may even coincide, resulting in a zero difference. It is also noticed that the sinusoidal variation behavior is affected by the depth of the soil. The greater the depth under analysis, the wave crests are smaller while their lengths are longer.

Finally, Fig. 8 presents a comparison between the temperature distribution for grassy and bare soil considering the depth of analysis equal to $3m$.

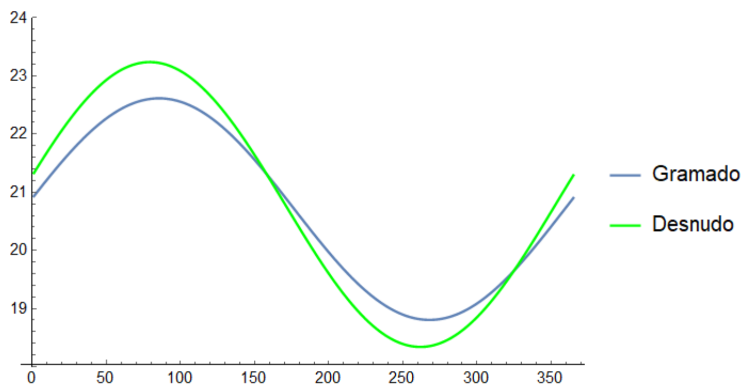


Figure 8. Comparação entre a distribuição de temperaturas a $3m$ de profundidade de dois tipos de solo na cidade de Pelotas, RS - Brasil.

The results presented in Fig. 8 indicate that the temperature variation in the soil depends directly on the presence of surface coating. In the case under analysis, the soil with lawn, with vegetation cover, showed milder variations in the amplitude of the distribution of average daily temperatures.

5. DESIGN OF AN EAHE

From the modeling of the dimensionless enthalpy presented in Eq. (2), it is proposed to model some physical parameters of the EAHE. In this work, the calculations and the modeling of the diameter are presented taking into account the cooling power and the variation of the enthalpy inside the EAHE.

The cooling power $\dot{Q}$ of EAHE, that is, the measure of heat exchanges that happen between the air inside the ducts and the soil, is written as:

$$\dot{Q} = (1 - \overline{h}) \cdot \Delta h \cdot \dot{m}_a, \tag{15}$$

where Δh is the difference between enthalpy at the entrance and on the wall of the ducts that make up the EAHE.

According to Brum *et al.* (2019a), the diameter of the EAHE can be equated as:

$$d = \left(- \frac{8\, \dot{Q}^3 f_D \varepsilon c_{p,ha} \ln \overline{h}}{\rho_{ha}^2 \pi^3 (1 - \overline{h})^4 \Delta h^4 h_{cv}} \right)^{\frac{1}{6}}, \tag{16}$$

where ε is the EAHE performance coefficient (ratio of cooling power to fan power) and the Darcy-Weisbach friction coefficient is calculated f_D by:

$$f_D = (0.79 \ln Re_D - 1.64)^{-2}, \tag{17}$$

where Re_D is the Reynolds number.

To determine the parameters f_D and h_{cv}, an iterative program is used, from an initial guess for the diameter, calculates all parameters dependent on it until the difference between two iterations is less than 10^{-3}.

Considering $\overline{h} = 0.05$ and $\varepsilon = 3$, the results shown in Fig. 9 are obtained.

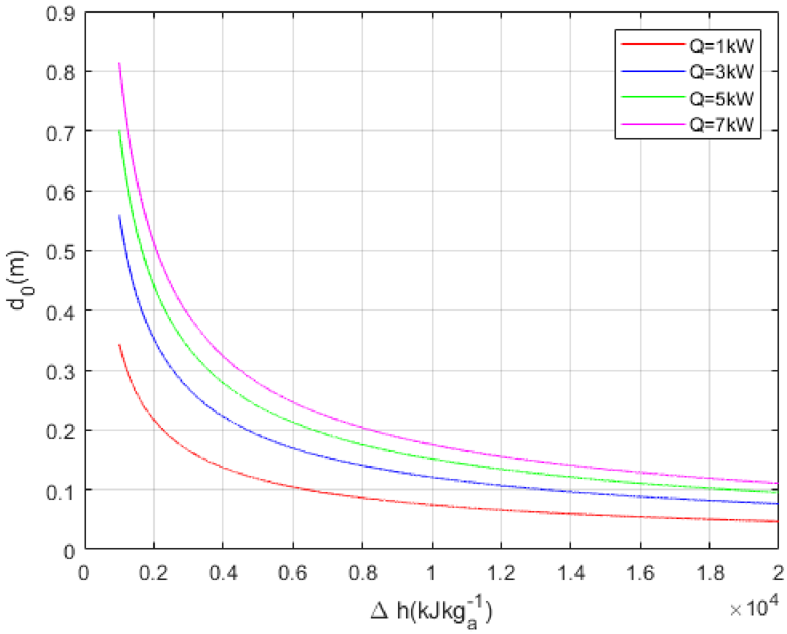


Figure 9. Duct internal diameter of an EAHE as a function of the variation in enthalpy and cooling power.

The results show that the variation in the internal diameter of an EAHE composed of a single duct significantly influences its performance. The greater the desired power, the greater the diameter to be used. In addition, it is noteworthy that both the variation in enthalpy and the variation in cooling power are directly proportional to the variation in diameter.

6. CONCLUSIONS

Earth-air heat exchangers are an alternative to indoor building cooling systems. Here, a study was developed about one of the most important physical parameters of this system, the inner diameter of the ducts.

The results show that the energy gain due to the length of the ducts is almost zero above $50m$ of length. This implies, first of all, ducts with a length greater than $50m$ aren't advantageous or represent any benefit. Consequently, the reasons for avoiding unnecessary costs for those who wish to use this system to ensure thermal comfort of buildings are also evident.

Also, the numerical modeling of the specific enthalpy of an EAHE, applied to a city in southern Brazil, was presented. The results, in agreement with the recent literature, indicate that the EAHE has great applicability in the city of Porto Alegre, due to its climatic characteristics.

In addition, the model developed to analyze the temperature inside the duct showed satisfactory results, compatible with the available experimental data. In this way, the algorithm implemented here can be applied to other cities and regions. It is advantageous in relation to other models because it is an analytical model, requiring low computational cost and delivering good solutions. In addition, the role played by the covering of the soil surface in the distribution of temperatures in the medium is highlighted.

It is intended to develop the calculations for the efficient design of an EAHE according to the variation in its length and the internal pressure in the system, as well as to evaluate other geometric dispositions and its influence on the thermal performance of the EAHE.

In view of the results obtained, it is intended to model the energy gain of an EAHE with multiple ducts and bifurcations. Based on the Constructal Theory, developed by Bejan (1997) and applied to heat exchangers by several authors, among them Brum *et al.* (2019b), it is intended to carry out such an analysis using the variation of the internal diameter of the ducts and its length or the pressure inside it.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE