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VALIDATION AND NUMERICAL ANALYSIS OF AN EARTH-AIR HEAT EXCHANGER (EAHE) IN STEADY-STATE

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Abstract. *The increasing demand for electricity is faced with the limitation of existing natural resources, with this, it becomes inevitable that the social sectors are concerned with developing their activities in a more efficient and sustainable way, with less impact on the environment. In addition, considering human thermal comfort inside buildings, linked to energy savings, studies have been realized, as well as less degrading practices or low energy consumption being adopted more frequently, to control the temperature in these environments with efficiency energetic. In order to reduce energy consumption in buildings, due to the use of heating, ventilation, and air conditioning (HVAC) equipment, the use of the ground as a source of energy is analyzed. Due to its high thermal capacity, the soil acts as a thermal reservoir, heating or cooling the air inside the buildings, depending on the weather conditions applied. The thermal performance of an Earth-Air Heat Exchanger (EAHE) is analyzed experimentally, the EAHE was installed at (Federal Technological University of Paraná -UTFPR, Ponta Grossa-PR) at a depth of 1,5 m, with 8 steps using 100 mm diameter white PVC tubes for air passage, and the EAHE has 44,5 m long. Furthermore, the thermal performance of an EAHE is numerically investigated using the Computational Fluid Dynamics (CFD) tool. For this, a CFD model has been developed in Ansys-Fluent software that is validated with experimental data. The CFD analysis has been performed using a three-dimensional numerical model in steady-state, and the turbulence has been modeled using k-ε turbulence model. Further, the different inlet velocities were analyzed in the thermal performance of an EAHE.*

Keywords: *Earth-Air Heat Exchangers (EAHE), Passive Cooling, Computational Fluid Dynamics (CFD).*

1. INTRODUCTION

The growing increase in electricity demand in line with sustainable development is faced with the limitation of existing natural resources. With this, it has become essential that the social sectors are concerned with developing their activities in a more efficient and sustainable way, with less impact on the environment (Altoé; Oliveira Filho and Carlo, 2012; Rupp and Ghisi, 2013; Fazlikhani; Goudarzi and Solgi, 2017). In this context, many researchers have been researching new climate control systems for buildings with greater energy efficiency. Among these systems, there is the Earth-Air Heat Exchanger (EAHE), which is an air conditioning system, used to reduce the use of conventional air conditioners and, consequently, reduce the electricity consumption of buildings. The EAHE is usually formed by a pipe or more underground pipes, and uses the thermal inertia of the soil as a source or heat sink, because the soil has high thermal inertia that keeps its temperature approximately constant at certain depths (Misra et al., 2013; Benhammou; Draoui and Hamouda, 2017).

EAHE can be used for heating and cooling buildings, as the ground temperature in winter is higher, and lower in summer than in the external environment (Mathur et al., 2015). The EAHE uses the external air of the environment or the internal air of the buildings, in this way the air flows through the underground pipes carrying out heat exchanges with the ground until it reaches the environment of the building. To understand and analyze the thermal performance of EAHE, mathematical, numerical, and experimental models have been developed.

Qi et al. (2021) developed EAHE models in ANSYS FLUENT 19.2 software, and numerically analyzed different configurations for EAHE, and found that U-type and L-type EAHEs had superior airflows and thermal uniformity than Z-type. Zajch et al. (2021) studied the seasonal sensitivity to atmospheric and ground surface temperature changes of an EAHE in Canadian climates. And they observed that EAHEs are susceptible to soil temperature variation in summer if the system is shallow (0.5m). Pakari and Ghani (2021) experimentally and numerically analyzed an EAHE in Doha, Qatar with ANSYS FLUENT 18.0. Then, they found that by increasing the thermal conductivity of the soil from 1 to 5 W m^{-1} K^{-1}, the outlet temperature decreased by about 4,4 °C. Lapertot et al. (2021) numerically studied, using a multi-criteria decision-making method, the optimization of EAHE in France, and obtained results that EAHE should be buried at 2,59 m, have a radius of 0,26 m, and a length of 94,3 m. Domingues et al. (2021) numerically studied from a 1D model the thermal performance of a EAHE in the Rio Grande do Sul (Brazil) and noted that the highest thermal performance of the EAHE was with a length of 50 m, a diameter of 0,11 m and a velocity of 3,3 m/s. Therefore, in this work, experimental work is realized, and a numerical CFD model has been developed for analyzing an EAHE in steady-state.

2. EXPERIMENTAL E NUMERICAL PROCEDURE

In this work, experimental analysis has been realized of an EAHE installed at the Federal Technological University of Paraná-Ponta Grossa-PR. In addition, numerical validation is done, and a steady-state numerical CFD model for EAHE analysis is proposed.

2.1 Experimental Procedure

The experimental apparatus was built at the Federal Technological University of Paraná (UTFPR), Ponta Grossa-PR. Figure 1 (a, b) shows the piping and sensor distribution along the EAHE.

Figure 1. The piping and sensor distribution along the EAHE

The 8-step EAHE was developed with 100 mm diameter polyvinyl chloride (PVC) tubes, in a serpentine format. Therefore, the EAHE steps have the following dimensions: 1st step of the EAHE has a length of 4,85 m, from the 2nd step to the 7th step has a length of 5,15 m, and finally the 8th step has a length of 5.5 m. In addition, each step was separated by a distance of 0,5 m between them. The EAHE is installed at a depth of 1,5 m from the surface, totaling 44.75 m of piping. Air is supplied to the EAHE by an AeroMack model cre-03 radial fan with a power of 2 hp and a maximum flow of 3,2 m³/min. The air inlet velocity in the EAHE, measured by a digital anemometer, was 0,774 m/s.

To measure air temperatures along the EAHE, 12 K-type thermocouples (model 6675) with an uncertainty of ± 0,25 K were used. The first five sensors are positioned in the 1st step of the EAHE, and from the 2nd step to the 8th step, the sensors are installed at the end of each step. The Figure 2 shows the data acquisition apparatus, it is composed of a Keysight™ DAQ970 data acquisition system (C), two Keysight™ multiplexers (B), and an Intel™ Core i7-7600 microcomputer at 3.5 GHz and 16 GB of ram (A). For the analysis of the EAHE, hourly air temperature data were collected along the EAHE, on 01/22/2022. In this way, the average air temperature of each sensor of the EAHE was calculated.

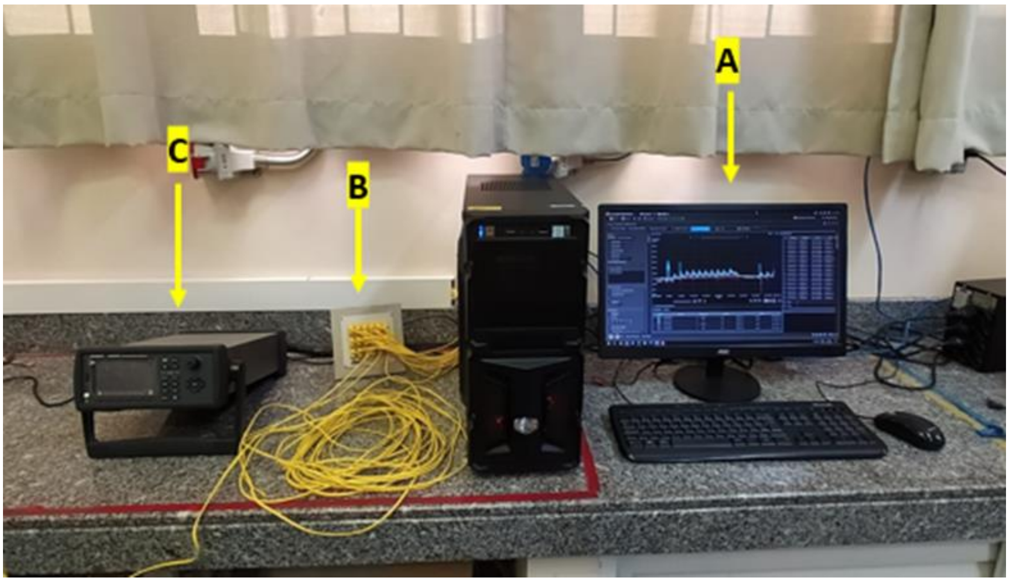

Figure 2. Data acquisition system

2.2 Numerical Procedure

A three-dimensional model in steady-state conditions has been developed to validate the experimental EAHE system. Too, the effects of different inlet velocities on the thermal performance of the EAHE have been verified. CFD simulations were performed using the Ansys Fluent 2020 software. Geometric modeling has been done using the Ansys Desing Modeler software and the 3-D mesh has been prepared through the Ansys Meshing.

2.1.1 EAHE model validation

The EAHE model of this work was developed based on the experimental EAHE, so the air volume was elaborated with 8 steps (Fig. 3). Thus, the 1st and 8th steps are 5,65 m long, and the 2nd to 7th steps are 5,15 m long, in addition, all steps are separated by a distance of 0.5 m. For the soil volume, the soil surfaces were developed so that they were at a distance of 0,5 m from the center of the air, so the vertical edges of the soil have 1 m and the horizontal edges 6,15 m.

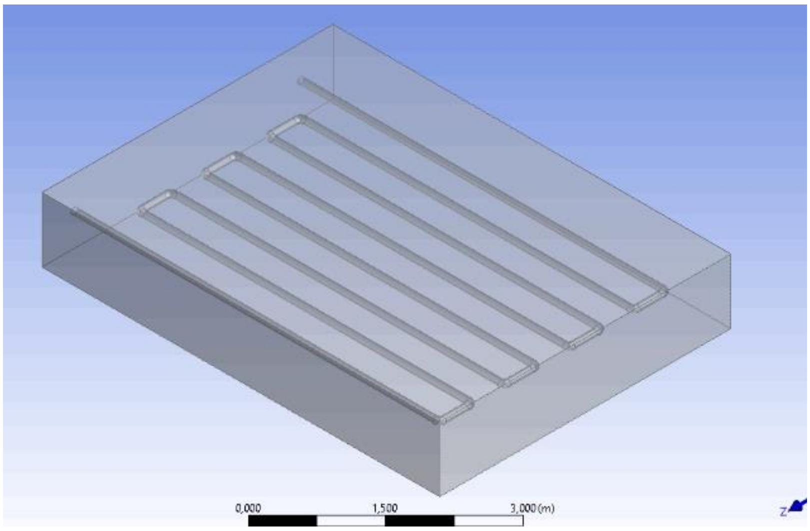

Figure 3. Numerical model geometry

For model validation and a mesh sensitivity analysis, three hybrid meshes were developed as shown in the Figure 4. Being a coarse with 3.794.940 elements, an medium with 4.609.993 elements and a fine with 5.131.309 elements.

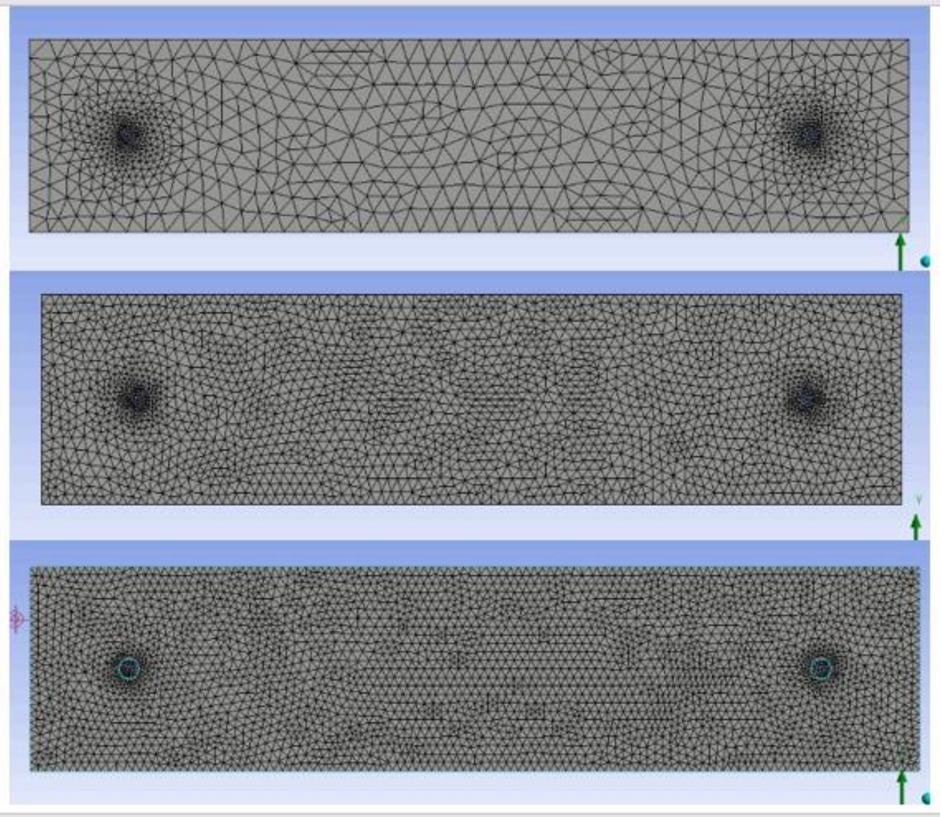

Figure 4. Coarse, medium, and fine meshes

Therefore, a steady-state CFD model was developed. In which, the air was considered incompressible, and the soil was treated as homogeneous. The thermal properties of the air and the soil were assumed constant (Tab. 1) for the analysis of the air flow inside the EAHE. In addition, the standard k-ε turbulence model was used. The convergence criteria adopted for the continuity equations, momentum and k-ε turbulence model were 10^{-3}, and for the energy equation, 10^{-6}.

Table 1. Thermal properties of the air and the soil

Parameters	Values
Air density	1,225 kg m^{-3}
Air thermal conductivity	0,0242 W m^{-1} K^{-1}
Air specific heat	1006,43 J kg^{-1} K^{-1}
Soil density	1650 kg m^{-3}
Soil specific heat	880 J kg^{-1} K^{-1}
Soil thermal conductivity	1,68 W m^{-1} K^{-1}

Boundary conditions for the CFD model validation:
- Air inlet: 0,774 m/s and 299 K have been utilized for inlet velocity and inlet temperature, respectively.
- Top soil temperature: a constant temperature of 297 K was considered.
- Lateral soil temperatures: a constant temperature of 296,7 K was considered.
- Bottom soil temperature: a constant temperature of 296,4 K was considered.
- Air outlet: pressure of 0 Pa has been used.

For the analysis of the thermal performance of the EAHE with different velocities, the only altered boundary condition of the validation model was the entrance velocity, which in this case were analyzed at 1, 3, and 5 m/s.

3. RESULTS AND DISCUSSIONS

In this section, the experimental and numerical values of the air temperature distribution along the EAHE are presented.

3.1 Model validation

Firstly, the EAHE CFD model was validated through the experimental data of the EAHE installed in Ponta Grossa/PR. For this, the daily average of air temperatures on the date of 01/22/2022 along the EAHE was compared with those of the CFD model. Figure 5 shows the air temperature distribution of the experimental data and the numerical model, for the different meshes analyzed. Therefore, it was found that the largest temperature difference between the experimental data and the numerical model in steady state was 0.3 K. Thus, the numerical model developed is valid for the analysis of EAHE in steady state. Furthermore, it can be noted that the temperatures of the three meshes were basically the same, with no significant differences. Thus, for further analyses, the coarsest mesh was used, in order to reduce computational time.

Thus, the cooling was shown throughout the EAHE, evidence that the inlet temperature was considerably higher than the outlet temperature, thus allowing the idea of the exchanger to be considered for projects that seek to reduce the internal temperature of the environments.

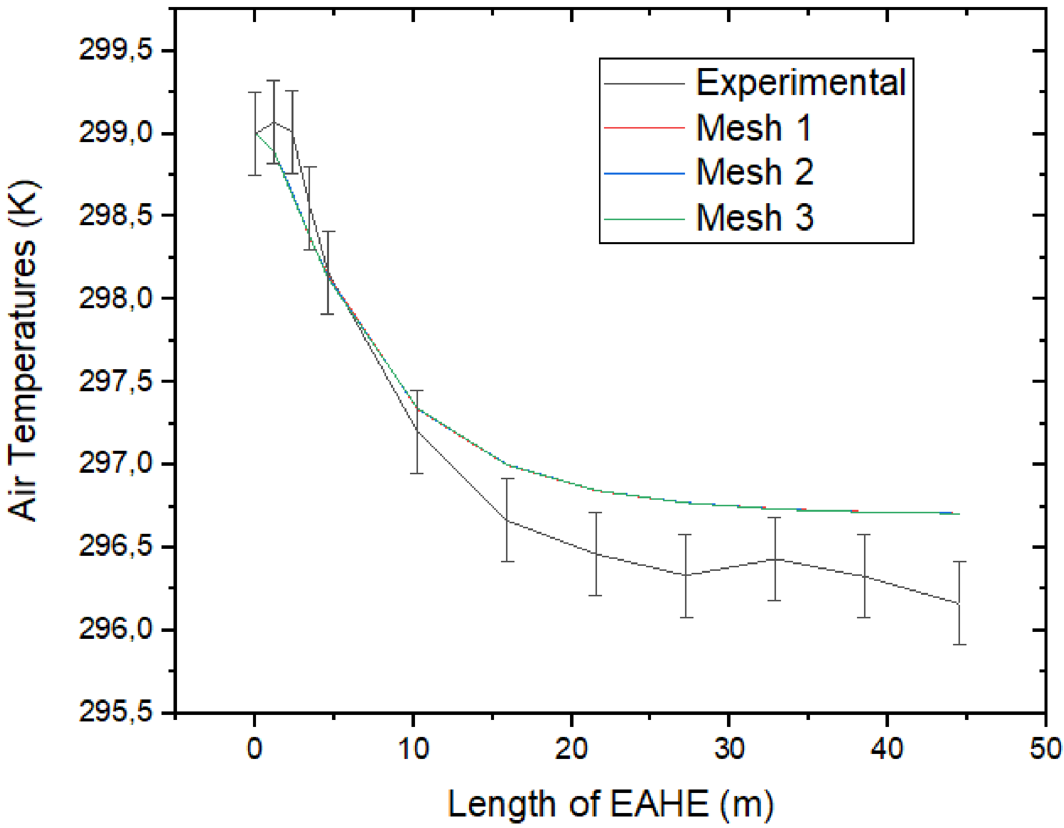

Figure 5. Temperatures along the EAHE

3.2 Analysis of inlet velocities on EAHE

Figure 6 shows the air temperature along the EAHE for each analyzed velocity of 1, 3, and 5 m/s. Thus, it was found that as the inlet air velocity increases, the air temperature along the EAHE also increases. Therefore, as the air temperature increases, the thermal performance of the EAHE is reduced, therefore, it is valid for the EAHE to operate with lower air inlet velocities so that its thermal performance is higher. As shown in Figure 6, the outlet temperature for the 1 m/s speed was 296.7 K, and the outlet temperature for the 5 m/s speed was 297.1 K, with an increase of 0.4 K.

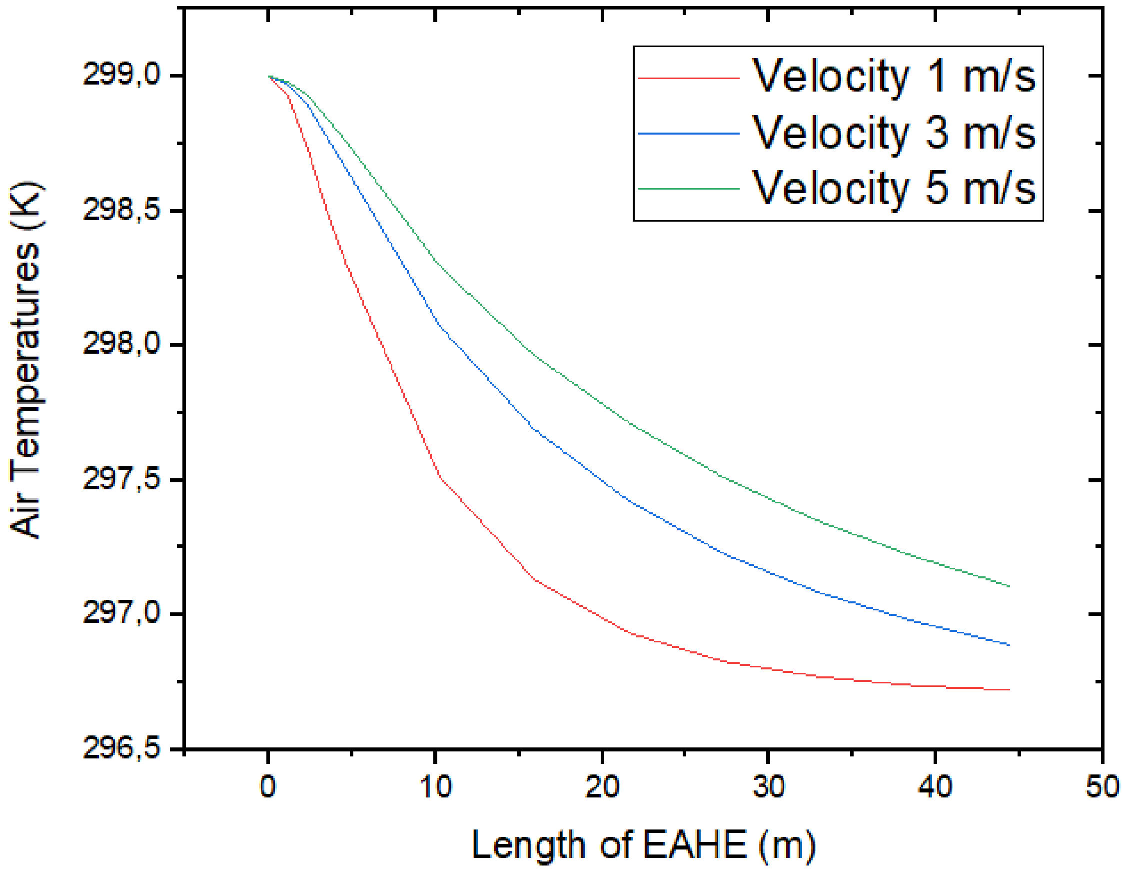

Figure 6. Temperatures along the EAHE

4. CONCLUSIONS

The thermal performance of an EAHE was analyzed experimentally and numerically. Thus, the CFD numerical model developed proved to be efficient for EAHE analysis in a steady state. Furthermore, the thermal performance of EAHE with different inlet velocities was analyzed, and it has been verified that the thermal performance of EAHE is decreased with increasing velocity.

From the results obtained numerically, it was possible to solidly conclude that the heat exchanger has a great possibility of viability for the city of Ponta Grossa and although only results for the summer are presented, the data already show to be quite promising.

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