Analysis of the soil domain size for simulations of ground-air heat exchangers.

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Abstract. Based on the fact that climatization systems are responsible for a large portion of electricity consumption worldwide, the present work was dedicated to analyzing the domain soil size required to simulate a Ground-Air Heat Exchanger (GAHE): a passive air conditioning system that uses the soil as a heat exchanger, heating or cooling buildings according to climatic conditions. In transient simulations, the computational time used for the analysis depends directly on the size of the domain imposed on the soil. However, if the dimensions of this domain are not adequate, large discrepancies can occur in the results obtained. To obtain the optimized dimensions of this domain, simulations using CFD (Computational Fluid Dynamics) were performed. First, the best time step was verified. After, the domain of soil and finally the installation depth of the exchanger were obtained, all under the same external condition. Sinusoidal equations representing the climatic conditions of the city of Ponta Grossa - PR were used in this study. The optimized values obtained were 8 hours of the time step, 4 m of soil domain width, and 2.5 m of pipe depth.

Keywords: Ground-Air Heat Exchanger, Passive Air Conditioning, Computational Fluid Dynamics.

1 Introduction

It is known that due to the great thermal inertia of the soil, its temperature at certain depths remains practically constant throughout the year. In this context, a Ground-Air Heat Exchanger (GAHE) can be used to heat or cool the air in a building, depending on its internal temperature. This exchanger, which has a simple constructive form, generally formed by PVC tubes, only needs a fan necessary for air circulation. It is an air heating or cooling system through underground ducts, where the air is ventilated and heat is exchanged with the ground through the duct walls. Thus, this process is called passive air conditioning, as it requires much less electrical energy compared to active air conditioning systems. These characteristics show the great potential for using this heat exchanger since the building sector is one of the most energy-consuming in Brazil (Plano Nacional de Eficiência Energética [1]). Many authors describe the GAHE as an efficient way to reduce costs for air conditioning. Vaz [2] conducted an experimental and numerical study of a GAHE. The results showed that the heat exchanger used for heating reached up to a 3K increase in temperature, with the potential to reach 8K. For cooling, the potential would reach up to 4K. The study by Abadie *et al.* [3], it was numerically analyzed the heating and cooling potential of buried pipes in three cities in southern Brazil: Porto Alegre, Curitiba, and Florianópolis. The study showed that different climatic conditions interfere in the performance of these heat exchangers, and showed that solar radiation must be considered in the calculations, with Curitiba having obtained the best results.

According to Bansal *et al.* [4], after simulations in transient regime using a CFD (Computational fluid dynamics) software, they concluded that the greater the thermal conductivity of the soil contributes to better performance of a soil-air heat exchanger. The authors also observed that the thermal performance of a heat exchanger decreases with continuous use for long periods. To quantify this decrease, the authors used the "Derating Factor", obtained by comparing the computational results of the heat exchanger in a steady-state with a transient one. Among the variables that this factor considers, the airflow and the pipe diameter stood out.

In J. Mathur *et al.* [5] the authors numerically studied the performance of a simple GAHE and one with an evaporative cooler, over one year, applied to the conditions of Ajmer, India. They concluded that it was possible to guarantee thermal comfort during 25.6% of the year using a simple exchanger, and with the use of an evaporative cooler this value rises to 34.16%. Rakesh Kumar [6] performed two analyses, using what he called a deterministic model and an intelligent model (neural network), to assess the cooling and heating potential of a ground-air heat exchanger. The author found that the intelligent model, in addition to needing fewer input data, presented greater accuracy compared to air outlet temperature values in experimental studies. The error presented by the deterministic model was ±2.6% while for the intelligent model was ±5.3%. Guohui Gan [7] performed a three-dimensional computational study to simulate the performance of a GAHE for air heating, analyzing the transfer of heat and moisture in the soil. The study showed that the heat transfer rate decreases along the length of the heat exchanger in a non-linear behavior. In addition, it was also found that using an analytical expression for the annual variation in soil temperature, ignoring the interactions between the heat exchanger and the atmosphere, would overestimate the thermal performance of the heat exchanger.

Hermes *et al.* [8] carried out a numerical study to analyze the thermal behavior of a GAHE, using soil properties from the Federal University of Rio Grande do Sul – UFRGS region. They obtained that the optimized depth for installing the heat exchanger should be 2 meters, for this region.

As observed in works that used transient numerical simulations, the computational time needed for the analysis depends directly on the size of the domain used for the soil. However, in cases where the dimensions of this domain are not adequate, large discrepancies may occur in the results obtained. Thus, to obtain the optimized dimensions of the domain, simulations were performed using the Ansys/Fluent software. First, the sensitivity of the results concerning the time step was verified. Then, the sensitivity about the size of the soil domain and, finally, to the depth of installation of the exchanger was verified. Sinusoidal equations representing the climatic conditions of the city of Ponta Grossa - PR were used in this study.

2 Methodology

To perform the simulations, the Ansys/Fluent® software version 18.1 was used. The optimized lengths of the soil and pipe (Figure 1) were obtained in Vasconcelos [9], which are listed in Table 1:

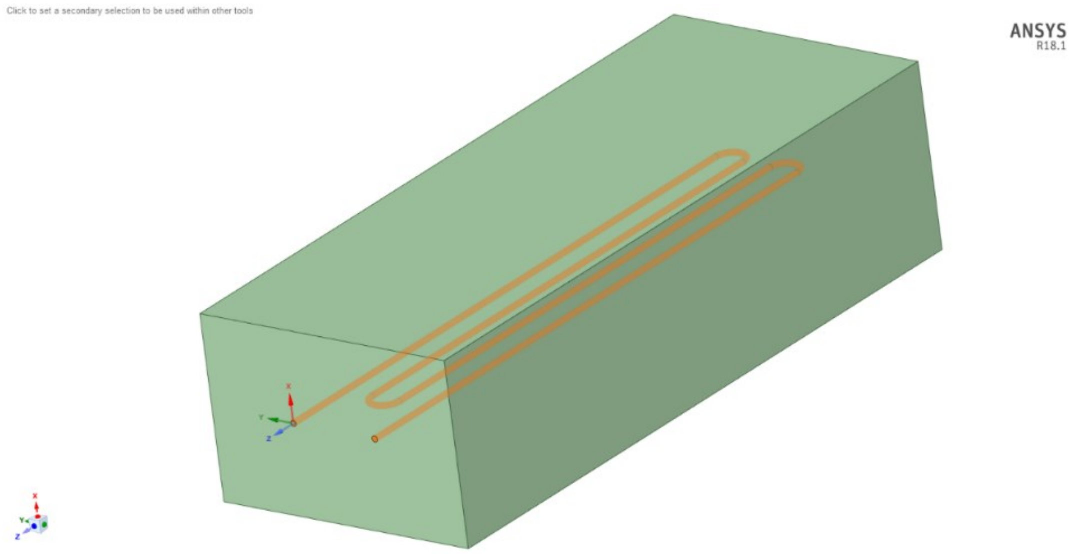

Figure 1. Ground-air heat exchanger geometry

Table 1. Dimensions of the Ground-air heat exchanger

Parameter	Dimension (meters)
Pipe diameter	0,1
Pipe length	40
Number of steps	4
Distance between the centers of the tubes	0,5
Length of the soil domain	11,5

The mesh was obtained based on the verification carried out by Vasconcellos [9], which was based on Misra et al. [10]. It was made by dividing the edge of the circumferences of the pipes into 20 parts. Figure 2 shows the resulting unstructured frontal mesh of the 3D model used in the simulations.

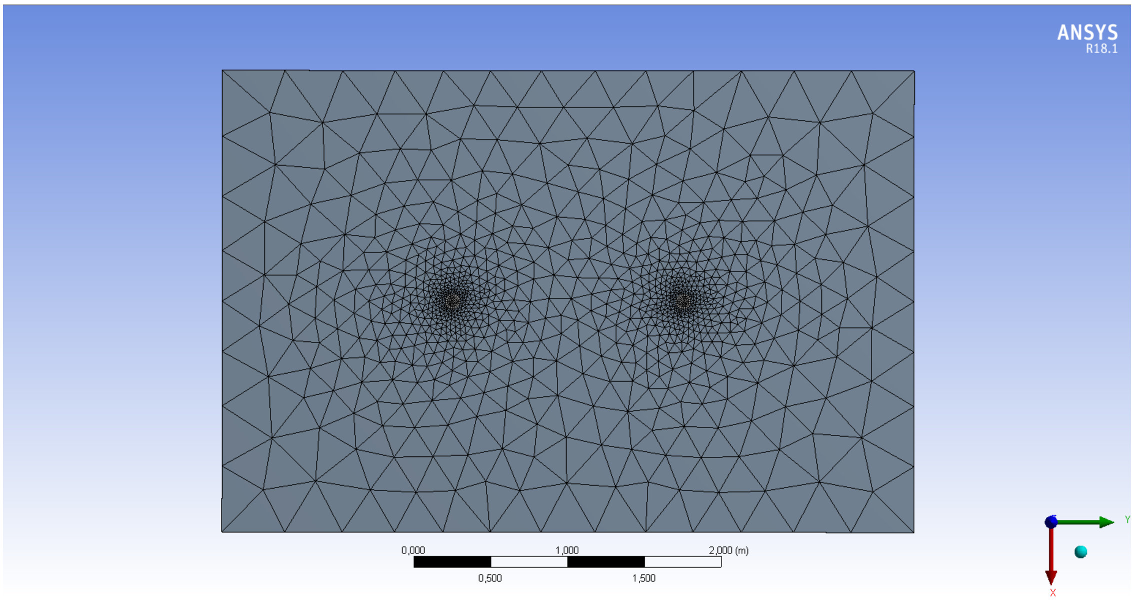

Figure 2. Generated mesh used for simulations

In this work, the soil and pipe lengths were kept constant to ensure the good performance of the exchanger. To verify the domain dimensions and installation depth of the exchanger, the energy equation and the k-ϵ turbulence model were used, both of which are standard in the program. The verified dimensions correspond to the distance between the pipe and the lateral and inferior surfaces of the soil domain, highlighted as H in Figure 3, obtained in Vasconcellos [9]. The soil properties referring to the Sandy Silt were obtained in Santos and Mendes [11]. The dry basis properties of soil are expressed in Table 2.

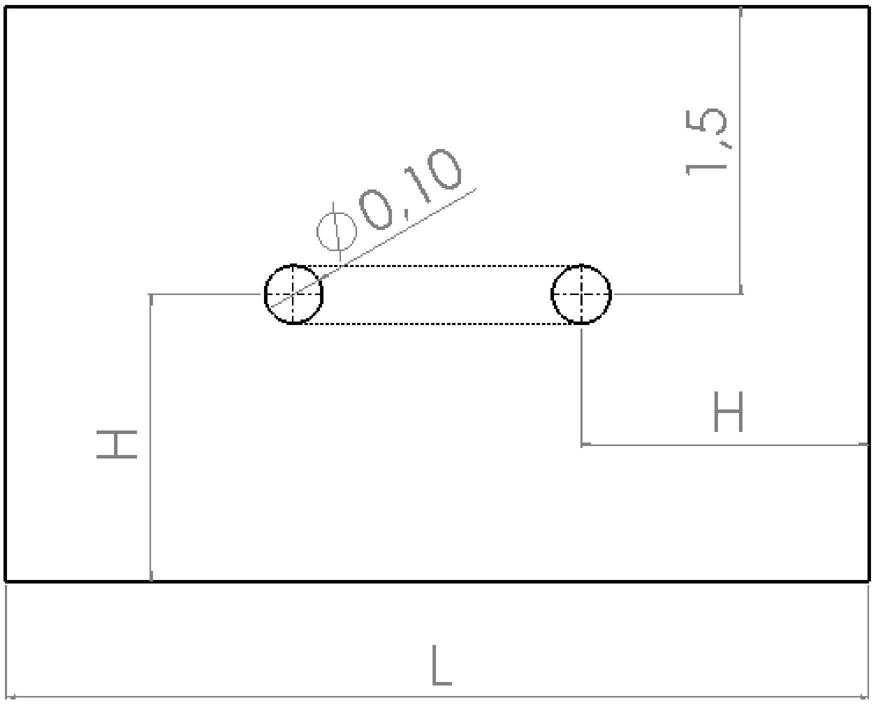

Figure 3. *H* dimension (m) verified in the simulations.

Table 2. Sandy Silt soil properties

Specific mass (kg/m³)	Specific heat (J/kg.K)	Thermal Conductivity (W/m.K)
1280	880	0.3

For the upper surface of the soil, a convection coefficient of 10 W/m²K was considered as boundary conditions, and a UDF (User Defined Function) was used to implement two sinusoidal equations, obtained in Santos and Mendes [12], to represent the climatic conditions (temperature and total solar radiation) of Ponta Grossa-PR city:

$$Text = 293 + 5\sin(\pi + \frac{\pi t}{31536000}) + 5\sin(\pi + \frac{\pi t}{43200}). \tag{1}$$

$$qrad = 600 + 200\sin(\pi + \frac{\pi t}{31536000})\sin(\frac{3\pi}{2} + \frac{\pi t}{43200}). \tag{2}$$

As the value of solar radiation (direct and diffuse) was imposed throughout the year, not counting the effects of cloudiness and losses from longwave radiation, soil temperatures were overestimated. In this case, the heat exchanger only performs the heating of the air with the initial conditions imposed in the analysis. The lateral and inferior surfaces of the soil domain were considered adiabatic. For the air domain, an inlet velocity of 2.5 m/s and a temperature of 308K were adopted in the pipe, based on the building condition in the summer. For the outlet parameters, a zero manometric pressure was considered. Initial soil and air temperatures were 292.5K.

A computer containing an Intel® Core™ i5-9400F processor, 16 GB memory (RAM), 3GB (VRAM) GTX 1060 video card, and 64-bit operating system was utilized for the simulations.

3 Results

Transient simulations for 1 year, *H* dimension of 1.5 meters, and installation depth of 1.5 meters, with time steps of 2, 4, 6, 8, and 12 hours were performed. The mesh for this geometry was composed of 2907217 elements. Computational times ranged between 5 and 30 hours. Figure 4 shows the daily average temperatures at the heat exchanger outlet.

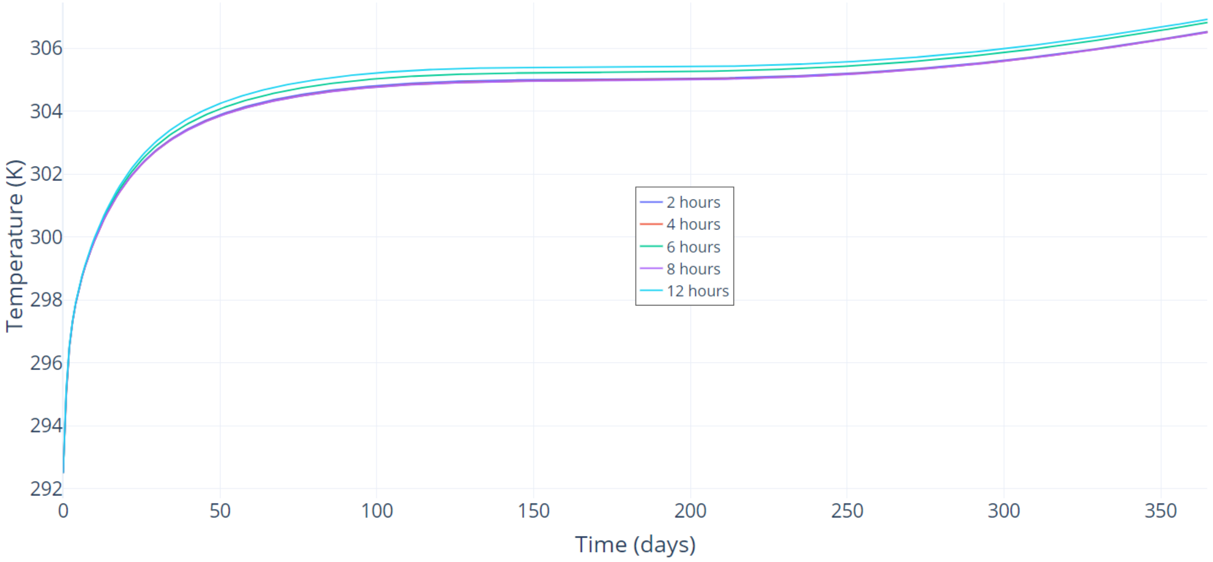

Figure 4. Daily average temperatures at the heat exchanger outlet varying the time step.

Due to the similarity between the obtained values, it was possible to verify that the 8-hour time step presents a good behavior concerning the precision of the results and computational time necessary for the simulations.

After determining the time step, simulations were carried out by varying the size of the soil domain (*H* dimension), for values of 1.5 m, 2 m, 4 m, and 6 m, for a simulation period of 4 years. Computational times ranged between 24 and 30 hours. Figure 5 shows the daily average air temperature at the pipe outlet, and Table 3 shows the number of elements that compose the mesh for each soil domain value.

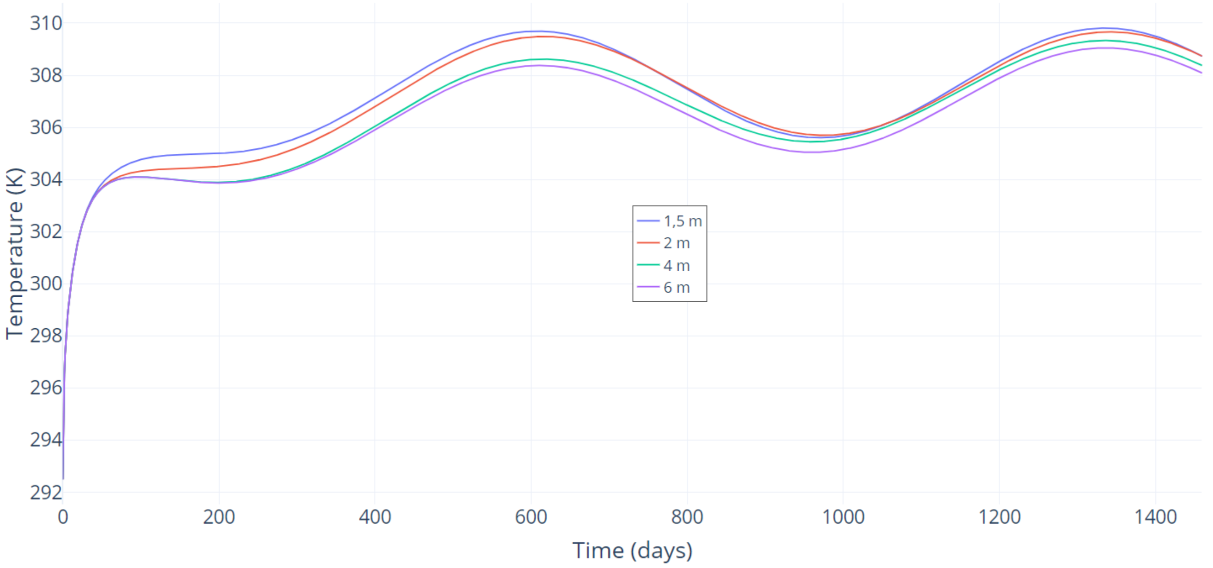

Figure 5. Daily average temperatures at the heat exchanger outlet varying the *H* dimension.

Table 3. Number of elements that compose the mesh for each soil domain value

Domain value (*H* dimension)	Number of elements
1.5 m	2907217
2 m	2829193
4 m	2975675
6 m	3012222

From the results obtained, the *H* dimension of 4 meters presented good results about the computational time necessary for the simulation.

After checking the best time step (8 hours) and domain dimensions ($H = 4$ m), simulations were performed varying the installation depth of the heat exchanger ducts, between 1.5 m, 2 m, 2.5 m, and 3 m. Computational times ranged between 24 and 30 hours. Again, heat exchanger outlet air temperatures results were obtained, as seen in Figure 6, and Table 4 shows the number of elements that compose the mesh for each ground depth value.

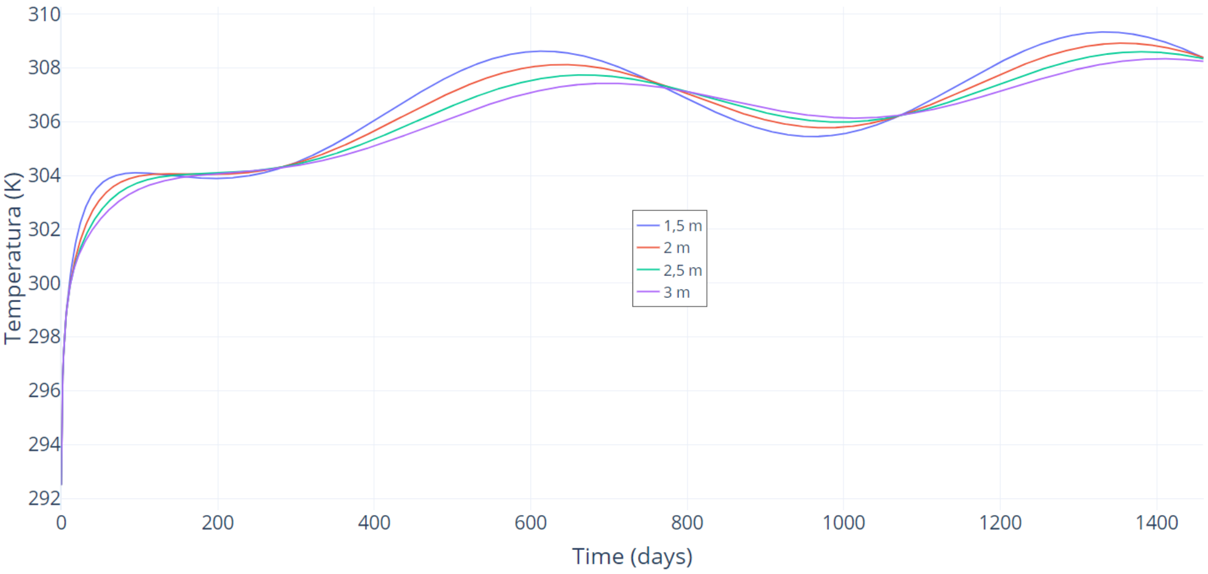

Figure 6. Daily average temperatures at the heat exchanger outlet varying the ground depth

Table 4. Number of elements that compose the mesh for each ground depth value

Ground depth value	Number of elements
1,5 m	2907217
2 m	2842848
2.5 m	2916923
3 m	2959187

The results showed that installing a depth of 2.5 meters is sufficient to obtain good performance. To verify if the domain dimensions are enough not to saturate the soil's thermal capacity, a simulation was carried out with the optimized values obtained (4 m of soil domain and 2.5 m of ground depth) for 8 years, whose computational time was 54 hours. The number of elements that compose the mesh was 2916923.

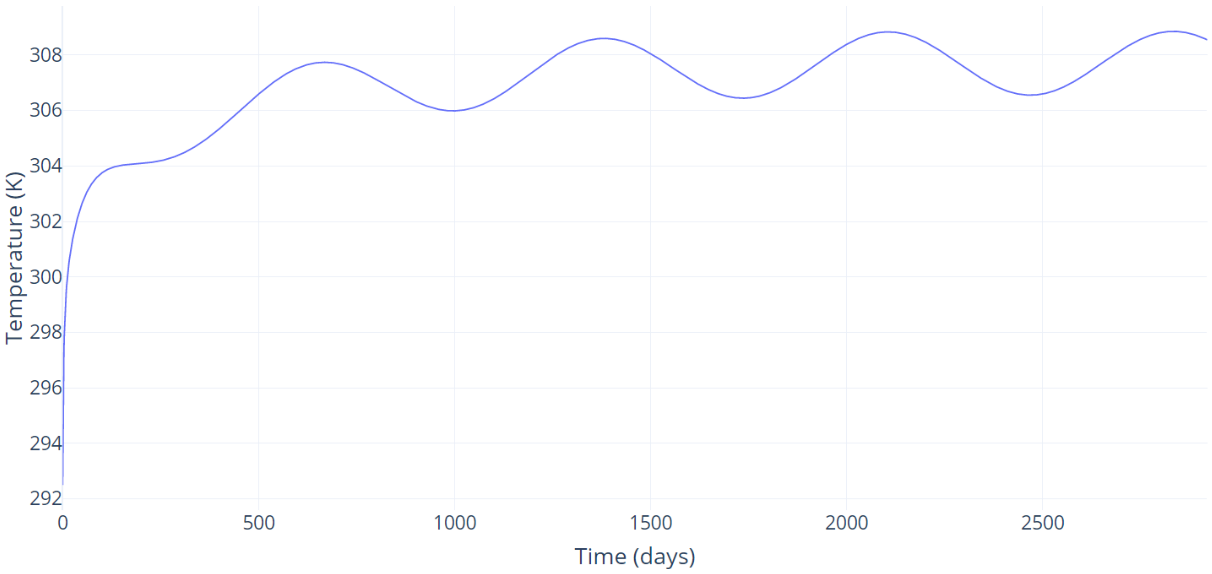

Figure 7. Average daily air outlet temperature at the GAHE for a long simulation period

From the results observed in Figure 7, periodicity in the values was obtained, indicating that the H dimension of 4 m is sufficient for preventing saturation of the soil thermal capacity.

4 Conclusion

Numerical transient simulations of a ground-to-air heat exchanger can require a lot of computational time. This fact is mainly due to the dimensions of the soil domain and the time step used in the simulations. Thus, several simulations were performed to verify the sensitivity of the results about these parameters. As optimized values, an *H* dimension of 4 meters and a time step of 8 hours were obtained. It is noteworthy that this large time step was possible due to the sinusoidal functions used to represent the climatic conditions. Another important factor that directly influences the efficiency of the exchanger is the installation depth in relation to the ground surface.

The results showed that a depth of 2.5 m of ground would be adequate to guarantee the performance of the equipment. To impose more realistic weather conditions, the cloud cover model will be considered for the next works and the sky temperature will be taken into account for the calculation of heat loss by longwave radiation.

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