A CONSTRUCTAL DESIGN OF EARTH-AIR HEAT EXCHANGERS COMPOSED BY FOUR DUCTS

Ruth da Silva Brum, ruthdasilvabrum@gmail.com[1]
Liércio André Isoldi, liercioisoldi@furg.br[2]
Jairo Valões de Alencar Ramalho, jairo.ramalho@ufpel.edu.br[3]
Luiz Alberto Oliveira Rocha, luizrocha@mecanica.ufrgs.br[1]
Michel Kepes Rodrigues, michel.professor@yahoo.com.br [2]
Elizaldo Domingues dos Santos, elizaldosantos@furg.br[2]

[1]Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Engenharia Mecânica, Rua Sarmento Leite, 425, 2. Andar, Porto Alegre, RS, 90050-170, Brazil.
[2]Universidade Federal do Rio Grande, Programa de Pós-Graduação em Modelagem Computacional, Av. Itália, Km 8, Rio Grande, RS, 96203-900, Brazil.
[3]Universidade Federal de Pelotas, Instituto de Física e Matemática, Campus Capão do Leão s/n, Pelotas, RS, 96160-000, Brazil

Abstract: *The Earth-Air Heat Exchangers (EAHE) systems offer an environmental friendly way to reduce the use of non-renewable energy for air conditioning by taking advantage of the thermal inertia of the ground, where the temperatures lag those on the surface, mainly in the summer and winter. For this, the EAHE make use of underground ducts where the ambient air is blown, to receive or lose part of its heat from/to the surrounding soil, and, finally, enter a building as conditioned air. Many works in the literature have focused in the thermal performance of EAHE composed by only one duct, and it is well known, for instance, that it can be improved to some extent by increasing the ducts size and/or reducing their diameter. However, to use the results of those papers, one needs to take the ducts far apart from each other, to avoid their mutual thermal influences. Taking a different approach, this article aims to explore new layouts to build EAHE with four ducts. Employing the constructal design method, this work presents as results the best spacings among the ducts in order to improve the heat transfer between soil and air, increasing the EAHE thermal potential. This is done varying the ratio between the vertical and horizontal spaces among the ducts, up to limiting global constraints, and using several simulations of the temperature fields in the ducts, with a verified and validated three-dimensional computational model.*
Keywords: *Constructal design, Earth-air heat exchangers (EAHE), Renewable energy devices, Air conditioning.*

1. INTRODUCTION

The energy being expended with conventional air-conditioning systems throughout the world is growing larger and larger every year. This comes from different factors, such as inappropriate design of buildings, augments of ambient temperature due to climate changes, and even problems caused by urban density (Rodrigues and Gillott, 2015). From the alternatives to help improving the thermal comfort at a low energetic cost, this paper investigates the Earth-air heat exchangers (EAHE). Such devices explore the thermal inertia of Earth to dissipate heat by circulating the air inside buried ducts. Thus, in a hot summer day, the air travelling through the ducts is cooled after giving up part of its heat to the surrounding soil. The reverse occurs in a winter day, when the air gains heat from the soil. In both cases, the air leaves the outlet of the ducts at a milder temperature.

Even though the concept of underground ducts/pipes has been known for centuries (Jacovides *et al.*, 1996; Rodrigues and Gillott, 2015), the interest for them has increased mainly over the last decade. Indeed, Diaz-Mendez *et al.* (2014) state that some countries still do not use them. On the other hand, one can find reports from installations in many countries, like in Germany (Pfafferott, 2003), in India (Misra *et al.*, 2013), in China (Yang *et al.*, 2010), and, of course, in Brazil (Vaz *et al.*, 2014), only to mention a few. In this regard, there is a growing literature aiming to study different themes like: the development and validation of complete or simplified models for their simulations, as well as the analyses of their operational parameters (Brum *et al.*, 2012; Brum *et al.*, 2013; Paepe and Janssens, 2003).

It should be noted that most of these references study EAHE composed by only one duct, or sets of ducts located far apart from each other to avoid mutual thermal interferences. A problem recently raised by Rodrigues *et al.* (2015) was how to arrange geometrically new layouts for two or more ducts aiming to improve their thermal performance. Inspired in the related work of Rocha *et al.* (2012), some answers were achieved by using the constructal design method (Bejan and Lorente, 2006; Bejan and Lorente, 2008). In short, the idea is to let the the flow configuration vary freely, up to volume constraints, towards the direction of the main flow currents, while one observe the evolution of some objective function. For EAHE, the current is the heat that mainly flows in the cross-sectional direction from the ducts to the ground. As for the objective function, this paper studies the so-called thermal potential, which is an average of the differences between the temperatures on the outlets and the inlets of the ducts.

This paper aims to use the constructal design method to improve the geometrical configuration of a new layout for EAHE with four ducts. As it is done in (Rodrigues *et al.*, 2015), we consider that the ducts form a prism whose shape can vary inside the soil (thus letting the flow configuration freely change) but its volume must remain constant. As it is shown ahead, we end up finding the best vertical and horizontal spacings among the ducts, in order to improve the EAHE thermal potential. Finally, it is important to mention that this work also presents new models for the thermal potential, allowing to simplify the analyses of the set of EAHE, as well as establish results for their energetic performance and effectiveness.

2. METHODOLOGY

Regarding the geometry, the soil is contained within a three-dimensional domain Ω consisting of a parallelepiped whose length, height and width are, respectively, $L_s = 26m$, $H_s = 15m$ and $W_s = 10m$. The EAHE is composed by four ducts inside Ω taking the shape of right circular cylinders with length $L_e = L_s$ and diameter $D_e = 0.11m$. The Fig. 1 shows a two-dimensional view of the four ducts over the xz-plane. The centers of the ducts are placed in the corners of a diamond which is centered around the point $Q(W_s/2, D_{ave})$, where $D_{ave} = 3m$, the same depth proposed by Brum *et al.* (2012) for EAHE with one duct. From the constructal design method, the vertical S_v and horizontal S_h spacings among the ducts (center to center) are free to vary under certain constraints. First, to avoid overlapping the ducts, and keep them in Ω, we imposed: $S_h > D_e$, $S_v > D_e$, $S_h < W_s - 2D_e$, $S_v < 2D_ave - 0.5$. Second, but very important, they must satisfy a fixed volume fraction:

$$\psi = \frac{V_E}{V_S} = \frac{L_e \frac{S_v S_h}{2}}{L_s H_s W_s} = \frac{S_v S_h}{2 H_s W_s}. \tag{1}$$

Here, V_E is the volume of the prism with length L_e and whose cross section is the diamond associated to the EAHE, while V_S is the volume of Ω. Therefore, with the constructal design, we are concerned to study how the overall performance of the EAHE varies when its prismatic structure is morphed (keeping its volume constant) towards the main heat currents which are flowing between the ducts and the soil. For this paper, we adopted $\psi = 0.01$, which is a volume fraction also used in (Rodrigues *et al.*, 2015), and we present ahead the results of 15 simulations varying the ratio $r = S_v/S_h$ from approximately 0.05 to 7.05.

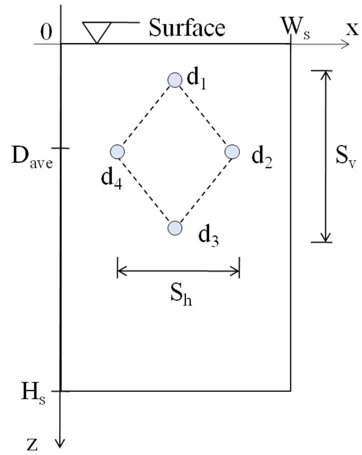

Figure 1: Cross-section view of the four ducts.

To study the EAHE, we adopted a relatively complete model, where the flow inside the duct is considered transient, incompressible, turbulent and described by time-averaged conservation equations of mass, momentum and energy (Versteeg and Malalasekera, 2007; Wilcox, 2002; Incropera *et al.*, 2011). In cartesian coordinates, these equations are, respectively:

$$\frac{\partial \overline{v_i}}{\partial x_i} = 0, \tag{2}$$

$$\frac{\partial \overline{v_i}}{\partial t} + \frac{\partial (\overline{v_i}\,\overline{v_j})}{x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{x_j}\delta_{ij} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{v_i}}{\partial x_j} + \frac{\partial \overline{v_j}}{\partial x_i}\right) - \tau_{ij}\right], \tag{3}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{v_j}\overline{T}) = \frac{\partial}{\partial x_j}\left[\alpha \frac{\partial \overline{T}}{\partial x_j} - q_j\right], \tag{4}$$

and we have to find the fields of temperature T (K), velocity v (m/s) and pressure p (N/m^2). Here, the overline is used to denote time-averaged terms and the equations obey the usual index notation where: the axis labels x, y and z are replaced, respectively, by x_1, x_2 and x_3, therefore, the integers i and j run from 1 to 3; the symbol δ_{ij} is the Kronecker delta (if $i = j$ then $\delta_{ij} = 1$, otherwise, $\delta_{ij} = 0$); the summation symbol is dropped, being replaced by repeated index notation, i.e., the Einstein notation. As for the other symbols (in order of appearance), t, ρ, ν, τ, α, and q, they represent, respectively, the time (s), the air density (kg/m^3), the kinematic viscosity of the air (m^2/s), the Reynolds stress tensor (m^2/s^2), the thermal diffusivity of the air (m^2/s), and the turbulent energy flux (mK/s). The models used for τ and q were:

$$\tau_{ij} = \overline{v_i' v_j'}, \tag{5}$$

$$q_j = \overline{v_i' T'}, \tag{6}$$

where the apostrophe ($'$) indicates the time varying fluctuating component (Versteeg and Malalasekera, 2007). To deal with the closure problem, we used the Reynold stress model (RSM), where it is necessary to solve the following additional transport equations for the Reynolds stresses:

$$\frac{\partial \tau_{ij}}{\partial t} + \overline{v_k}\frac{\partial \tau_{ij}}{\partial x_k} = -\left(\tau_{ik}\frac{\partial \overline{v_j}}{\partial x_k} + \tau_{jk}\frac{\partial \overline{v_i}}{\partial x_k}\right) - \frac{\partial C_{ijk}}{\partial x_k} + \Pi_{ij} - \varepsilon_{ij} + \nu\nabla^2\tau_{ij}. \tag{7}$$

Here the correlations for pressure strain C_{ijk}, dissipation rate Π_{ij}, and third-order diffusion ε_{ij} are given by:

$$C_{ijk} = \overline{v_i' v_j' v_k'} + \frac{1}{\rho}(\overline{p' v_i'}\delta_{jk} + \overline{p' v_j'}\delta_{ik}), \tag{8}$$

$$\Pi_{ij} = \overline{\frac{p'}{\rho}\left[\frac{\partial v_j'}{\partial x_i} + \frac{\partial v_i'}{\partial x_j}\right]}, \tag{9}$$

$$\varepsilon_{ij} = 2\nu\overline{\frac{\partial v_i'}{\partial x_k}\frac{\partial v_j'}{\partial x_k}}. \tag{10}$$

Additional modelling to close the set of equations are provided by references like (Versteeg and Malalasekera, 2007; Wilcox, 2002), and we do not present more details here for the sake of brevity.

Regarding the temperature field in the soil, it was computed from the conservation equation of energy, i. e.:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_j}\left(\alpha_s\frac{\partial T}{\partial x_j}\right), \tag{11}$$

where α_s is thermal diffusivity of the soil (m^2/s).

This model for EAHE, was first introduced in (Brum *et al.*, 2012), where it was validated through comparisons with the experimental data available from a research involving a set of EAHE installed in the southern brazilian city of Viamão (Vaz *et al.*, 2014). Therefore, the simulations in this paper are also related to the conditions find in that part of Brazil. This is the case of the boundary conditions for the temperatures on the soil surface T_s and at the inlet of the ducts T_i, which are given by:

$$T_s(t) = 18.70 + 6.28 sin(0.0172t + 26.24), \tag{12}$$

$$T_i(t) = 23.03 + 6.92 sin(0.0172t + 26.42), \tag{13}$$

where the temperatures in these models are in ^oC and the time in days. These equations were obtained from the experimental data using the algorithm for the least squares method described in (Brum *et al.*, 2015). The other surfaces of the domain were assumed to be thermally insulated. As for the air velocity at the ducts inlet, we adopted the value of $3.3 m/s$ which was also used experimentally. For the outlet, it was assumed to be at atmospheric pressure. Regarding the initial condition, all the domain was considered at 18.70^oC, which is the mean temperature of the soil, as it can be seen in Eq. (12). Naturally, the thermo-physical properties of the air and soil also follow the work (Vaz *et al.*, 2014) and they are summarized in the Tab. 1.

Table 1: Thermophysical properties of air and soil

	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Absolute Viscosity (kg/ms)
Air	1.16	0.0242	1010	1.789×10^{-5}
Soil	1800	2.1	1780	-

To make the simulations, we first constructed the computational domain using the GAMBIT software. The mesh was composed by tetrahedral cells, and it was more refined inside the ducts than in the portion of soil to better capture the higher temperature gradients. Here, we followed the pattern suggested in (Rodrigues *et al.*, 2015), where the maximum sizes for the cells in the ducts and in the soil were $D_e/3$ and $3D_e$, respectively. As it was done in the same reference, we neglected the material properties and the thickness of the ducts. After that, we solved the governing equations with the FLUENT software which adopts the finite volume method. Moreover, from all the available options regarding: algorithms for the treatment of transient pressure and velocity fields, and schemes to handle numerical instabilities due to advection terms; we adopted, respectively, the Coupled algorithm, and the Upwind scheme. Finally, the simulations covered a period of two years divided in time steps of $3600s$ which advanced after the residuals (between two successive iterations) of mass, momentum and energy balance become lower than 10^{-3}, 10^{-3} and 10^{-6}, respectively, meeting the convergence criterion.

3. NEW MODELS AND RESULTS

3.1 Modeling the instantaneous thermal potential

For EAHE composed by four ducts, the instantaneous thermal potential P can be defined by:

$$P(t) = \sum_{k=1}^{4} [T_{o,k}(t) - T_{i,k}(t)]/4, \tag{14}$$

where $T_{o,k}(t)$ and $T_{i,k}(t)$ represent, respectively, the temperatures on the outlet and on the inlet of the k-th duct, at the time t. Here, for all ducts, $T_{i,k}(t) = T_i(t)$ which is given by Eq. (13). Nonetheless, P is also a function of other variables, in particular, it varies with the ratio between the ducts vertical and horizontal spacings, i. e., $r = S_v/S_h$. In this paper, we find that P can be modelled by sine-based functions like:

$$P(t, r) = a(r) sin(bt + c) + d, \tag{15}$$

where b, c and d are real constants and a is a function of r. As usual, we also call a, b, c, and d, respectively, the amplitude, angular frequency, phase and mean value of P. The idea that the variations in r affect mainly the amplitude of P can be noticed in the graphics of the Fig. 2. It shows that increasing r from 0.05 to 7.05 decreases the amplitude of the instantaneous thermal potential, while the changes in frequency, phase and mean value are little noticeable.

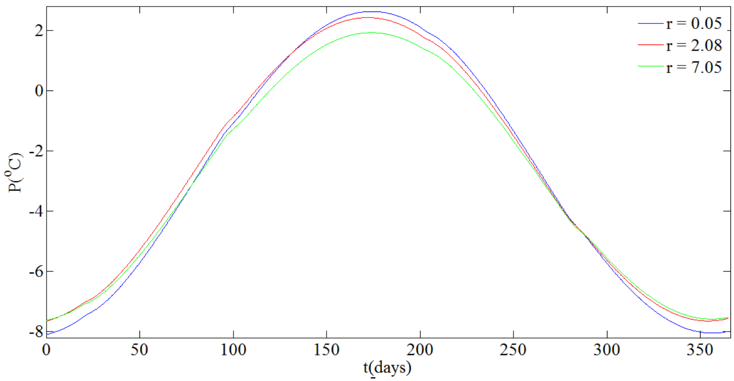

Figure 2: Graphics of P along the year for three different ratios $r = S_v/S_h$.

Using the least squares method as in (Brum *et al.*, 2015), we first explored models for P by fitting the numerical discrete results to sine-based functions in the form:

$$P_j(t) = a_j sin(b_j t + c_j) + d_j, \tag{16}$$

where a_j, b_j, c_j and d_j are real coefficients. We notice that $j = 1, 2, \ldots, 15$, since we simulated EAHE instalations with 15 different values of r which are displayed approximately in the Tab. 2, together with the corresponding coefficients.

Table 2: Values of a_j, b_j, c_j and d_j for each r

r	0.05	0.16	0.33	0.56	0.85	1.20	1.61	2.08	2.61	3.20	3.85	4.56	5.33	6.16	7.05
a_j	5.374	5.342	5.247	5.175	5.096	5.102	5.083	5.073	5.055	5.031	4.999	4.958	4.910	4.854	4.788
b_j	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
c_j	-1.443	-1.430	-1.415	-1.406	-1.373	-1.403	-1.404	-1.408	-1.411	-1.415	-1.419	-1.423	-1.427	-1.430	-1.434
d_j	-2.705	-2.661	-2.598	-2.558	-2.588	-2.552	-2.572	-2.598	-2.625	-2.654	-2.687	-2.720	-2.755	-2.788	-2.823

These results confirm that the variations in r affect much more the coefficient a_j than the other ones. In fact, the variations in b_j are negligible. We also computed the standard deviations (Bulmer, 1979) of a_j, b_j, c_j and d_j, obtaining the following respective values: 0.165, 0.000, 0.017 and 0.085. This justifies adopting a model for P, like the one in Eq. (15), where the coefficients b, c and d are given, respectively, by the mean values of b_j, c_j and d_j, while a is a function of s. Using least squares, we fitted the discrete values of a_j by polynomials. As it can be seen in the comparison shown by the Fig. 3, the data can be properly fitted by third and fourth degree polynomials, however, we chose the later to increase correlation, attaining a Pearson's R correlation (Bulmer, 1979) of 0.99. Therefore, we modelled a and P by the following functions:

$$a(r) = 0.0021r^4 - 0.0341r^3 + 0.1827r^2 - 0.4113r + 5.3794, \tag{17}$$

$$P(t, r) = a(r) sin(0.0172t - 1.4160) - 2.6589. \tag{18}$$

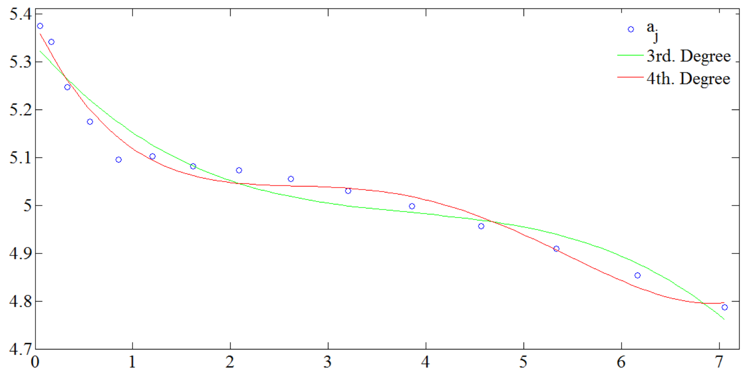

Figure 3: Comparison between a third and fourth degree polynomial to fit a_j.

3.2 Design and Potential

It is important to find such models, because they sum up in a few equations a great amount of numerical data obtained in the simulations of the EAHE installations, thus simplifying their analyses. A first concern with EAHE is to use them to improve thermal comfort, mainly in summer and winter to, respectively, cool and warm buildings. Thus, if in the summer one wants to decrease P as much as possible, in the winter occurs the opposite. In general, from the model for P given by the Eq. (18), this is satisfied by maximizing its amplitude. Studying the function $a(r)$ given by Eq. (17) inside the interval of simulations considered for $r = S_v/S_h$, then the maximum amplitude occurs for $r = 0.05$, while the minimum one for $r = 7.05$. In design terms, these results help to understand part of the relations between the EAHE thermal performance and the geometry of the installation. Looking at the two-dimensional view of the Fig. 1, where the ducts form a diamond, then reduce its height to widen the base improves the instantaneous thermal potential.

3.3 Thermal Potential

Since the EAHE are usually more useful during the summer or the winter, it is convenient to study their performance during warmer or colder months. In this regard, some references (Brum *et al.*, 2012; Rodrigues *et al.*, 2015;Vaz *et al.*, 2014; Brum *et al.*, 2013) employ a monthly average of the instantaneous thermal potential, which is simple called the thermal potential P_t and it is given by:

$$P_t = \frac{\int_{t_f}^{t_l} P(t,r)dt}{t_l - t_f}. \tag{19}$$

Here, t_f and t_l are, respectively, the first and last day of the month, and the integral can be computed for fixed values of r. The Tab. 3 presents the values of the P_t during the summer months of December and January, as well as in the winter months of June and July, for $r = 0.05$ and $r = 7.05$, which represent the best and worst geometries, respectively. From these results, the thermal potential is relatively improved by more than 7% and 25% in the summer and the winter, respectively.

Table 3: Thermal potential (^oC) for the warmer and cooler months of the year.

	December	January	June	July
$r = 0.05$	-7.94	-7.49	2.52	2.19
$r = 7.05$	-7.39	-6.98	1.99	1.69

3.4 Energetic Performance

Besides the thermal comfort, the thermal potential is also directly proportional to the amount of conventional energy that one can save in a month with air conditioning. The power, or energy performance (Incropera *et al.*, 2011; Pfafferott, 2003) of the EAHE can be monthly estimated by:

$$Q = 4\rho_{air} v_{air} A_D c_{air} P_t, \tag{20}$$

where ρ_{air}, c_{air} and v_{air} are the density, specific heat and mean velocity of the air in the ducts. The first two parameters are given in the Tab. 1 and we assume $v_{air} = 3.3m/s$, which is also the air velocity at the ducts inlet. Finally, $A_D = \frac{\pi D_e^2}{4}$ is the cross-sectional area of the ducts. From the results shown in the Tab. 4 below, considering the best geometry for the EAHE installations, they can achieve more than $1100W$ and $320W$, respectively, of cooling and heating power. This represents energetic savings with air conditioning higher than $810kWh$ and $230kWh$ in the summer and the winter, respectively.

Table 4: Power (Q) and energy (E) during the warmer and cooler months of the year for $r = 0.05$.

	December	January	June	July
$Q(W)$	1166.4	1100.5	370.6	322.1
$E(kWh)$	867.8	818.7	275.7	239.7

3.5 Effectiveness

Even though the previous results helped to compare the different geometries for EAHE and provide an idea of their energetic capacity, they do not offer a measure of efficiency. In other words, we do not know how much we achieved from the soil potential. For different references, like (Incropera *et al.*, 2011; Lee, 2010; Pfafferott, 2003; Paepe and Janssens, 2003), a measure of effectiveness is given by a temperature ratio:

$$\theta = \frac{T_o - T_i}{T_{soil} - T_i}, \tag{21}$$

where T_{soil} is the soil temperature while T_0 and T_i are the air temperatures on the outlet and on the inlet, respectively.

To estimate the effectiveness over a year of operation of the EAHE, we adopt in this work a variation of the previous equation, computing the efficiency by:

$$\theta_m = \frac{\sqrt{\int_0^{365} P(t,r)^2 dt}}{\sqrt{\int_0^{365} \big[T_{soil}(t) - T_i(t) \big]^2 dt}}, \tag{22}$$

where $T_i(t)$ is given in Eq. (13), while

$$T_{soil}(t) = 18.70 + 1.94 sin(0.0172t - 0.11) \tag{23}$$

is the soil temperature at the center of the installation, i. e., at the depth of $3m$ (Brum *et al.*, 2013). One also can note that we are computing the numerator and denominator of the Eq. (22) by the usual norm of the square-integrable function space $L^2[0, 365]$ (Reddy, 1998). Having stated the above, we found that the efficiency also increased by reducing r, more specifically, the higher and lower values of θ_m were 71.6% and 66.7% for $r = 0.05$ and $r = 7.05$, respectively.

4. CONCLUSIONS

This paper presented recent results obtained by the application of the constructal design method to enhance the geometric distribution of four ducts buried in the soil to form EAHE. Taking a cross-sectional view of the ducts, they were assembled in the form of a diamond with height and base measuring, respectively, S_v and S_h. Based on many numerical simulations, varying the ratio $r = S_v/S_h$, under limiting constraints, we showed that the thermal performance of the EAHE can be enhanced by reducing r, or, in other words, by elongating the diamond base.

This work also brought new contributions regarding the development of simple sine-based models to study the so-called instantaneous thermal potential P of EAHE. From these efforts, we found that that the variations in r affect mostly the amplitude of P. This simplified our analyses and allowed to determine the best geometric configuration from the examined ones.

The results also indicated the following possibilities: (1) to increase the thermal potential over summer and winter months by more than 7% and 25%, respectively; (2) to improve the energetic savings with air conditioning, by more than $810kWh$ in the summer and $230kWh$ in the winter; (3) to raise the annual efficiency by more than 70%.

5. ACKNOWLEDGEMENTS

R. da S. Brum thanks to CNPq for her doctoral scholarship. L. A. Isoldi thanks to CNPq (Process: 445558/2014-8). E. D. dos Santos, L. A. Isoldi and L. A. O. Rocha thank to CNPq for financial support.

6. REFERENCES

Bejan, A. and Lorente, S., 2006. "The constructal law (la loi constructale)". *International Journal of Heat and Mass Transfer*, Vol. 49, pp. 445–445.

Bejan, A. and Lorente, S., 2008. *Design with Constructal Theory*. John Wiley & Sons, Hoboken.

Brum, R.S., Ramalho, J.V.A., Rocha, L.A.O., Isoldi, L.A. and Santos, E.D., 2015. "A matlab code to fit periodic data". *Revista Brasileira de Computação Aplicada*, Vol. 7, No. 2.

Brum, R.S., Rocha, L.A.O., Vaz, J., Santos, E.D. and Isoldi, L.A., 2012. "Development of simplified numerical model for evaluation of the influence of soil-air heat exchanger installation depth over its thermal potential". *International Journal of Advanced Renewable Energy Research*, Vol. 1, pp. 505–514.

Brum, R.S., Vaz, J., Rocha, L.A.O., Santos, E.D. and Isoldi, L.A., 2013. "A new computational modeling to predict the behavior of earth-air heat exchangers". *Energy and Buildings*, Vol. 64, p. 395–402.

Bulmer, M.G., 1979. *Principles of Statistics*. Dover Publications Inc, New York.

Diaz-Mendez, S.E., no Carachure, C.P. and Herrera-Castillo, J.A., 2014. "Reducing the energy consumption of an earth–air heat exchanger with a pid control system". *Energy Conversion and Management*, Vol. 77.

Incropera, F.P., Dewitt, D.P., Bergman, T.L. and Lavine, A.S., 2011. *Fundamentos de transferência de calor e de massa*. LTC, Rio de Janeiro.

Jacovides, C.P., Mihalakakou, G., Santamouris, M. and Lewis, J.O., 1996. "On the ground temperature profile for passive cooling applications in buildings". *Solar Energy*, Vol. 57, No. 3.

Lee, H.S., 2010. *Thermal design: heat sinks, thermoelectrics, heat pipes, compact heat exchangers, and solar cells*. John Wiley & Sons, Hoboken.

Misra, R., Bansal, V., Agrawal, G.D., Mathur, J. and Aseri, T.K., 2013. "Cfd analysis based parametric study of derating factor for earth air tunnel heat exchanger". *Applied Energy*, Vol. 103.

Paepe, M. and Janssens, A., 2003. "Thermo-hydraulic design of earth-air heat exchangers". *Energy and Buildings*, Vol. 35.

Pfafferott, J., 2003. "Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency." *Energy and Buildings*, Vol. 35.

Reddy, B.D., 1998. *Introductory functional analysis: with applications to boundary value problems and finite elements*. Springer-Verlag, New York.

Rocha, L.A.O., Lorente, S., Bejan, A. and Anderson, R., 2012. "Constructal design of underground heat sources or sinks for the annual cycle". *International Journal of Heat and Mass Transfer*, Vol. 55.

Rodrigues, L.T. and Gillott, M., 2015. "A novel low-carbon space conditioning system incorporating phase-change materials and earth–air heat exchangers". *International Journal of Low-Carbon Technologies*, Vol. 10.

Rodrigues, M.K., Brum, R.S., Vaz, J., Rocha, L.A.O., Santos, E.D. and Isoldi, L.A., 2015. "Numerical investigation about the improvement of the thermal potential of an earth-air heat exchanger (eahe) employing the constructal design method". *Renewable Energy*, Vol. 80, pp. 538–551.

Vaz, J., Sattler, M., Brum, R.S., Santos, E.D. and Isoldi, L.A., 2014. "An experimental study on the use of earth-air heat exchangers (eahe)". *Energy and Buildings*, Vol. 72, p. 122–131.

Versteeg, H.K. and Malalasekera, W., 2007. *An Introduction to Computational Fluid Dynamics – The Finite Volume Method*. Pearson Education, London.

Wilcox, D.C., 2002. *Turbulence Modeling for CFD*. DCW Industries.

Yang, W., Zhou, J., Xu, W. and Zhang, G., 2010. "Current status of ground-source heat pumps in china". *Energy Policy*, Vol. 38.

7. RESPONSIBILITY NOTICE

The author are the only responsible for the printed material included in this paper.