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CONSTRUCTAL DESIGN OF A T-SHAPED EARTH-AIR HEAT EXCHANGER INSTALLED AT RIO GRANDE CITY

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Abstract. *Earth-Air Heat Exchangers (EAHE) are devices used on buildings aiming the improvement of its thermal conditions. It enables a reduction in electrical energy consumption since it reduces the usage of traditional air conditioners. These devices have a simple operating principle: an imposed airflow inside a buried duct leaves it with a milder temperature due to the exchanging heat occurred with the surrounding soil. Given the above, the main goal here is to combine Analytical Solutions, Computational Modelling, Constructal Design method and Exhaustive Search technique for the analysis of a T-shaped EAHE (with one inlet e two outlets), located at the city of Rio Grande, at the south of Brazil. To do so, an EAHE with a straight duct is adopted as a reference, from which different geometric configurations of the T-shaped EAHE are proposed by means of the Constructal Design. The degree of freedom considered is the ratio between the length of bifurcated and the main branch (L_1/L_0). In addition, three performance parameters were considered: soil volume occupied, pressure drop of the airflow on the duct, and thermal performance of the EAHE. The performances of the proposed geometric configurations were compared to each other; and the configuration with L_1/L_0 = 5.0 had the best global performance, reaching a thermal potential for heating of +5.78 °C and for cooling of -5.25 °C, with an approximate reduction of 49 % in pressure drop and 12 % in soil occupation.*

Keywords: *Earth-Air Heat Exchanger, Computational Modelling, Numerical Simulation, Constructal Design.*

1. INTRODUCTION

The Civil Construction industry has been increasingly concerned about the thermal comfort in buildings, in order to reduce its needs of electrical energy consumption. As energy labelling of edifices becomes popular, it is expected from real estate construction companies to adjust its products, aiming to reach an acceptable level of energy usage to provide users a good experience. It is also known that the soil can be used as an energy source, since it has the ability to storage radiation energy provided by the Sun (Sen, 2008). Accordingly to Vaz et al. (2011), it is possible to adopt the soil as a natural reservoir of thermal energy, in which an Earth-air Heat Exchangers (EAHE) can be installed to be used for the thermal condition improvement of a building environment. The EAHE operation principle is very simple and can be described as buried ducts into which air is blown, forcing this flow to exchange heat with the surrounding soil. During hot days, the air loses heat to the soil, which has milder temperature, and the opposite occurs in colder days. With this equipment, it is possible to reduce the usage of air conditioners, hence decreasing the energy consumption to maintain the inhabited places with a more pleasant temperature.

Experimental (Vaz et al., 2014; Agrawal et al., 2018; Durmaz and Yalcinkaya, 2019), analytical (Belatrache et al., 2017; Zhengxuan et al., 2019) and numerical (Misra et al., 2013; Vaz et al., 2011; Brum et al., 2013; Rodrigues et al., 2015; Ahmed et al., 2016; Brum et al., 2019; Rodrigues et al., 2019) studies of EAHE's operation can be found in the literature. In this study, it is expected to reach the best solution for the geometry of a T-shaped EAHE, varying the ratio of the length of its branches. The adopted method to do this evaluation employs the Constructal Design, based on the universal Constructal Law of design and evolution of any finite flow systems (Bejan and Lorente, 2010); allowing a geometric evaluation based on constraints and degrees of freedom (dos Santos et al., 2017). In addition to the Constructal Design, the Exhaustive Search technique was also applied. In other words, the Constructal Design was used to define the search space where the Exhaustive Search was applied. The Constructal Design associated with Exhaustive Search to EAHEs has already been employed by Rodrigues et al. (2015), Rodrigues et al. (2019), and Rodrigues (2019).

2. METHODOLOGY

This study is done for the installation of an EAHE in Rio Grande city, at the south of Brazil. As previously explained, it contemplates the analysis of the geometry of a T-shaped EAHE. Figure 1 shows the scheme of the proposed installations. The ratio between the lengths of the main and the bifurcated branches is the degree of freedom studied and it is represented by L_1/L_0, being L_1 and L_0 as displayed in Fig. 1. Constructal Design is applied as a resource to stipulate a range of cases studied, allied with Exhaustive Search, where all installations are tested and compared among each other to evaluate performance. The diameter of the ducts is kept constant throughout all installations and its value is adopted as 0,11 m, same as in Vaz et al. (2014). The total length of ducts on the installation is considered constant, and equivalent to 30 m, as in Rodrigues et al. (2019). Rodrigues et al. (2015) previously stated that to prevent the computational domain to interfere on the results, a distance of 2 m from the walls of the domain must be established, so the full length of the soil volume was taken as being the main branch added 2 m. As previously studied by Hermes et al. (2019), for the chosen location the ideal depth of installation should be 2 m, distance adopted in this study.

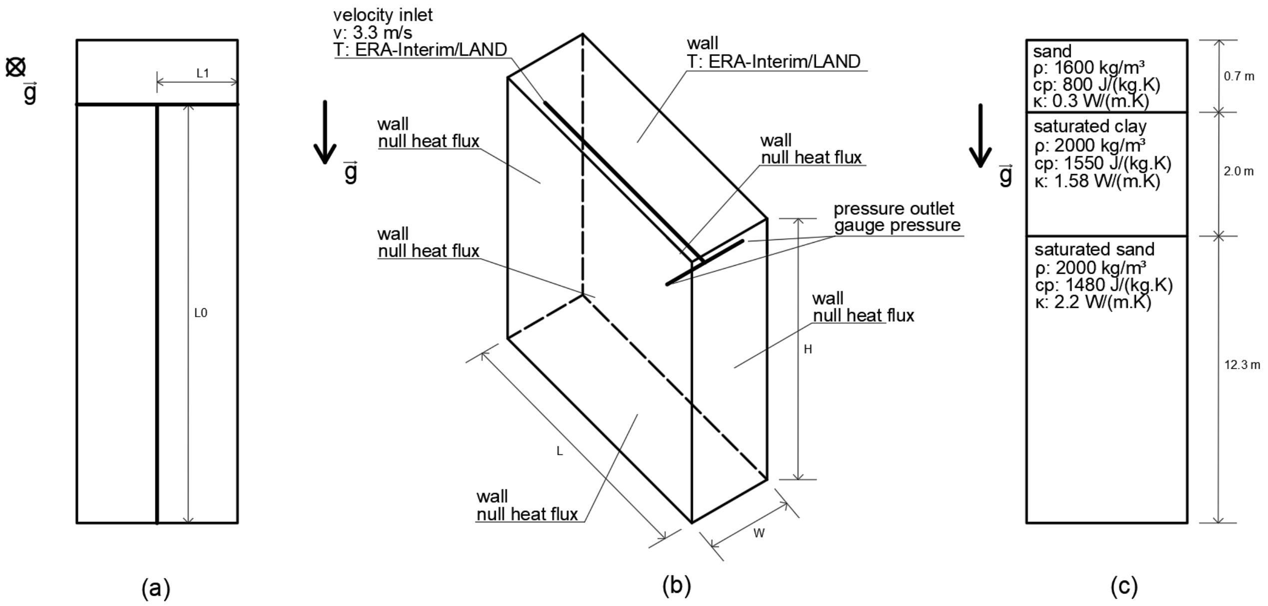

Figure 1. EAHE Computational domain. (a) Upper view with T-shaped duct dimensions; (b) Perspective view with boundary conditions; and (c) Frontal view with soil stratification and material properties.

Figure 1 also shows the boundary conditions configuration. The walls of the soil were thermally insulated, meaning there was no heat flux (Vaz et al. 2011; Brum et al., 2012; Rodrigues et al., 2015), except for the superior surface, into which a prescription of temperature was set with ERA-Interim realistic data for the proposed location (Balsamo et al., 2013; Balsamo et al., 2015). At the inlet of the duct, it was set the velocity of the airflow to be normal to facet and equal to 3.3 m/s (Vaz et al., 2011) as well as its temperature was taken from the same dataset as for the soil surface, the only difference that for the airflow it was taken the temperature for 1 m above the surface. Regarding the soil information, the stratification was obtained from a Standard Penetration Test (SPT) bulletin also shown in Fig. 1, being its properties (density – ρ; specific heat – c_p; and thermal conductivity – κ) adopted according to Oke (1987). For the sake of brevity, this methodology allying the usage of SPT and ERA-Interim dataset will not be represented in this study, but it can be found in literature: Rodrigues (2019), Hermes et al. (2019) and Victoria et al. (2020). Both outlets are considered to be under atmospheric pressure. The air thermo-physical properties were adopted in agreement with the experimental data of Vaz et al. (2014) and taken equal as: ρ = 1.16 kg/m³; c_p = 1010 J/(kg·K); κ = 0.0242 W/(m·K); and absolute viscosity of ν = 1.7894×10^{-5} kg/(m·s). The experimental data of Vaz et al. (2014) was originally obtained for the city of Viamão, at the same state of Brazil, and since it is well known that there are no significant variations for the air properties, the same values were adopted in this study.

Concerning the spatial discretization, this study was based on Rodrigues et al. (2015) mesh convergence test, stating that for tetrahedral cells the sizes of 3*d*, for the soil, and *d*/3, for the duct, being *d* the duct diameter, were able to reach good results. Alongside that, the temporal discretization used was 3600 s with a total amount of time steps of 17568, or 63244800 s, totalizing 2 years of simulation – considering 2016 to be a leap year. Since all zones were initially set to have the soil average temperature, the first year is only to reach the adequate soil temperature distribution, being not taken into consideration for the analysis (Vaz et al., 2011; Brum et al., 2012; Rodrigues et al., 2014; Rodrigues et al., 2019).

As this airflow is not characterized as laminar, the modelling of its turbulence is needed. Therefore, the conservation of mass, momentum and energy equations were solved in association with k-ε turbulence model, consisting in two different equations to represent the turbulent kinetic energy (k) and turbulent viscous dissipation (ε) (Rodrigues et al., 2019). The SIMPLE algorithm was used to represent the pressure-velocity coupling. This computational model was previously validated when comparing the results with the experimental data of Vaz et al. (2014) (Rodrigues et al., 2015). The computational modelling was done with the aid of ANSYS Fluent software, which solved the proposed problems by means of the Finite Volume Method (FVM).

2.1 Performance Analysis

As earlier mentioned, the performance indicators adopted in the proposed geometric evaluation were the soil volume occupied by the EAHE installation, the pressure drop of the airflow on the EAHE duct, and the thermal performance of the EAHE. Regarding the occupied soil volume and the airflow pressure drop, the determination was performed by means of analytical solutions widely employed in related literature. While the volume was simply obtained using the dimensions of the soil portion necessary for the installation, the pressure drop (h) was estimated by means of Eq. 1. It considers the losses due to the duct wall influence over the flow in straight tubes, causing pressure to gradually decrease along its length (h_f) and the losses due to localized drops (h_s) in reason of accessories used to connect the ducts, i.e. to bifurcate the flow in the T-shaped EAHE.

$$h = h_f + \sum_{i=1}^{n} h_{s,i} \tag{1}$$

Concerning the distributed pressure drop, it was considered accordingly to the broadly used Moody-Rouse method. In turn, the localized pressure drop, it was obtained with the aid of a loss coefficient in function of the Kinect Energy of the flow and it was determined in accordance with the accessories used in the installation. For the reference installation, no localized pressure drops were considered, since it only concerns a straight duct; while for the T-shaped proposed geometry a factor of 1.8 was adopted in reason of the accessory needed to let the flow be bifurcated into the two branches, as in Barral (2018). In addition, for the distributed pressure drop the conservation of mass must be taken into consideration to set airflow velocity on the bifurcated branches analytically. That said, it was considered to be half of the prescribed velocity at the entrance of the main duct since there are two exits.

Differently from the other two parameters, EAHE thermal performance was defined from the results numerically obtained by means of ANSYS Fluent. The indicator used to gauge average performance, either for cooling or heating, was the Thermal Potential (*TP*). By its means it is possible to infer an EAHE performance based on the difference summation between the inlet (T_i^s) and outlet (T_i^e) average air temperature divided by the time. It is possible to calculate daily, monthly or annually thermal potential, varying only the time variable. For this analysis, the daily average thermal potential was considered. Its equation is given by:

$$\text{TP} = \sum_{i=1}^{n} \left(\frac{\overline{T_i^s} - \overline{T_i^e}}{t} \right) \tag{2}$$

With that, it was possible to study the geometry influence over each parameter, resulting in a best case for thermal potential, soil occupation and pressure drop. However, these parameters analysed separately cannot describe a global performance of the proposed installations. In this context, a vector analysis was proposed aiming to evaluate all parameters simultaneously by means of normalized parameters, being taken as the case value divided by the reference one. A unitary value for any normalized parameter represents the same value as for the reference installation. In this study, normalized values are presented with the sub-index *N*. A R³ space was considered with its axis being each normalized parameter. The vector module represents the global performance of the EAHE and a null module is considered an ideal installation, which can minimize the pressure drop, the volume soil occupation, and the inverse of thermal potential (since *TP* must be maximized).

3. RESULTS AND DISCUSSION

As before stated, the adopted reference installation consisted of a straight duct with only one outlet. The air temperature at the outlet was monitored, being taken its facet average hourly throughout all the year of 2016 for the proposed location (Rio Grande City: 32º2'26.4" S, 52º5'21.6" W). Figure 1 shows the annual air temperature variation at the inlet and outlet surfaces of Reference EAHE Installation, while the inlet series is the boundary condition that is the temperature prescription, while the outlet series is the product of the numerical simulation in Fluent. One can infer that the proposed behaviour of an EAHE can be checked since the temperature at the outlet of the duct is much milder than at the inlet. That said, it was possible to check its thermal potential, resulting in a highest *TP* of +6.50 °C and the lowest of -5.93 °C.

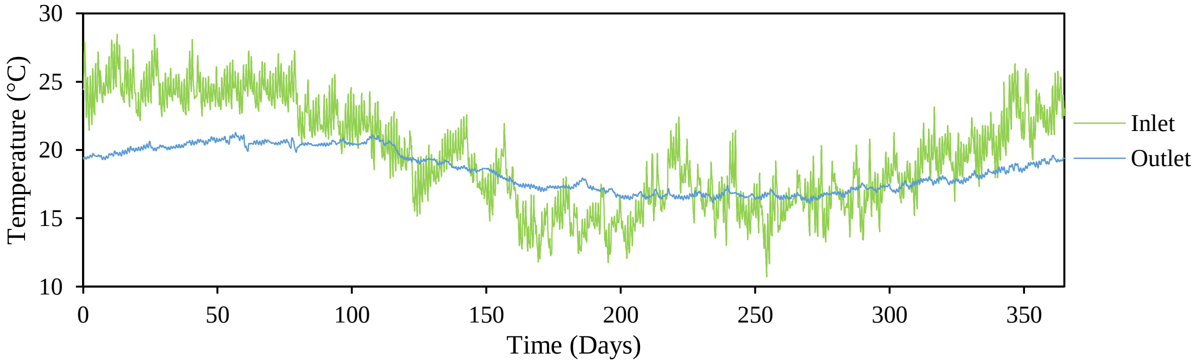

Figure 1. Annual air temperature variation at the inlet and the outlet for the Reference Installation.

Regarding the soil volume occupation, it was considered a prism of a length of 30 m, a height of 15 m and a width of 5 m, totalizing 2,250 m³ of soil needed. Concerning the pressure drop, its result was taken considering no localized pressure drop since there was not any accessory that would justify considering its loss, being the result of distributed pressure drop of 3.81 m of water column.

Concerning the T-shaped cases, the influence of the geometry was evaluated varying the ratio L_1/L_0. It started in 0.1, where the main branch is much bigger than the bifurcated one, and the cases for 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 were also tested, being the latter case the one where the very opposite occur, when the bifurcated branch is much bigger than the main one. Results are presented divided by each parameter as follows.

3.1 Thermal Potential (*TP*)

The main concern to employ thermal potential as a parameter of analysis is to enable to take into consideration the operational conditions, such as velocity and air temperature, constitutive aspects, such as thermo-physical properties of soil, and constructive design specifically over the thermal performance of the equipment. In Tab. 2 it is shown the highest and lowest daily average *TP*, being the representation of the capability of the EAHE to reduce air temperature in the outlet. These results show a better cooling performance for the proposed region when compared to the study carried out for the city of Viamão, in the same state in Brazil, by Rodrigues et al. (2019).

Table 1. Best daily average thermal potential for heating and cooling.

L_1/L_0	Heating *TP* (°C)	Cooling *TP* (°C)
0.1	+6.40	-5.83
0.5	+6.10	-5.55
1.0	+5.96	-5.43
2.0	+5.89	-5.36
3.0	+5.83	-5.30
4.0	+5.66	-5.15
5.0	+5.78	-5.25

As one can infer in Tab. 1, no T-shaped installation was able to reach a *TP* better than the Reference Installation The installation characterized by L_1/L_0 = 1.0 was able to reach almost the same *TP* values as the reference, with only 0.10 °C difference for cooling and heating. The worst case, defined by L_1/L_0 = 4.0, only had a difference of 0.84 °C. It is also possible to check that thermal potential tends to decrease as L_1/L_0 ratio increases until the last installation, where L_1/L_0 = 5.0, when *TP* had a small improvement when compared to the previous case.

Concerning the TP_N, which is presented in Fig. 2, it is possible to note that performance tends to decrease as the L_1/L_0 ratio increases, being around 0.9. Installation represented by L_1/L_0 = 5.0 shows a slight improvement in thermal behaviour when compared to the one with L_1/L_0 = 4.0.

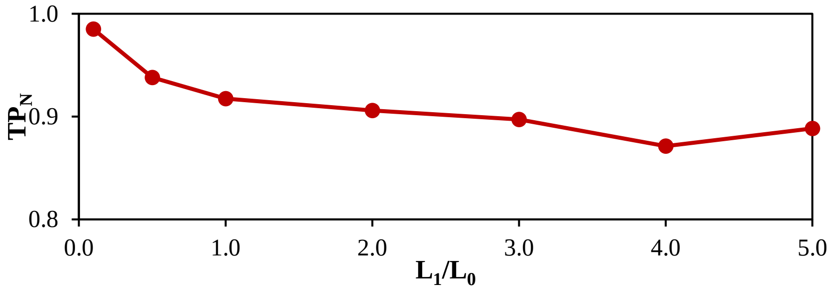

Figure 2. Geometry influence over the TP_N.

3.2 Soil Occupation (*V*)

As for the soil occupation, the values are presented in Tab. 2. Among all cases, installations defined by L_1/L_0 = 0.1, L_1/L_0 = 4.0 and L_1/L_0 = 5.0 were able to be installed in an excerpt of soil smaller than the Reference. The L_1/L_0 = 5.0 was the best geometry, among the proposed ones, to minimize soil occupation, with a *V* of 1981.50 m³, against 2173.84 m³ and 2461.45 m³ of the other two installations, respectively. The soil volume occupation is an important factor to be taken into account in EAHE designing, once it is developed to attend not only country areas or new urban buildings but also already built environments in city areas where lack of space is an obstacle to be overcome by EAHE designers.

Table 2. Soil occupation for the proposed installations.

L_1/L_0	V (m³)
IR	2250.00
0.1	2033.25
0.5	3849.75
1.0	3630.71
2.0	2919.59
3.0	2461.45
4.0	2173.84
5.0	1981.95

Normalized volumes values for the soil volume occupation can be checked in Fig. 3. Installations given by L_1/L_0 = 0.1, L_1/L_0 = 4.0 and L_1/L_0 = 5.0, as previously stated, were able to save space in their construction, resulting in improvements of soil usage by 9.63 %, 3.38 % and 11.91 %, respectively.

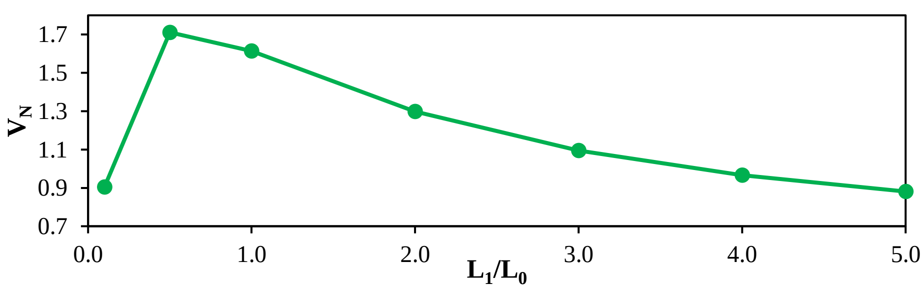

Figure 3. Geometry influence over the V_N.

3.3 Pressure Drop (*h*)

Finally, regarding the pressure drop, the values analytically calculated, by means of Eq. 1, are shown in Tab. 3. Installation defined by $L_1/L_0 = 0.1$ was the only configuration which presented a bigger pressure drop during the airflow than the Reference Installation. All the other cases, more or less, ended up reaching similar values. Hence, it is possible to notice that the L_1/L_0 degree of freedom has low influence over h. The best configuration was the one with $L_1/L_0 = 5.0$ with a h of 1.865 m of water column.

Table 3. Pressure drop for the proposed installations.

L_1/L_0	h (m)
IR	3.81
0.1	4.27
0.5	3.19
1.0	2.65
2.0	2.22
3.0	2.04
4.0	1.93
5.0	1.87

In Fig. 4 it is presented the normalized values for pressure drop. One can infer that as the ratio between lengths increases, there are no major differences. The best configuration reached a h_N of 0.49, indicating a performance 51.02 % better when compared to the Reference Installation.

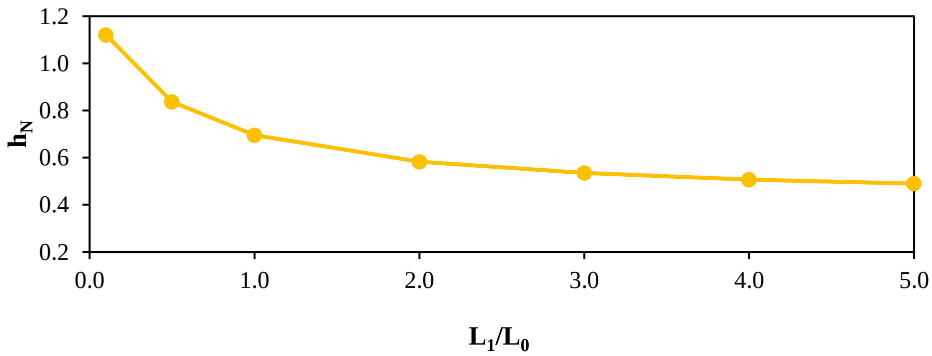

Figure 4. Geometry influence over the h_N.

3.4 Global Analysis

Until here, results indicated only the best geometries to optimize each parameter, not enabling a more in-depth analysis of all installations. With that in mind, a vector study was proposed to take all parameters, simultaneously, into consideration. This pondered performance may not represent the best when separately observed any of the criteria previously stated, however, indicates the best option when it is globally studied all cases and all performance parameters here proposed. That said, the vector analysis was carried out with the generation of a R^3 space where each axis represents a different normalized parameter. The lowest vector module was taken as the best configuration when the goals of maximizing thermal potential and minimizing pressure drop and soil occupation were set, being the origin as an ideal installation. Differently from the other parameters, the thermal potential was considered the inverse value, since the goal was to maximize, rather than minimize as the other ones. From this consideration, the inverse of thermal potential also needs to be minimized to indicate the better performance of the thermal potential. Figure 5 shows the vector module for all studied cases.

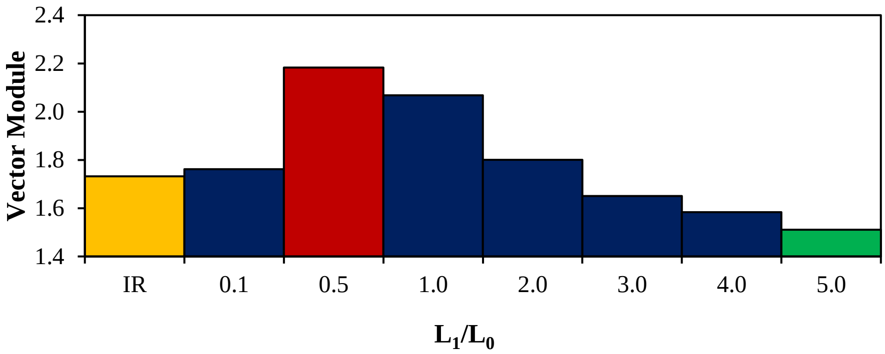

Figure 5. Vector module of each installation considering TP_N, V_N and h_N.

In Fig. 5 one can infer that installation defined by L_1/L_0 = 5.0, in green, showed itself to have the best performance among all studied ones, with a vector module of 1.51. On the other hand, L_1/L_0 = 0.5 case, in red, had the worst performance, with a module of 2.18. It is important to highlight the fact that, configurations with L_1/L_0 of 3.0, 4.0 and 5.0 had a smaller vector module than the reference installation, in spite of their worse behaviour for thermal potential.

If the best global T-shaped configuration is compared with the Reference Installation, an improvement around 25 % is reached. In addition, the usage of T-shaped installations is an even more interesting solution when it is taken into consideration the capability of the geometry to attend two different edified environments. This possibility represents a considerable gain of performance since two reference installations would be necessary to fulfil both places and with only one T-shaped EAHE it is possible to have similar thermal behaviour.

4. FINAL CONSIDERATIONS

This study aimed at the geometric evaluation of a T-shaped EAHE installed at the city of Rio Grande, in the south of Brazil. That said, its importance lays on the understanding of the best configuration possible, among 7 proposed cases, to be used in two rooms with the same buried ducts, rather than one to the Reference Installation. This analysis is important to reach the best levels of electrical energy savings with the same usage of material and reducing soil occupation, enabling it to be used on areas with a lack of space. Hence, a numerical analysis of thermal behaviour with the analytical solution of soil occupation and head loss were carried out combining Constructal Design, Exhaustive Search and computational modelling. Previous studies carried out similar approaches concerning T-shaped EAHEs, however, different soil stratification, which justified the present investigation.

To do so, a performance analysis was developed with the usage of three performance parameters. Firstly, the thermal potential showed that T-shaped geometry was able to reach similar thermal performance when compared themselves to the Reference Installation (an EAHE with straight duct). It showed that there was only 0.10 °C difference for cooling and heating for the best T-shaped configuration, L_1/L_0 = 0.1. Regarding the soil usage, L_1/L_0 = 5.0 was able to reduce in almost 12 % the space needed for the Reference Installation, being a great option for urban areas and already built environments. It was possible to infer that as the ratio between length increases soil occupation decreases. In turn, pressure drop did not present the geometry as a major factor to be considered since, despite the drops existing due to velocity decrease after the bifurcation in almost every configuration, geometry did not show itself to be decisive between the last 4 analysed cases.

In conclusion, a global analysis with normalized parameters was done intending to elect the best configuration considering all performance parameters simultaneously. The optimal installation among the ones studied was the one with L_1/L_0 = 5.0, which had a vector module of 1.51, while the one with L_1/L_0 = 0.5 had the worst performance, with a module of 2.18. The best configuration had an improvement of 12 % in relation to the Reference Installation, which had a module of 1.73.

Finally, the usage of T-shaped EAHE is highly recommended for regions with lack of space – as urban areas – and intent to attend two different places in the Rio Grande city, with the sureness of a good performance for cooling and heating purposes. Further studies can be done with the addition of other degrees of freedom to the analysis; the study different soil stratification; the evaluation of other EAHE geometric configurations; and the employment of finned tubes.

5. ACKNOWLEDGEMENTS

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