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THERMAL PERFORMANCE AND GEOMETRIC OPTIMIZATION OF AN EARTH-PIPE-AIR HEAT EXCHANGER (EPAHE) IN DIFFERENT SOILS

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Abstract. The concept of using the soil as a heat sink has increased in recent years. Nowadays, the earth-pipe-air heat exchanger (EPAHE) is considered a promising alternative to the problem of rational use of energy and comfort control in buildings, due to their higher energy efficiency compared to the conventional heating and cooling systems. In this context, in order to optimize the installation of these systems, different geometric configurations and thermal performance of an earth-air heat exchanger were analyzed numerically using a Computational Fluid Dynamics (CFD) tool. Two configurations of earth-pipe-air heat exchangers (EPAHE) (two tube passes and four tube passes) were analyzed and the spacing between the tubes has also been verified. Three-dimensional CFD analysis were performed in steady state condition and the standard k- ϵ turbulence model has been used for the air flow. The results showed that the four tube passes model provide better thermal performance than the two tube passes system, requiring smaller area for installation. Furthermore, it has been found that saturated soils increase the performance of EPAHE.

Keywords: EPAHE, Passive Cooling, CFD.

1. INTRODUCTION

Heating, ventilation and air conditioning systems (HVAC) are the main responsible for the high electric energy consumption in the buildings (Pérez-Lombard *et al.*, 2008). In this context, many countries support the development of new climate control technologies in buildings. In order to minimize the energy consumption with HVAC systems, the use of earth-pipe-air heat exchangers (EPAHE) as passive air conditioning has increased in recent years (Michopoulos *et al.*, 2009; Soni *et al.*, 2015; Chen *et al.*, 2016; Kaushal, 2017).

EPAHE are generally composed of one or more underground pipes in which the systems use the thermal energy from soil as a source or heat sink, due a high thermal inertia that maintains its temperature approximately constant at certain depths (Olfman *et al.*, 2014).

These systems are used for heating and cooling of buildings, since the soil temperature in winter is higher than the external environment and lower in summer (Hollmuller *et al.*, 2014). EPAHE can use the internal or external air as showed in Fig. 1, where the air flows through the underground pipes and exchanges heat with the soil.

In order to understand the thermal performance of EPAHE systems, numerical and experimental models have been developed. Kupiec *et al.* (2015) utilized a mathematical model for a horizontal EPAHE based on a one-dimensional transient equation with an internal heat source. Another work, Benhammou *et al.* (2015) elaborated a transient analytical model to analyze the performance the influence of parameters of an EPAHE coupled to a wind tower. Selamat *et al.* (2016) using a three-dimensional CFD model verified three EPAHE geometries and the effect of different pipe materials in the thermal performance. Congedo *et al.* (2012) also executed comparisons among different configurations of EPAHE and several types of soil using CFD. In previous work (Vasconcellos *et al.*, 2017), a pipe with 40 m of length and 0.10 m of diameter has showed to be sufficient for the air cooling. In this study, a constant temperature of 292.5 K was utilized in the exterior surface of the soil (Curitiba City). In this context, in order to optimize the installation of these systems, different geometric configurations and thermal performance of an earth-air heat exchanger were analyzed using the Ansys Fluent 18.0 (commercial software). Effects of the domain geometry and pipe material are also presented. Furthermore, geometries of two and four tube passes of (EPAHE), are analyzed in different soils.

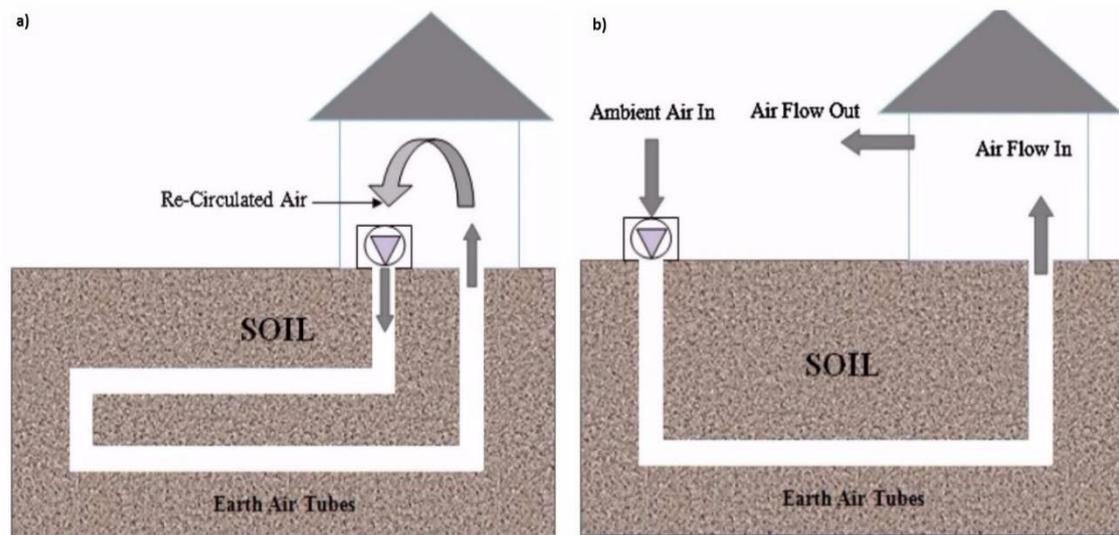


Figure 1. Building system coupled to a soil heat exchanger (Kaushal, 2017).

2. COMPUTATIONAL PROCEDURE

Three-dimensional model in steady state condition has been developed for the earth-pipe-air heat exchanger (EPAHE) system. Effects of different configurations in the thermal performance of the EPAHE have been verified. CFD simulations were performed using the Ansys Fluent 18.0 software. Geometric modeling has been done using the Solid Edge ST8 software and the 3-D mesh has been prepared through the Ansys Meshing.

2.1 EPAHE Model Verification

The EPAHE model utilized in this work (Fig. 2) has been verified through the numerical and experimental study presented by Misra *et al.* (2013). Maximum temperature difference of 0.7 K has been observed in steady state condition, as shown in Fig. 3. However, in transient conditions, the temperature difference between the models is practically imperceptible, after 12 hours (Fig. 4).

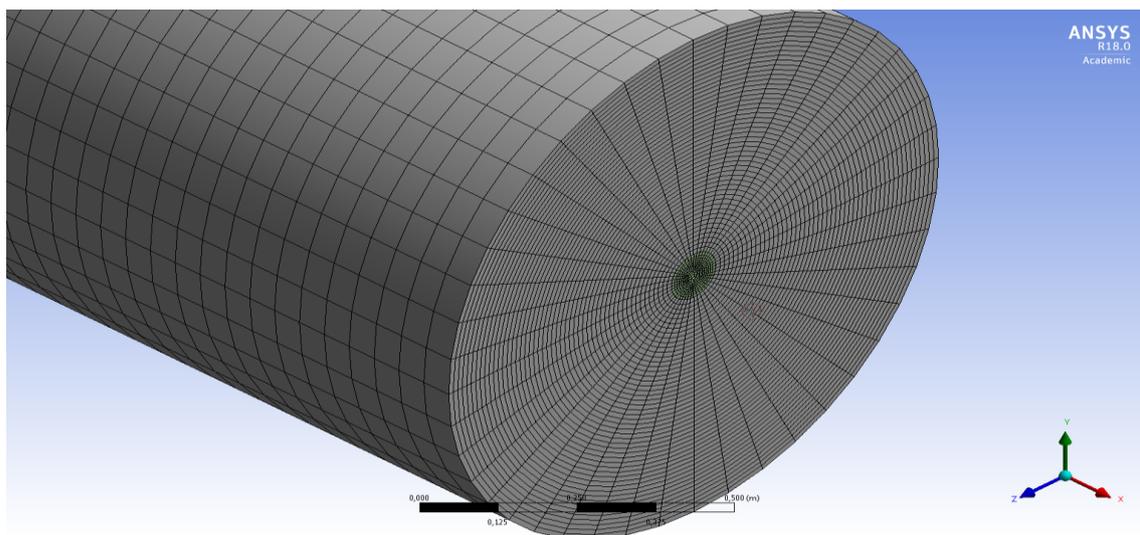


Figure 2. Details of domain and mesh used in this work.

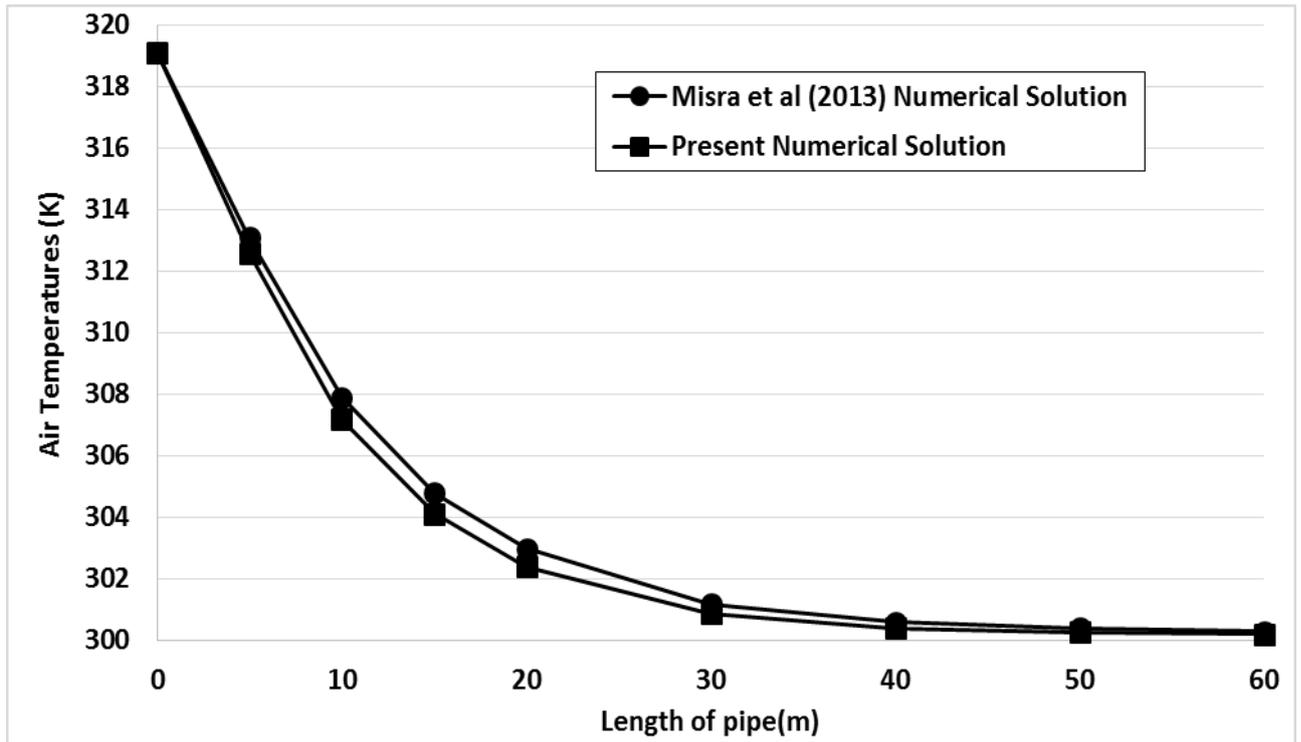


Figure 3. Validation in steady state.

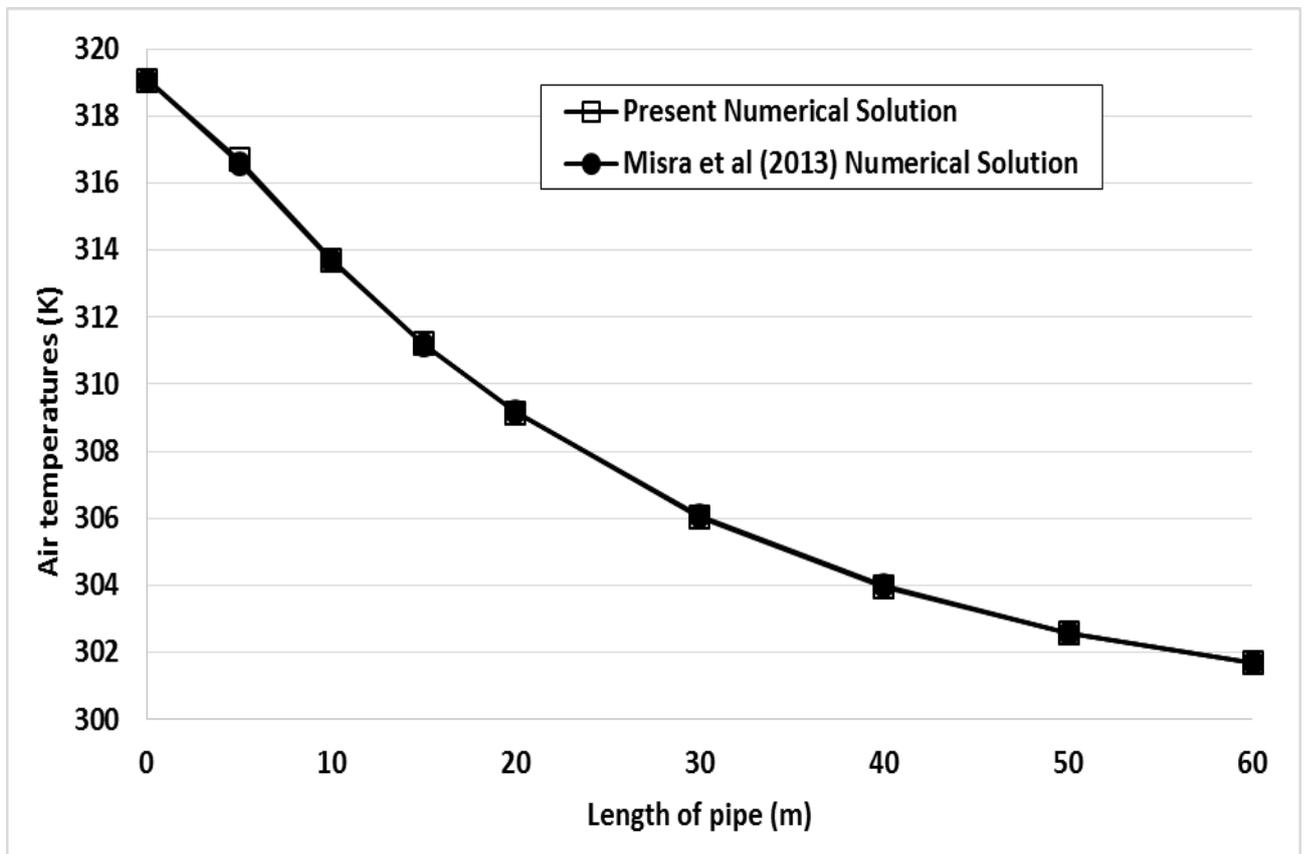


Figure 4. Transient validation (after 12 hours).

In this verification, geometric parameters and thermal properties used in the comparison are shown in the Tab. 1.

Table 1. Parameters used in the validation (Misra *et al.*, 2013).

Parameters	Values
EPAHE length	60 m
Pipe diameter	0.1 m
Surrounding soil diameter	1.1 m
Air density	1.225 kg m ⁻³
Air thermal conductivity	0.02 W m ⁻¹ K ⁻¹
Air specific heat capacity	1006 J kg ⁻¹ K ⁻¹
Soil density	2050 kg m ⁻³
Soil specific heat	1840 J kg ⁻¹ K ⁻¹
Soil thermal conductivity	0.52 W m ⁻¹ K ⁻¹
PVC pipe density	1380 kg m ⁻³
PVC thermal conductivity	1.16 W m ⁻¹ K ⁻¹
PVC specific heat capacity	900 J kg ⁻¹ K ⁻¹

Boundary conditions utilized were:

- Air inlet: 5 m/s and 319.1 K have been utilized for inlet velocity and inlet temperature, respectively.
- Pipe and soil walls: the front and back surfaces were considered as adiabatic.
- Exterior surface of the soil: a constant temperature of 300.2 K was considered.
- Air outlet: pressure of 0 Pa has been used.

2.2 Cubic Domain

In order to apply a climatic condition on the upper surface of the soil domain in future works, a cubic domain has been tested as presented in Fig. 5.

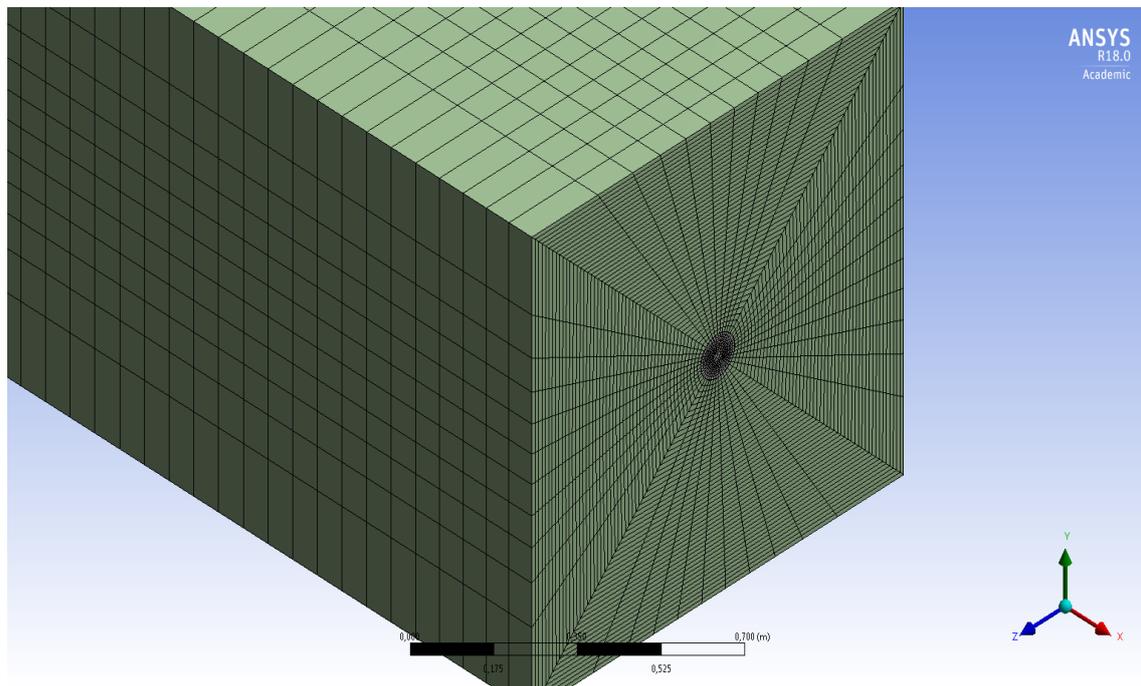


Figure 5. Mesh model of cubic domain.

In the comparison between cylindrical and cubic domains, geometric parameters and the thermal properties are shown in the Tab. 2.

Table 2. Parameters used to verify the domains.

Parameters	Values
EPAHE length	60 m
Pipe diameter	0.1 m
Surrounding soil diameter	1.1 m
Edge cube	1.1 m
Air density	1.225 kg m ⁻³
Air thermal conductivity	0.02 W m ⁻¹ K ⁻¹
Air specific heat capacity	1006 J kg ⁻¹ K ⁻¹
Soil density	1650 kg m ⁻³
Soil specific heat	800 J kg ⁻¹ K ⁻¹
Conductivity Dry Sand	0.4 W m ⁻¹ K ⁻¹
Conductivity Sand 40%	2.4 W m ⁻¹ K ⁻¹
PVC pipe density	1380 kg m ⁻³
PVC thermal conductivity	1.16 W m ⁻¹ K ⁻¹
PVC specific heat capacity	900 J kg ⁻¹ K ⁻¹

Boundary conditions applied in the domains were:

- Air inlet: 2.5 m/s and 308 K have been utilized for inlet velocities and inlet temperature, respectively, based on the temperature of an environment in a summer building.
- Pipe and soil surfaces: the front and back surfaces were considered as adiabatic.
- Air/pipe and pipe/soil interfaces: coupled interface conditions were used.
- Exterior surface of the soil: a constant temperature of 292.5 K obtained from Santos, *et al.* (2004) has been considered (Curitiba City)
- Air Outlet: 0 Pa has been used.

Figs 6 and 7 show that the two domain configurations do not interfere the thermal performance of the EPAHE. The two soils with both domains showed the same thermal behavior.

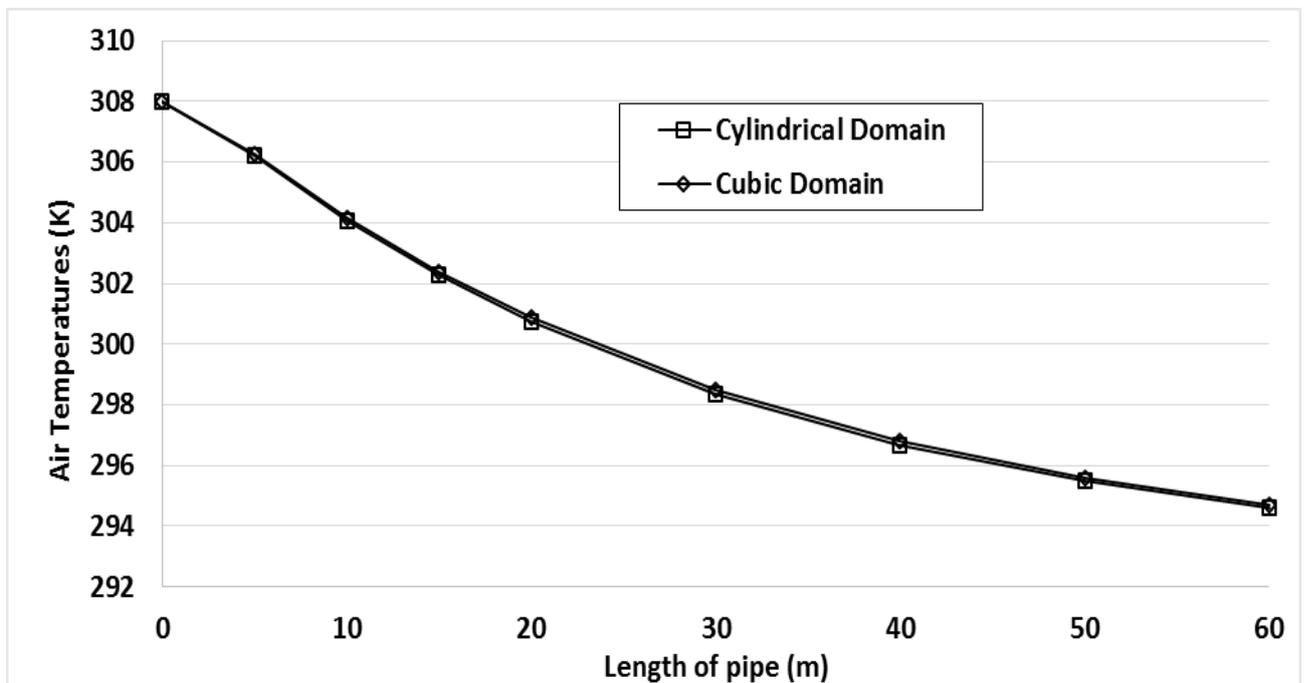


Figure 6. Temperature distribution for velocity of 2.5 m/s and dry sand.

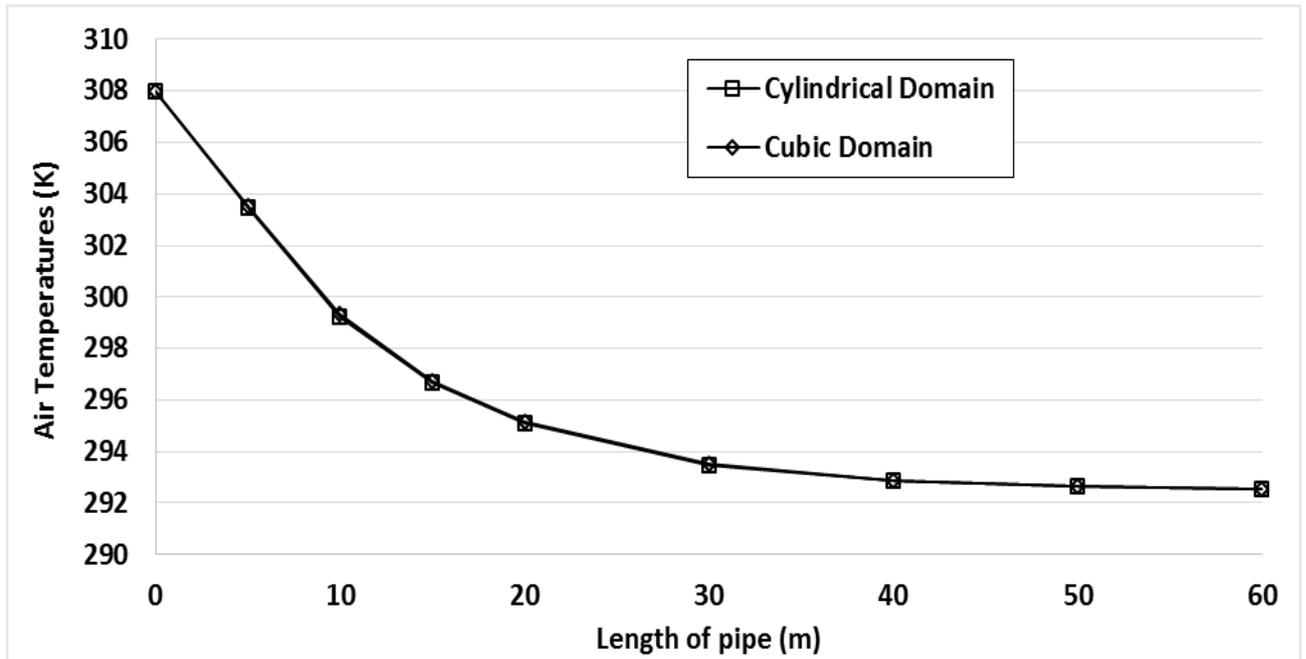


Figure 7. Temperature distribution for velocity of 2.5 m/s and sand with 40% of saturation.

2.3 Effect of material pipe in the thermal performance of the EPAHE.

The thin tube thickness can cause some problems in the mesh generation. In order to analyze this effect, simulations were executed disregarding the tube material. Figure 8 shows that the effect of the material pipe is irrelevant in the temperature distribution of the EPAHE system, due to the low thermal resistance. In these simulations, the same boundary conditions and soil properties were used.

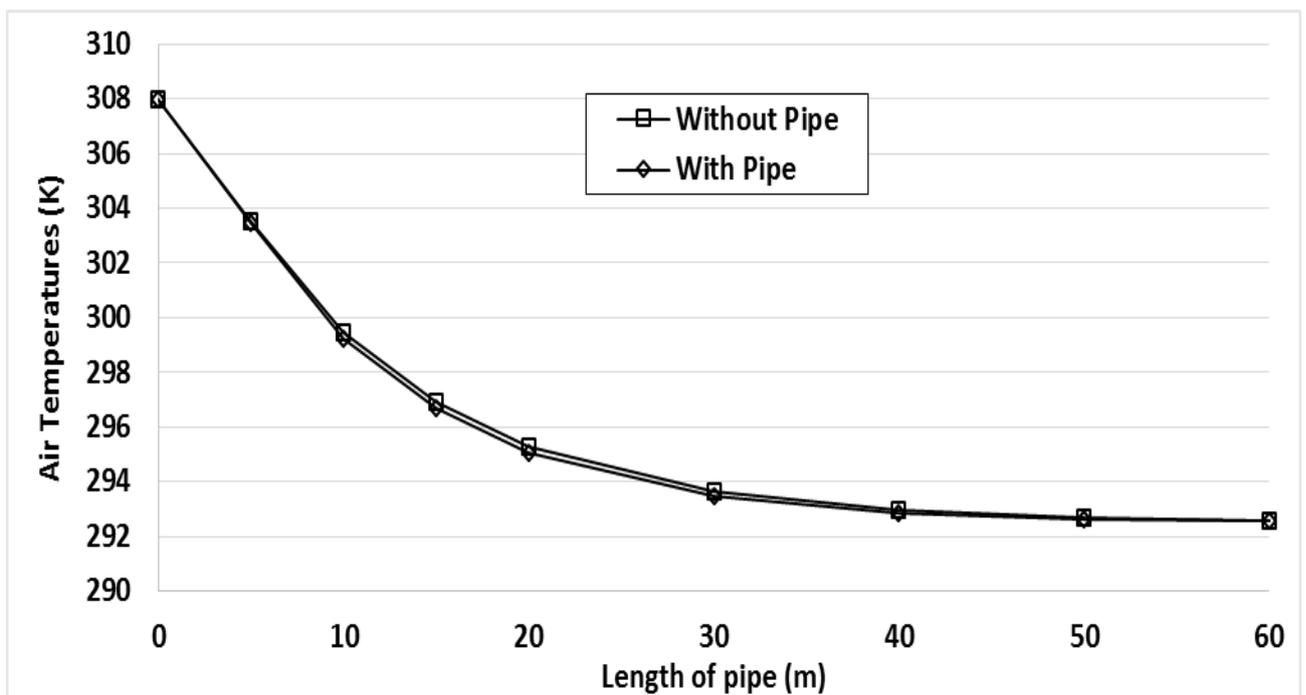


Figure 8. Temperature distribution for velocity of 2.5 m/s and sand 40%.

2.4 Two tube passes and four tube passes configurations

In previous sections were showed that the domain geometry and the material pipe do not influence the thermal performance of the EPAHE system. Thus, considering the same boundary conditions and properties of soil, a cubic domains and unstructured mesh were utilized in the simulations as presented in Fig. 9.

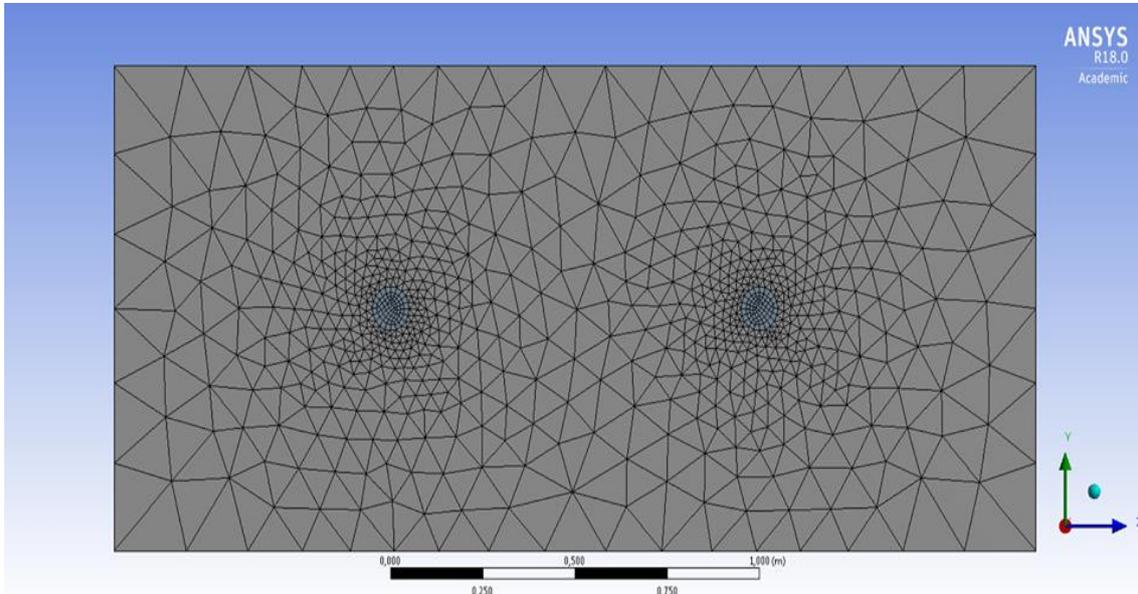


Figure 9. Mesh model generated in the EPAHE system.

In a previous work, Vasconcellos *et al.* (2017) obtained good thermal performance of the EPAHE system using a air flow velocity of 2.5 m/s with diameter and length of pipe of 0.1 m and 40 m, respectively, in a sandy silt soil with 70% of saturation. Thus, these parameters were used in a two tube passes EPAHE system, where the impact of the temperature gradients was analyzed along the pipe. Distances between the pipes of 0.2, 0.5, 0.7 and 1 m, were verified in the EPAHE system, as presented in the Fig. 10.

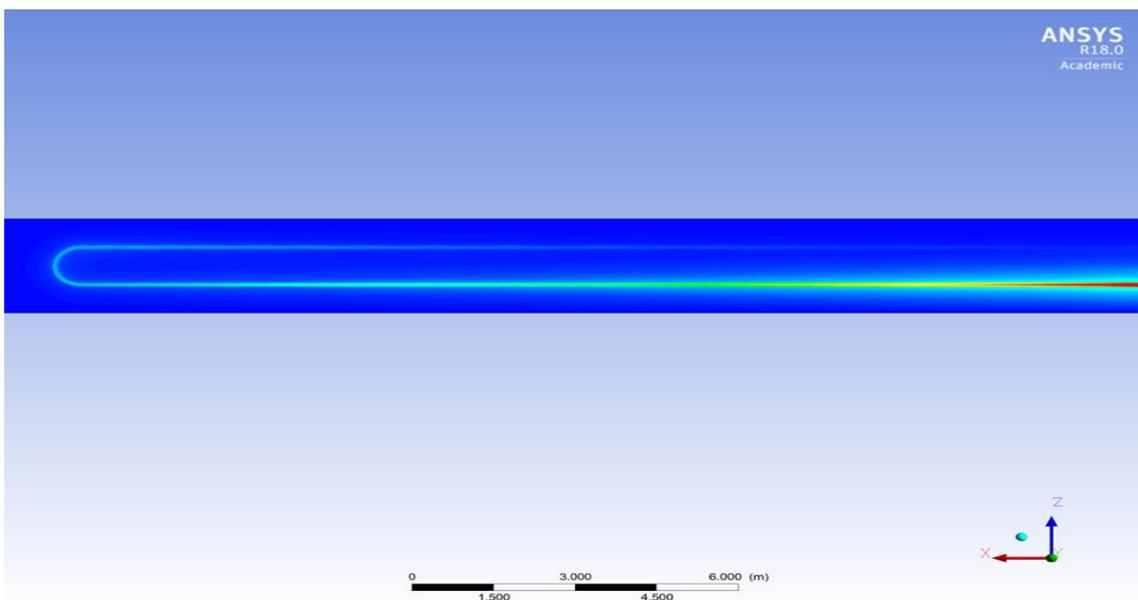


Figure 10. Two tube passes configuration in the EPAHE system.

Consequently, the thermal performance of four tube passes with 40 m of length and using the same distances between the pipes (0.2, 0.5, 0.7 and 1 m) were verified (Fig. 11). All simulations were performed maintaining a distance of 0.5 m from the upper surface of the soil.

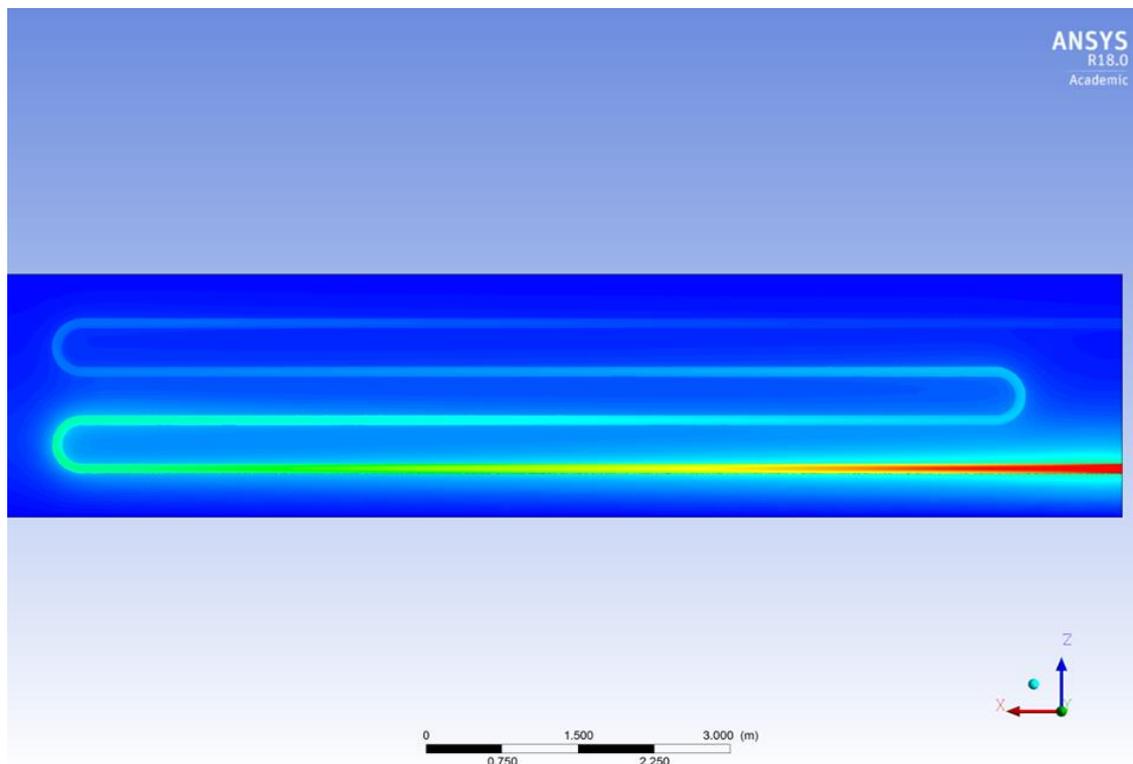


Figure 11. Four tube passes configuration in the EPAHE system.

In these simulations, air was considered incompressible and the soil treated as homogeneous. Standard $k-\epsilon$ turbulence model and standard wall functions were considered for the air flow. The convergence criteria adopted for the equations of continuity, momentum and the $k-\epsilon$ turbulence model were of 10^{-3} and for the energy equation, of 10^{-6} .

2.5 Soils properties

After verification of the geometries, two soil types with different thermal properties were selected as shown in the Tab. 3. Soils dry and saturated, have 0% and 100% of volume of water in your composition, respectively.

The sand and sandy silt, after 40% and 70% of saturation, respectively, have the thermal conductivity approximately constant up to 100%. Specific heat and density were considered constant.

Table 3. Soil properties (Santos and Mendes, 2005; 2006).

Soils	Thermal Conductivity	Specific heat	Density
Dry Sand	0,4 W m ⁻¹ K ⁻¹	800 J kg ⁻¹ K ⁻¹	1650 kg m ⁻³
Sand 40%	2,4 W m ⁻¹ K ⁻¹	800 J kg ⁻¹ K ⁻¹	1650 kg m ⁻³
Dry Sandy Silt	0,3 W m ⁻¹ K ⁻¹	880 J kg ⁻¹ K ⁻¹	1280 kg m ⁻³
Sandy Silt 70%	1,68 W m ⁻¹ K ⁻¹	880 J kg ⁻¹ K ⁻¹	1280 kg m ⁻³

3. RESULTS AND DISCUSSIONS

The simulations were developed to determine the air temperature distribution along the EPAHE systems in steady state condition. Figure 12 and 13 shows the effect of the distances between the pipes in the thermal performance of the two and four tube passes configurations.

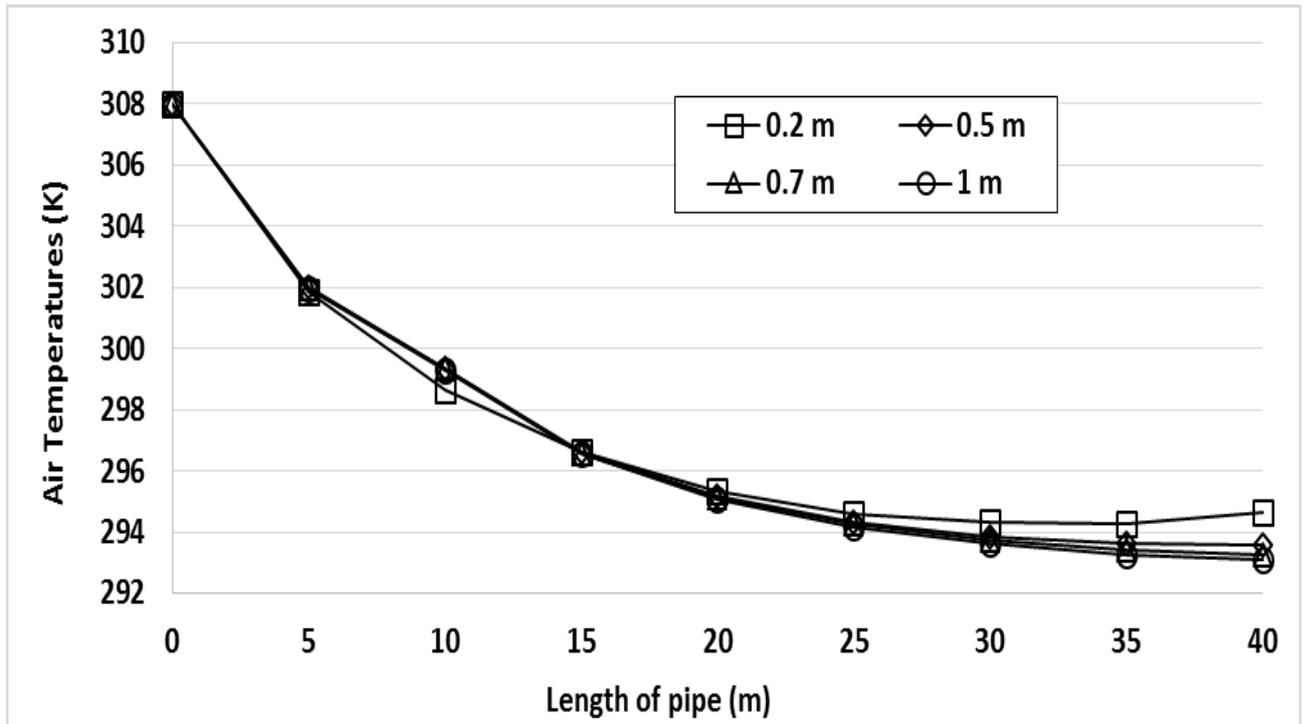


Figure 12. Temperature distribution for the two tube passes configuration in the soil Sandy Silt 70%.

Results show a similar behavior for both configurations. The greatest difference in temperature distribution was observed for the four tube passes configuration (Fig. 13) where the distance between the pipes was of 0.2 m. In all other cases, the difference among the results were less than 0.5 K. In order to optimize the space required for the installation of the system, a distance of 0.5 m between the pipes is suggested.

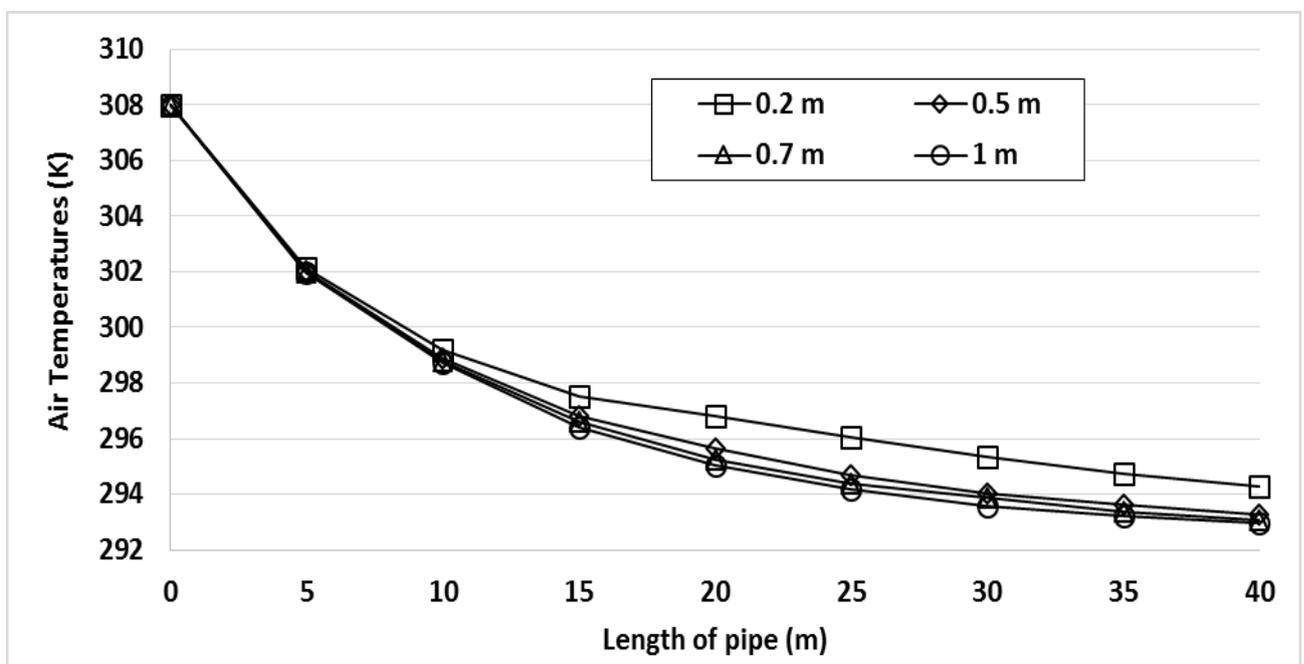


Figure 13. Temperature distribution for the four tube passes configuration in the soil Sandy Silt 70%.

Verified that a distance of 0.5 m between the tubes would be required for geometries two and four tube passes.

Thus, the geometries were analyzed in different soils, where the Figures 14 and 15, present the temperature distributions.

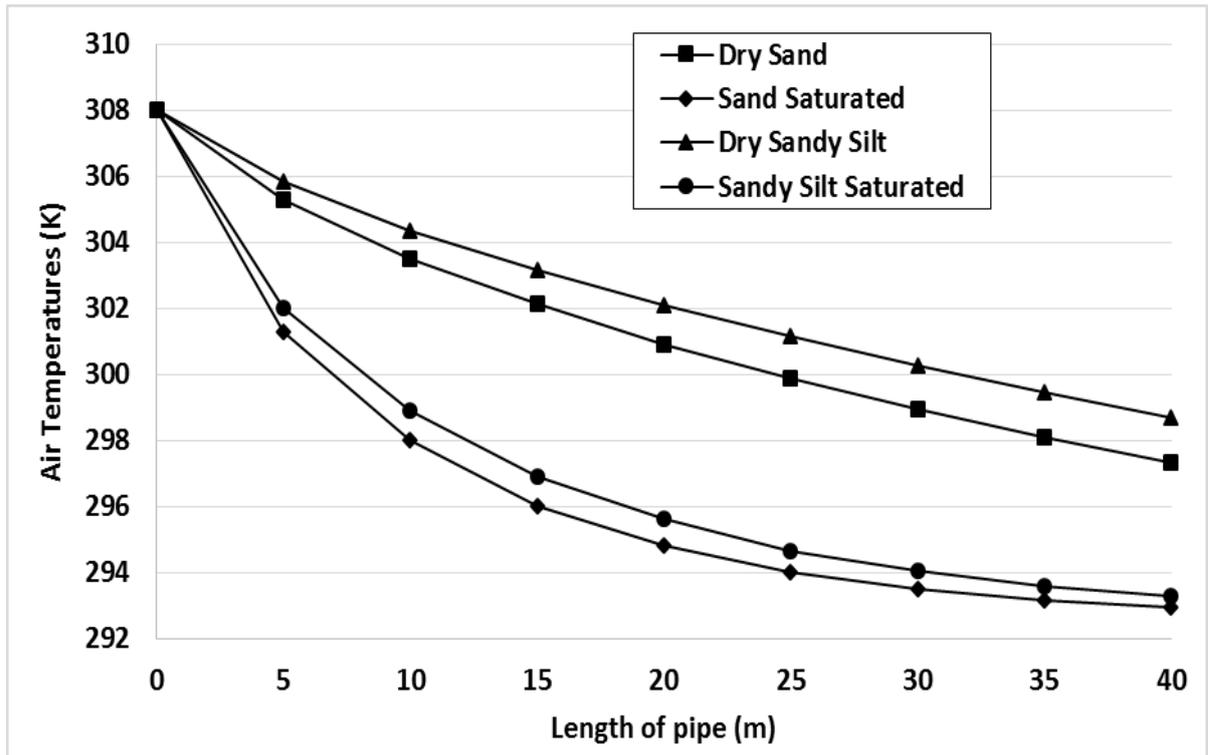


Figure 14. Temperature distribution for the two tube passes in different soils.

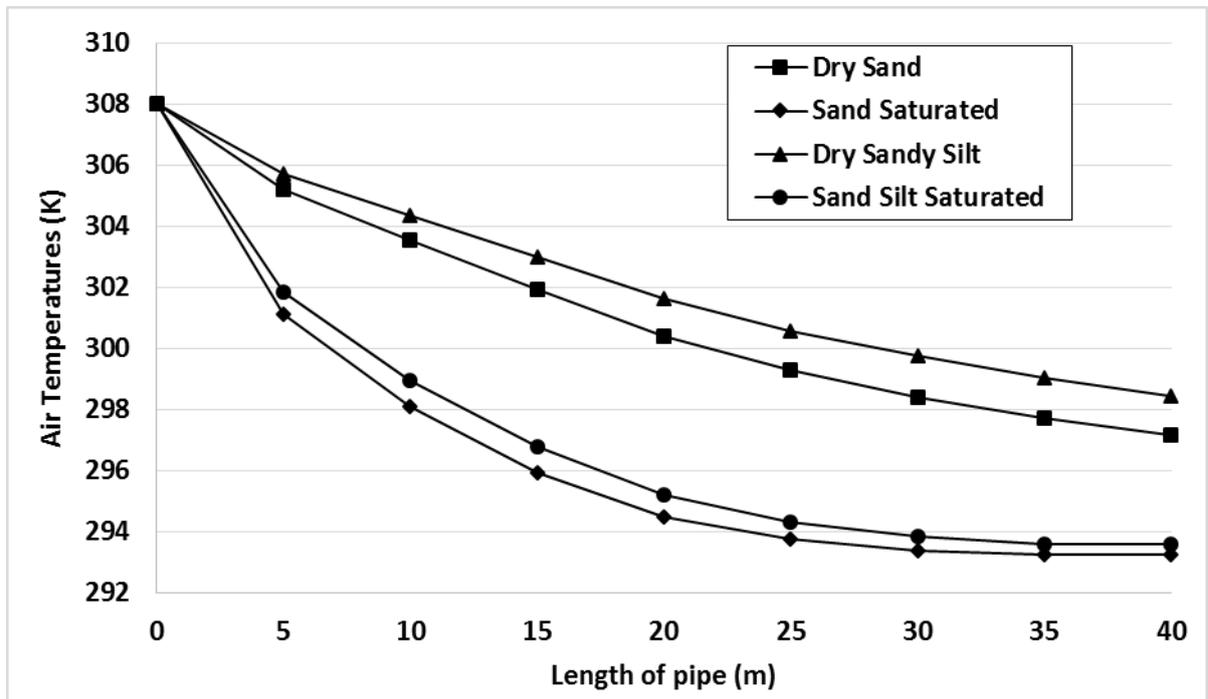


Figure 15. Temperature distribution for the four tube passes in different soils.

Figures 14 and 15 showed the same behavior, where the soil sandy saturated and sandy silt saturated presented the best performance. However, the dry soils obtained a lower thermal performance.

4. CONCLUSIONS

In order to optimize the installation of EPAHE systems, different geometric configurations were verified numerically using a Computational Fluid Dynamics (CFD) tool. Effects of the domain geometry and material pipe were also analyzed and the results showed that these parameters do not influence the thermal performance of the EPAHE.

Furthermore, has been found that in both geometries of two and four tube passes, a distance of 0.5 m between the tubes was necessary so that the temperature gradients did not affect the thermal performance of the EPAHE. Likewise, the soils saturated presented the best thermal performance, regardless of the use of the geometry of two and four tube passes.

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