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ENHANCING EFFICIENCY AND THERMAL POTENTIAL OF EARTH-AIR HEAT EXCHANGERS WITH GALVANIZED MATERIALS AND ELLIPTICAL SHAPES

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Abstract. *This study presents simulations of a Earth-Air Heat Exchanger (EAHE), a sustainable and energy efficient alternative for air heating and cooling. The simulated system harnesses the thermal potential of the earth and consists of buried ducts in the earth through which air flows forcibly, exchanging heat with the earth, which can promote an improvement in the thermal condition of the air inside built environments. The simulations were conducted using a one-dimensional EAHE model present from the literature, and the soil temperature was numerically estimated in two dimensions. The MATLAB software was used for the processing and post-processing stages, while the GMSH software was used for geometric construction and mesh generation. The objective of this research is to perform simulations incorporating a galvanized material with an elliptical shape around the duct to enhance the thermal conductivity of the region with the aim of maximizing the thermal potential of the earth. Two different areas for the ellipse were tested, and the results demonstrate that the coupling of the galvanized material improves the system efficiency as well as the thermal potentials of the soil and EAHE, compared to simulations without any additional structure. Additionally, it was possible to perceive that larger ellipses does not always lead to improving the thermal potentials of the soil and the EAHE.*

Keywords: *Earth-Air Heat Exchanger (EAHE), Thermal potential, Efficiency, Elliptical shape, Gavanized structure.*

1. INTRODUCTION

Environmental issues are among the most discussed topics currently. Concerns about global warming affect the global population, and there is growing development in the search for alternatives to reduce the impacts caused by humans. Secondly WRI (2020), energy consumption is by far the largest source of greenhouse gas emissions caused by human activities, accounting for 73% of global emissions. The energy sector includes transportation, electricity and heat generation, buildings, manufacturing and construction, fugitive emissions, and other fuel combustion. Additionally, Li *et al.* (2019) state that energy consumption in buildings accounts for 40% of the total global primary energy consumption. Therefore, alternatives to minimize these impacts are being investigated, and one of them is the Earth-Air Heat Exchangers (EAHEs), which consist of one or more buried ducts, using the ground as a source or sink of heat (Brum, 2016). In EAHE devices, air is the fluid flowing through the ducts and exchanging heat with the surrounding soil, which is cooler than the ambient air in hot periods and warmer in cold periods. As a result, the air enters the buildings cooled in hot periods and heated in cold periods (Bisoniya, 2015). Figure 1 illustrates the operating principle of EAHE for hot days.

Numerous research studies have been conducted to ensure a better utilization of the EAHE in terms of its thermal potential and efficiency (Brum, 2016; Rodrigues *et al.*, 2015; Hermes *et al.*, 2020; Rodrigues *et al.*, 2021). Some research works that served as inspiration for this study address the conventional EAHE system with the integration of galvanized materials[1] around the duct (Hassanzadeh *et al.*, 2018; Olivera, 2022; Pastor, 2022; Ramalho *et al.*, 2022). These materials

[1] Here, galvanization is defined as the process of surrounding the duct with materials that have a higher thermal conductivity than the surrounding soil.

have a higher thermal conductivity than the surrounding soil, enabling the system to harness almost the entire thermal potential offered by the ground, thereby improving its performance.

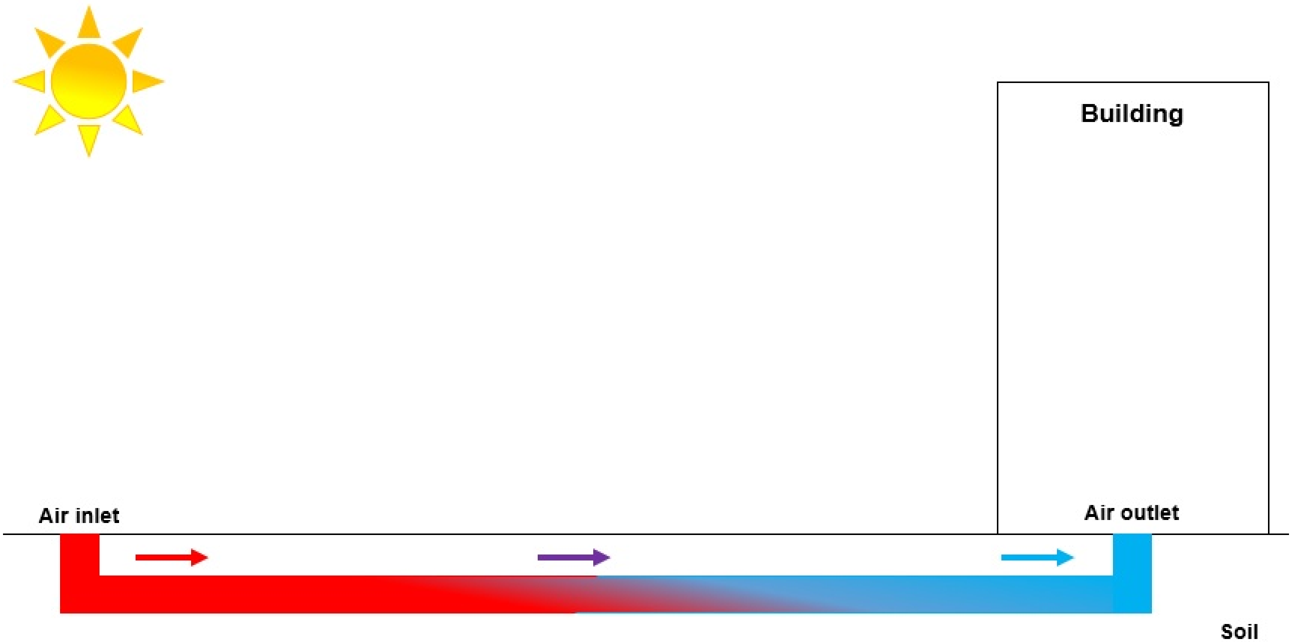

Figure 1. Operating principle of the EAHE for hot periods.

The study conducted by Hassanzadeh *et al.* (2018) addresses the use of a EAHE with different physical configurations of blocks and galvanized fins around the duct. The aim is to improve heat transfer in the soil. The researchers investigated this problem in three types of soil with different thermal conductivities. The results revealed that the coupling of bridges between the duct and the soil led to an increase in heat transfer, being more effective in soils with lower thermal conductivity.

Some studies, such as Olivera (2022), Pastor (2022) and Ramalho *et al.* (2022), were inspired by the work of Hassanzadeh *et al.* (2018) and obtained interesting results. In Pastor (2022), the thermal performance of the EAHE was evaluated through its thermal potential and efficiency. Similarly to Hassanzadeh *et al.* (2018), the author coupled a set of blocks and galvanized fins around the duct. As a result, it can be highlighted that the thermal potential of the EAHE is maximized by equipping the ducts with blocks and fins, and the annual system efficiency reaches over 90%. In Olivera (2022), in addition to studying the physical arrangement involving blocks and fins, the author conducted a parametric study, examining the possibilities of reducing the size of the duct. The results indicate that it is possible to reduce the size of the installation by almost half. In the study conducted by Ramalho *et al.* (2022), different arrangements of galvanized materials were explored around the duct, including circular and rectangular blocks with a maximum of four fins. The results revealed that the coupling of these materials increased the annual system efficiency to 95%. Furthermore, it allowed for a reduction in the size of the installation by almost 50%. Regarding the circular blocks, the authors observed a decrease in the thermal potential of the soil as the area of the circle increased. Finally, by varying the size of a rectangular structure without fins, the authors were able to increase the thermal potential of the soil by 25% and the EAHE by 60.5%.

Therefore, the objective of this study is to assess the relevance of using an elliptical galvanized material in EAHE simulations and determine the area of the material that ensures higher thermal potentials of the soil and EAHE.

2. METHODOLOGY

2.1 Constitutive and operational parameters and performance evaluation

The methodology used to perform simulations with a EAHE that includes a duct and an elliptical-shaped galvanized material attached to it will be presented. For the tests, the thermophysical properties of soil and air of Viamão city were considered, as described in Vaz *et al.* (2011). The properties of the galvanized material were the same employed by Hassanzadeh *et al.* (2018). These data are presented in Table 1. It should be noted that ρ, c_p, λ and μ represent the density, specific heat, thermal conductivity, and dynamic viscosity, respectively.

Table 1. Thermophysical properties.

	ρ **(kg/m^3)**	c_p **(J/kgK)**	λ **(W/mK)**	μ **(kg/ms)**
Soil	1800	1780	2.1	-
Galvanized materials	7800	446	52	-
Air	1.16	1010	0.0242	1.789×10^{-5}

The soil thermal potential (P_s) is characterized as the difference between the air temperature (T_a), considered here as the temperature at the duct inlet, and the soil temperature at the duct location (T_s), which can be expressed as: (Ramalho *et al.*, 2022).

$$P_s(t) = T_s(t) - T_a(t). \tag{1}$$

In addition to the thermal potential of the soil, the EAHE thermal potential (P_{EAHE}) is defined as the difference between the temperatures at the duct outlet (T_o) and the air temperature (Ramalho *et al.*, 2022), that is:

$$P_{EAHE}(t) = T_o(t) - T_a(t). \tag{2}$$

The equation provides the formula used to calculate the annual efficiency of EAHE (Hermes *et al.*, 2020; Brum, 2016):

$$\theta_a = \frac{\sqrt{\int_0^{365} P_{EAHE}(t)^2 dt}}{\sqrt{\int_0^{365} P_s(t)^2 dt}}. \tag{3}$$

2.2 Elliptical Shape

In Ramalho *et al.* (2022), the authors adopted a circular region around the duct, as depicted in Figure 2(a). This involved employing a galvanized block in the form of a disk with a radius r, centered on $x_0 = 5$ m and $z_0 = 1.6$ m, which coincides with the duct center. The objective in Ramalho *et al.* (2022) was to vary the disk area, considering the following.

- The domain area is constant and equal to $A = 150$ m^2;
- The area fraction, between the disk (A_d) and the computational domain (A) areas is given by

$$\psi = \frac{A_d}{A}100\% = \frac{\pi r^2}{1.5}\% \tag{4}$$

- The radius r was constrained to vary between 0.055 and 1.6 m. First, this ensures that the disk's area remained greater than the duct's cross-sectional one. Second, it prevents the disk from extending beyond the domain.

The trouble with that approach was that it improved the thermal efficiency θ_a (and, consequently, the EAHE thermal potential P_{EAHE}) but there was no gain in the soil thermal potential (P_s). Moreover, increasing A_d decreased the soil thermal potential, while the efficiency remained almost constant and close to 95%. The best result in Ramalho *et al.* (2022) was obtained with $\psi = 0.1\%$, giving $\theta_a = 94.9\%$, $P_s = 2.58$°C, and P_{EAHE} =2.46°C.

Given that a circle is a particular case of an ellipse and to explore the effects of different geometries, we opted to use elliptical shapes in this paper, as illustrated by Figure 2(b). Starting with a fixed area fraction ψ, we obtained the radius r of a disk following Ramalho *et al.* (2022), i.e., by using Equation 4. However, such radius is only used to determine the position of the top ellipse vertex, which has coordinates x_0 and $z_0 - r$. In contrast to the disk, the center of the ellipse does not coincide with the duct center; instead, it has coordinates x_0 and $z_0 - r + b$. Here, 'a' and 'b' represent the horizontal and vertical axis of the ellipse, respectively (see Figure 2 (b)). Lastly, we select different values of 'a' and compute 'b' ensuring that the ellipse's area A_e remains equal to the disk's area A_d, thereby maintaining the fixed value of ψ. This is expressed by

$$A_e = A_d \implies \pi ab = \pi r^2 \implies b = \frac{r^2}{a}, \tag{5}$$

In Figure 2, the duct drawing is purely illustrative since the soil temperature simulations conducted within this domain do not take its presence into account (as we see ahead in the numerical model description). For the simulations with the ellipse, we used fraction areas ψ of 1 and 2%. The meshes for the simulations were generated using the software GMSH. For the duct geometry, the parameters described in Vaz *et al.* (2011) were used, where the duct length is 25.77 m and the diameter is 0.11 m.

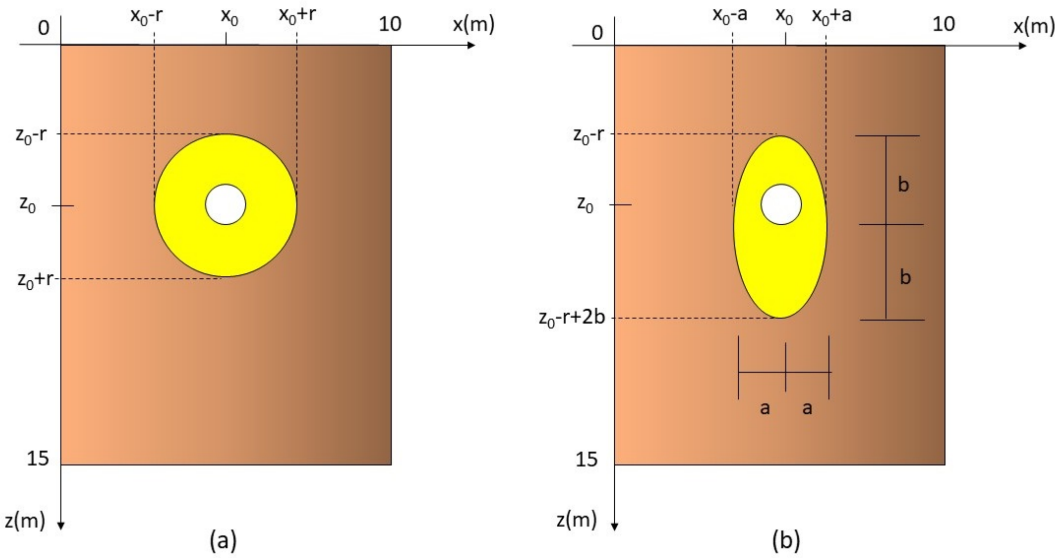

Figure 2. Cross-sectional views of the computational domain. Here, the soil, galvanized region, and duct are in brown, yellow, and white, respectively.

2.3 GAEA Model

The simulations of the EAHE used a model described in the literature (Benkert *et al.*, 1997; Ramalho *et al.*, 2022). This model is called GAEA (Graphic design of geothermal heat exchangers) and is an analytical model that allows for faster simulations, providing the temperature along the duct and estimating heat transfer coefficients for the heat flow between the air, the duct walls, and the surrounding soil.

The dimensionless parameter for the heat transfer mode ratio is given by:

$$U^* = 2\pi \frac{\lambda_s}{U_L ln\left(\frac{2z_0}{D_0} + \sqrt{(\frac{2z_0}{D_0})^2 - 1}\right)}. \tag{6}$$

where λ_s is the thermal conductivity of the soil, and z_0 and D_0 represent, respectively, the depth to the center of the duct and its diameter.

The overall heat transfer coefficient (per duct length) between the air stream and the duct walls is presented in the following equation:

$$U_L = \pi D_0 h. \tag{7}$$

The convection coefficient at the inner surface of the duct is given by:

$$h = \frac{\lambda_a N_u}{D_0}, \tag{8}$$

where λ_a represents the thermal conductivity of the air and N_u is the Nusselt number, which can be calculated using:

$$N_u = 0.0214\,(R_e^{0.8} - 100)\,P_r^{0.4}. \tag{9}$$

where Re and Pr are the Reynolds and Prandtl numbers, respectively.

In the work of Benkert *et al.* (1997), the duct of the EAHE is divided into multiple segments, allowing for iterative calculation of the temperature of the duct wall and the soil in each segment. Based on this, the temperature at the duct wall in each segment k is calculate by:

$$T_{c,w}^k = \frac{U^* T_s + T_{a,i}^k}{U^* + 1}, \tag{10}$$

where $T_{a,i}^k$ is the air temperature at the inlet of each segment and T_s is the soil temperature. Thus, it is also possible to estimate the air temperature at the outlet of the segments:

$$T_{a,o}^k = T_{a,i}^k + \frac{\Delta x\, U_L\left(T_{c,w}^k - T_{a,i}^k\right)}{\dot{m} c_{p,a}}. \tag{11}$$

where Δx is the size of each segment, $\dot{m}$ is the air flow rate, and $c_{p,a}$ is the specific heat of air.

The air temperature at the inlet of the first segment is considered to be equal to the ambient air temperature, which is known. From there, the wall and outlet temperatures of the duct are calculated in the first segment, where the outlet air temperature will be equal to the inlet air temperature of the second segment. This repetition is done until the last segment, which will have the temperature equal to the outlet temperature of the EAHE. It should be noted that the air temperature can be obtained from climatologycal bulletins and literature, while the soil temperature can be numerically estimated, as is the case in this research.

For the simulations of the GAEA model, it is necessary to know the soil temperature unaffected by the characteristics of the EAHE. Therefore, it was numerically solved in a two-dimensional manner. The temperatures, $T = T(x, z, t)$, in the soil and the block are estimated by solving the heat conservation equation, which models the problem in two dimensions (Özisik, 1993; Ramalho *et al.*, 2022):

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \nabla^2 T \qquad \text{em} \qquad \Omega \times (0, \tau_0], \tag{12}$$

where $\overline{\Omega} := [0, 10] \times [0, 15]$ of Ω is the spatial domain (see illustration in Figure 2). As boundary conditions complementing Equation (12), we have $T(x, 0, t) = T_a(t)$ on the boundary z=0 and 0 < x < 10, and adiabatic conditions on the remaining boundaries of $\overline{\Omega}$ as illustrated in Figure 2. The time period of the simulations τ_0 covers one year and two months, but the first two months are disregarded to avoid numerical influences from the initial condition given by:

$$T = T_0(z) = 20.49 - 5.66 sen(5.30 + 0.39z) e^{-0.39z} \qquad \text{em} \qquad t = 0\ s. \tag{13}$$

The equations were numerically solved using the Galerkin finite element method for spatial discretization (Hughes, 1987) and the implicit first-order Euler finite difference method for time discretization (Özisik, 1993). Since the equations are solved using finite elements, the continuity condition of heat flux between the soil and the galvanized material is absorbed in the variational formulation of the problem. Mesh independence tests were conducted, and the entire process is described in Ramalho *et al.* (2022). A time step of Δt = 1800 s (half an hour) was adopted for temporal discretization. Based on the obtained results, it was considered sufficient to use meshes with more than 2000 nodes and more than 3000 triangular elements. The simulations were performed using the MATLAB software. For more details on the adopted methodology, mesh tests, and validation of the EAHE model, we suggest referring to the article by Ramalho *et al.* (2022).

3. RESULTS

3.1 Evaluation of the use of galvanized material

Initially, simulations were conducted to compare the results obtained with and without the use of galvanized material. The simulations aimed to evaluate the impact of incorporating galvanized material on the thermal performance of the system. This comparative analysis is illustrated in Figure 3. In this test, an ellipse with an area equivalent to 1% of the computational domain was employed, with a horizontal semi-axis dimension of a = 0.2 m.

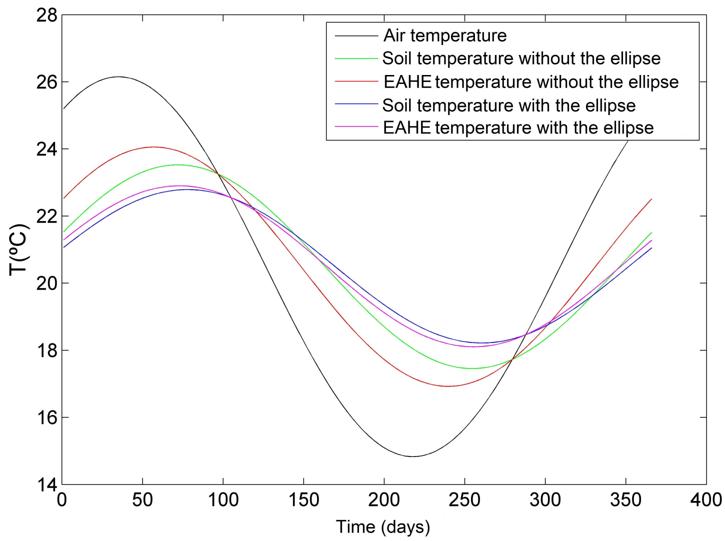

Figure 3. Comparison between the results with and without the galvanized material.

From Figure 3, an increase in the potentials of the soil and the EAHE can be observed. Without the ellipse, they were 2.59°C and 1.9°C, respectively, and increased to 3°C and 2.85°C with the ellipse, respectively.

The EAHE efficiency also increased with the coupling of the ellipse. The results without the material had an efficiency of 73%, while with the ellipse it was 95%.

The results showed superior performance due to the higher thermal conductivity of the galvanized material. This results in a greater capacity for thermal diffusion in the region surrounding the duct.

These results clearly indicate the benefits of using galvanized material, providing a significant increase in the thermal potentials of the soil and the EAHE, as well as a substantial improvement in EAHE efficiency. These findings highlight the importance of proper design, where geometric investigation plays an important role in the process, and appropriate material selection to maximization the performance of earth-air heat exchanger.

3.2 Comparison between different areas

For this study, two different areas for the ellipse were analyzed: the area corresponding to 1% of the computational domain (referred to as Area 1) and the area corresponding to 2% (Area 2). Figure 4 compares the thermal potentials of the soil for these areas, varying the measurement of the vertical semi-axis b.

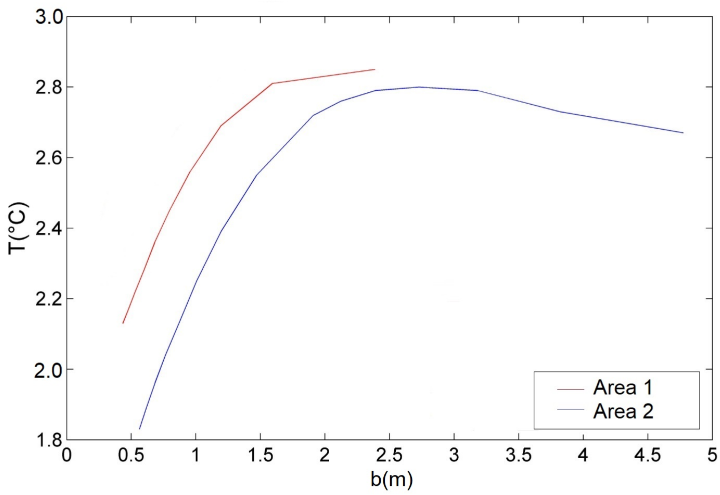

Figure 4. Comparison of the thermal potentials for the Areas 1 and 2.

It can be observed that Area 1 yielded superior results, reaching a maximum soil thermal potential of 3°C at b = 2.39 m. On the other hand, Area 2 had its maximum soil potential at b = 2.73 m, reaching 2.94°C. As for the EAHE thermal potential, we have, for Area 1, 2.85°C at b = 2.39 m, and for Area 2, 2.8°C at b = 2.73 m.

Interestingly, in the case of Area 2, it can be noticed that the potential decreased as the values of b increased. This phenomenon can be explained by the fact that as the vertical axe of the ellipse increases in size, it gets closer to the surface, becoming more influenced by local climatic conditions. Consequently, the effectiveness of heat transfer between the soil and the EAHE diminishes. This observation indicates that simply enlarging the area of the ellipse will not necessarily lead to higher levels of thermal potential.

These findings underscore the importance of carefully considering the dimensions and proportions of the elliptical area to maximize the performance of EAHE. Balancing the size and position of the ellipse is crucial to achieve the desired thermal efficiency and maximize heat transfer.

4. CONCLUSIONS

This study conducted simulations of a EAHE considering the climatic and geotechnical characteristics of Viamão city, in Rio Grande do Sul, Brazil. In addition to the EAHE traditional, a galvanized elliptical structure was incorporated to increase thermal conductivity in the region surrounding the duct, aiming to maximize the earth thermal potential. Simulations were performed with two different areas for the ellipse to determine which area provides the superior thermal potential.

The results of this study have demonstrated that the inclusion of galvanized material significantly improved the efficiency of the system and the thermal potentials of the soil and the EAHE. Moreover, a comparative analysis was performed between two areas of the ellipse, namely Area 1 and Area 2, with Area 1 yielding superior outcomes. It was observed that increasing the vertical length of the ellipse does not necessarily result in higher thermal potentials of the soil and the EAHE. This can be attributed to the fact that such modification brings the structure closer to the earth surface, making it more susceptible to the influence of surface climatic conditions.

As future research perspectives, simulations can be conducted with different areas for the ellipse and explore alternative shapes of galvanized materials.

5. ACKNOWLEDGEMENTS

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