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Heat transfer in Oxisol in heat storage process[1]

Transferência de calor em latossolo vermelho (Oxisol) em processo de armazenamento de calor

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HIGHLIGHTS:
Soil temperature increased logarithmically as a function of heat transfer time.
The type of material of the linear heat exchanger (PVC and copper) had no influence on soil temperature variation.
The installation distance between geothermal heat exchangers must be greater than 50 cm.

ABSTRACT: Geothermal energy is a renewable source that can assist in the thermal conditioning of constructed environments. The objective of this study was to analyze the heat transfer in a Red Latosol (Oxisol), in heat storage process, using two linear heat exchangers. The treatments were arranged in a 3 × 2 × 3 factorial scheme, corresponding to three temperature differentials between soil and water (5, 10 and 15 °C), two types of materials (PVC and copper) and three radial distances (10, 20 and 25 cm), with three replicates. Soil temperature variations were obtained continuously for a period of 12 hours using DS18B20 sensors. These variations were logarithmic as a function of heat transfer time and radial distance and linear as a function of the temperature differential between soil and water (θ). The temperature differential between soil and water was the main factor that influenced soil temperature variation, and the material employed was insignificant in this variation. The minimum distance between heat exchangers should be greater than 50 cm, and PVC pipes proved to be more attractive for use involving thermal exchange with the ground as they are more viable than copper and easier to implement.

Key words: soil thermal behavior, horizontal linear heat exchanger, surface geothermal energy

RESUMO: A energia geotérmica é uma fonte renovável que pode auxiliar no condicionamento térmico de ambientes construídos. O objetivo deste estudo foi analisar a transferência de calor em um Latossolo Vermelho (Oxisol), em processo de armazenamento de calor, utilizando dois trocadores de calor lineares. Os tratamentos foram dispostos em esquema fatorial 3 × 2 × 3, correspondendo a três diferenciais de temperatura entre solo e água (5, 10 e 15 °C), dois tipos de materiais (PVC e cobre) e três distâncias radiais (10, 20 e 25 cm), com três repetições. As variações de temperatura do solo foram obtidas continuamente por um período de 12 horas usando sensores DS18B20. Essas variações foram logarítmicas em função do tempo de transferência de calor e da distância radial, e lineares em função do diferencial de temperatura entre o solo e a água (θ). O diferencial de temperatura entre o solo e a água foi o principal fator que influenciou na variação da temperatura do solo, sendo que o material empregado foi insignificante nessa variação. A distância mínima entre os trocadores de calor deve ser maior que 50 cm, e os tubos de PVC se mostraram mais atrativos para uso envolvendo troca térmica com o solo por serem mais viáveis que os de cobre e mais fáceis de serem executados.

Palavras-chave: comportamento térmico do solo, trocador de calor linear horizontal, energia geotérmica de superfície

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Introduction

The thermal energy contained in the soil, known as geothermal, has gained importance as a renewable alternative source of high potential for heating and cooling environments. The subsoil has thermal amplitudes that decrease with increasing depth, showing stable temperatures throughout the year, regardless of season and climate change (Bucci et al., 2020; Noman et al. 2022).

Surface geothermal heat can be utilized through heat exchange systems buried in the ground coupled to a heat pump, allowing the air conditioning of environments, both in summer and winter (Christodoulides et al, 2019; Deymi-Dashtebayaz et al., 2020; Xie et al., 2020). In these pipes, the circulation of a fluid, usually water, water with glycol, or air, allows the exchange of heat with the soil (Boban et al., 2021). D'arpa et al. (2016) analyzed ground-source heat pump (GSHP) systems for heating agricultural greenhouses in southern Italy and highlighted that the mechanism can bring improvements in yield and reductions of costs, in addition to contributing to the reduction of CO_2.

Some studies have already analyzed temperature distribution in the soil (Sanches et al., 2021; Tonus et al., 2022). Wu et al. (2018), Boban et al. (2021) and Vieira et al. (2022) studied the influence of soil depth on temperature stability. Xu et al. (2022) found that the process of heat storage and release in the soil shows a symmetrical behavior when subjected to the same temperature differential between the fluid and the soil.

In this context, the present study aimed to analyze heat transfer in a Red Latosol (Oxisol) in heat storage process, for two horizontal linear heat exchangers, one consisting of PVC pipe and the other of copper pipe. In addition, the minimum installation distance between serpentine pipes for heat exchange with the soil was determined and an equation to predict the temperature change in the soil was developed.

Material and Methods

The present study was carried out in the municipality of Dourados-MS, located in the Midwest region of Brazil, state of Mato Grosso do Sul (Figure 1), at the Federal University of Grande Dourados (UFGD, experimental area of the Faculty of Agrarian Sciences - FCA), with 22° 11' 53" South latitude, 54° 56' 03" West longitude and 430 m of altitude. According to Köppen's classification, the climate of the region is classified as Am (Alvares et al., 2013), with rainy summer and dry winter.

The annual average temperature and precipitation are between 22 and 24 °C and between 1500 and 1700 mm, respectively (INMET, 2019). The rains are concentrated in the period from October to March, with reductions between April and September. The municipality of Dourados has a 95.75% predominance of Oxisol (United States, 2014), which corresponds to a Latossolo Vermelho in the Brazilian Soil Classification System (EMBRAPA, 2018) as detailed in Table 1.

The passage of water through the pipes occurred simultaneously, guaranteeing the same environmental conditions during the 12 hours of operation in each prototype,

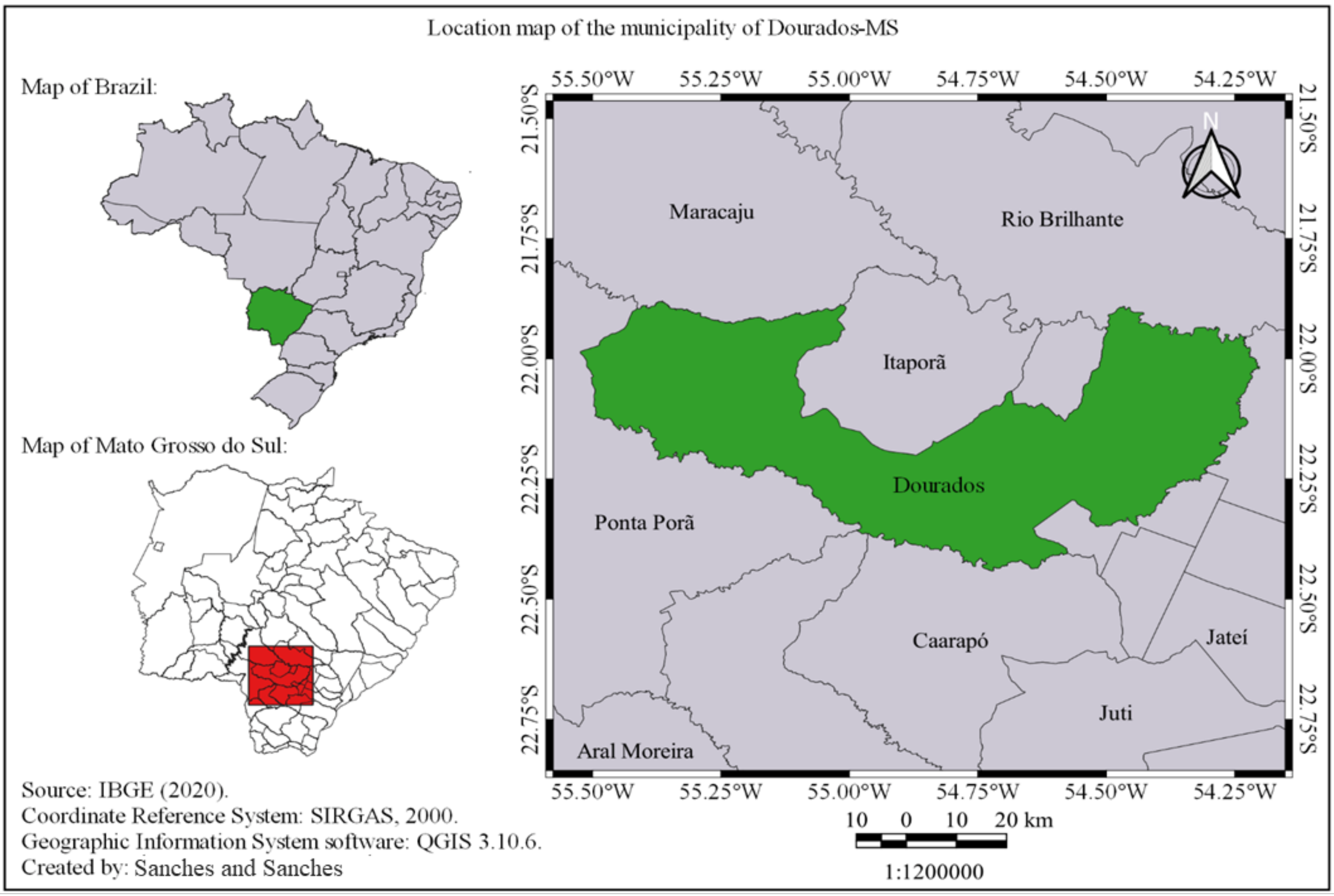


Figure 1. Location of the municipality of Dourados-MS

Table 1. Physical characteristics of the Oxisol

Soil layer (cm)	Texture			BD (kg dm^{-3})	Ma	Mi	Pt	AWC (mm)	TWA (mm cm^{-1})
	Sand	Silt	Clay						
	(g kg^{-1})				(m^3 m^{-3})				
0-10	262	110	628	1.153	0.196	0.312	0.508	76.33	1.527
10-20	238	126	636	1.199	0.189	0.290	0.479	73.68	1.474
20-30	230	130	640	1.179	0.174	0.293	0.467	82.24	1.645
30-40	223	132	645	1.176	0.163	0.323	0.486	94.43	1.889
40-50	220	124	656	1.151	0.157	0.327	0.484	85.23	1.705
Mean	235	124	641	1.172	0.176	0.309	0.485	82.45	1.649

BD - Bulk density; Ma - Macroporosity; Mi - Microporosity; Pt - Total soil porosity; AWC - Available soil water capacity; TWA - Total soil water availability
Source: Daniel et al. (2022), adapted

with information being recorded every 5 minutes to calculate hourly averages and determine the difference between the inlet and outlet temperatures of water from both systems.

The experimental part of the study was carried out in January 2022. Initially, three days of data were collected in a preliminary test, and once the environmental structure necessary for carrying out the experiment was confirmed, fifteen days of experimental data were collected.

A 3 × 2 × 3 factorial scheme with three replicates was used. The factors considered were: three temperature differentials between soil and water (5, 10 and 15 °C), two pipe materials (PVC and copper) and three radial distances (10, 20 and 25 cm). Fifteen repetitions (experimental days) were considered, with data collected from 06:00 to 18:00 hours, in continuous periods, which stayed subject to a turbulent regime, with information being recorded every 5 minutes and hourly averages being calculated.

The principle of the experiment was the passage of water at different temperatures through two linear heat exchangers, one made of PVC and one of copper, in order to observe the thermal behavior of the soil and the difference between the water inlet and outlet temperatures in the heat exchanger, according to the schematic model in Figure 2. The length and nominal diameter of the PVC and copper pipes were 10 m and 25 mm and 8 m and 20 mm, respectively. Thus, the flow rates used for the PVC and copper heat exchangers were 10 and 8 L min^{-1} (LPM), respectively, ensuring a turbulent regime in both.

A water pump was responsible for making the water circulate between the tank and the PVC and copper heat exchangers at the same time (Figures 3A and B). The water flow was kept constant in both pipes through a rotameter (Figure 3C).

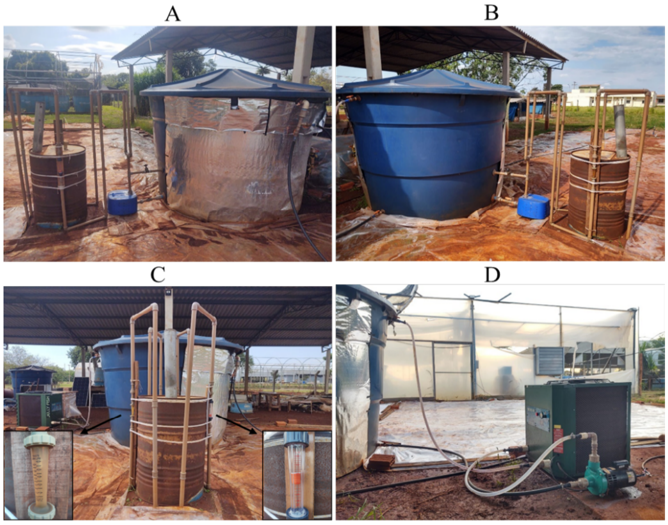


Figure 3. Circuit for the passage of water in (A) PVC pipe and (B) copper pipe, (C) Rotameters and (D) Water heating system

Aided by a heat pump (Figure 3D), the water could be heated to three temperatures: 30, 35 and 40 °C, which ensured temperature differentials between soil and water of 5, 10 and 15 °C, respectively. The water was stored in a 5,000 L tank and reused in all replicates. The soil, in turn, was covered with an aluminized polyethylene thermal-reflective insulating film, followed by two layers of transparent plastic film.

Analysis of the thermal behavior of the soil was carried out in three cross sections for each heat exchanger, with spacings of 3.0 m for the PVC pipe and 2.5 m for the copper pipe, with

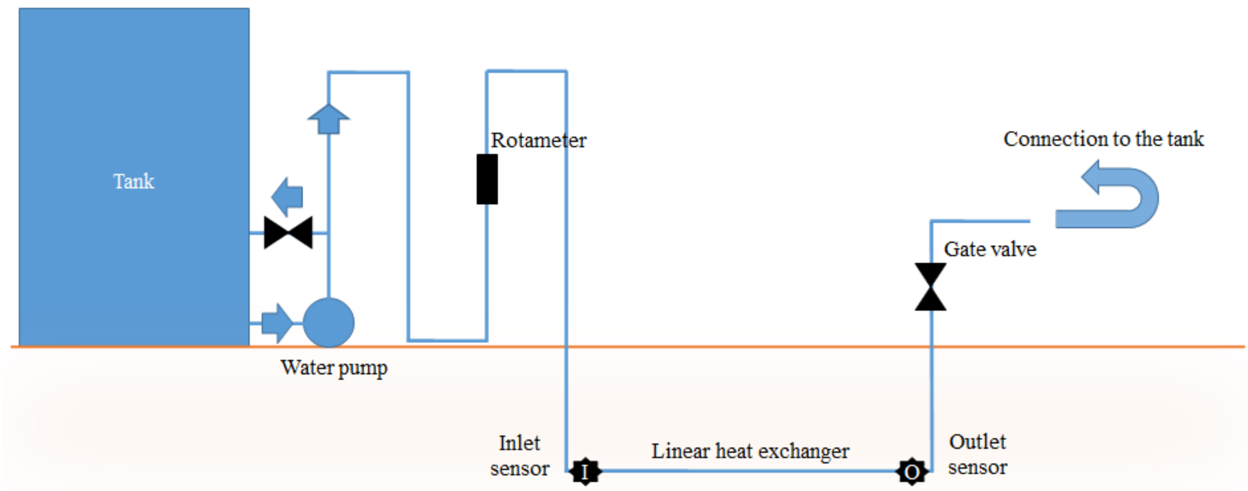


Figure 2. Schematic model for the passage of water through the linear heat exchanger

each section being monitored, in only one side, following a radial line of 10, 20 and 25 cm relative to the pipe installed at 70 cm depth (Figure 4A).

Soil temperature data were collected using DS18B20 sensors, which generate voltage signals proportional to the measured temperature (Figure 4B). The data were recorded at 2-min intervals with the aid of Arduino Mega 2560 R3 boards (free hardware electronic prototyping platform), real time clock RTC DS3231 modules (for date and time recording) and micro SD modules (for data storage).

Soil heat transfer analysis was performed based on the methodology used by Zhu et al. (2021). Thus, the temperature differential was obtained by Equation 1.

$$\theta = \Delta Twater - \Delta Tsoil \quad (1)$$

wherein:

θ - temperature differential between soil and heated water (°C);

ΔTwater - water inlet temperature difference (°C);

ΔTsoil - soil temperature difference at a given time of heat transfer (°C).

In the present study, ΔT_{soil} was defined as the difference between the soil temperature at a given moment of heat transfer ($T_{final\ soil}$) and its temperature at the beginning of the experiment ($T_{initial\ soil}$), data in °C, according to Equation 2.

$$\Delta Tsoil = T_{final\ soil} - T_{initial\ soil} \quad (2)$$

ΔTWater was also defined as the difference between the inlet water ($T_{water\ inlet}$) and outlet water temperature ($T_{water\ outlet}$) in the heat exchangers, given in °C, according to Equation 3.

$$\Delta Twater = T_{water\ outlet} - T_{water\ inlet} \quad (3)$$

A general equation for the thermal behavior of the soil in the radial direction to the pipe was also defined using the same principle as the authors Zhu et al. (2021). Thus, it was considered that the regression assumed a power form (Equation 4):

$$\Delta\theta = A \cdot \theta^B \cdot r^C \cdot t^D \quad (4)$$

which can be rewritten as a linear equation (Equation 5):

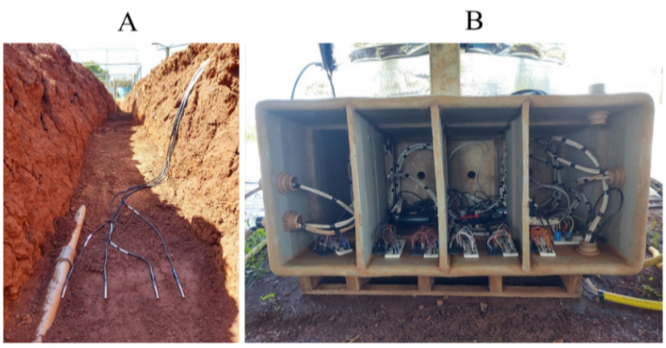


Figure 4. (A) Radial distances of 10, 20 and 25 cm and (B) Data collection and storage system

$$Ln(\Delta\theta) = Ln(A) + B \cdot Ln(\theta) + C \cdot Ln(r) + D \cdot Ln(t) \quad (5)$$

wherein:

Δθ - soil temperature variation (°C);

θ - temperature differential between soil and heated water (°C);

r - radial distance (cm);

t - test time (hours);

A, B, C and D – constants determined for the soil used.

Data were subjected to analysis of variance and to polynomial regression. The soil and water temperature means were compared by Tukey's test at $p \leq 0.05$ and F test at $p \leq 0.01$ using the Sisvar® software. The coefficient of variation (CV) of the data series tabulated was calculated using the function STDEV (data)/AVG (data) from the Excel spreadsheet package.

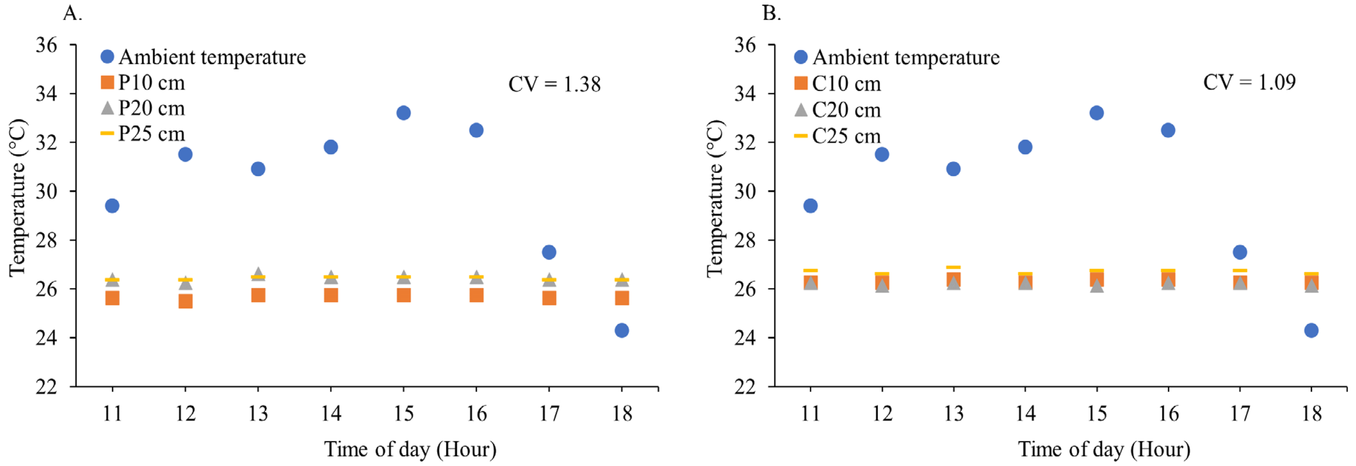
Results and Discussion

In order to assess heat preservation at the installation depth (70 cm), an initial thermal monitoring of the soil was carried out at eight moments for three consecutive days, and hourly averages were generated (Figure 5). In Figures 5A and 5B, it is possible to observe the behavior of the soil in the radial direction of 10, 20 and 25 cm for the PVC pipe (P10 cm, P20 cm and P25 cm) and copper pipe (C10 cm, C20 cm and C25 cm), respectively. There was no significant interference of solar radiation in the layer under study, thus ensuring the reliability of the tests performed in 12-hours periods.

The thermal behavior of the soil (Figure 6) was analyzed preliminarily from the soil temperature variation (θ), for 12 hours, at the three radial distances (10, 20 and 25 cm), for each heat exchanger (PVC and copper). The coefficients of variation (CV) were below 3.95%, which indicates good experimental accuracy. Espinoza-Canaza & Gurbillón (2019) studied copper and PVC tubes for solar collectors in order to analyze the sustainability provided by each one of them. In the end, they concluded that the energy efficiency of each tube must be analyzed for each individual application. Thus, in this study, comparative analyses were performed between the materials copper and PVC.

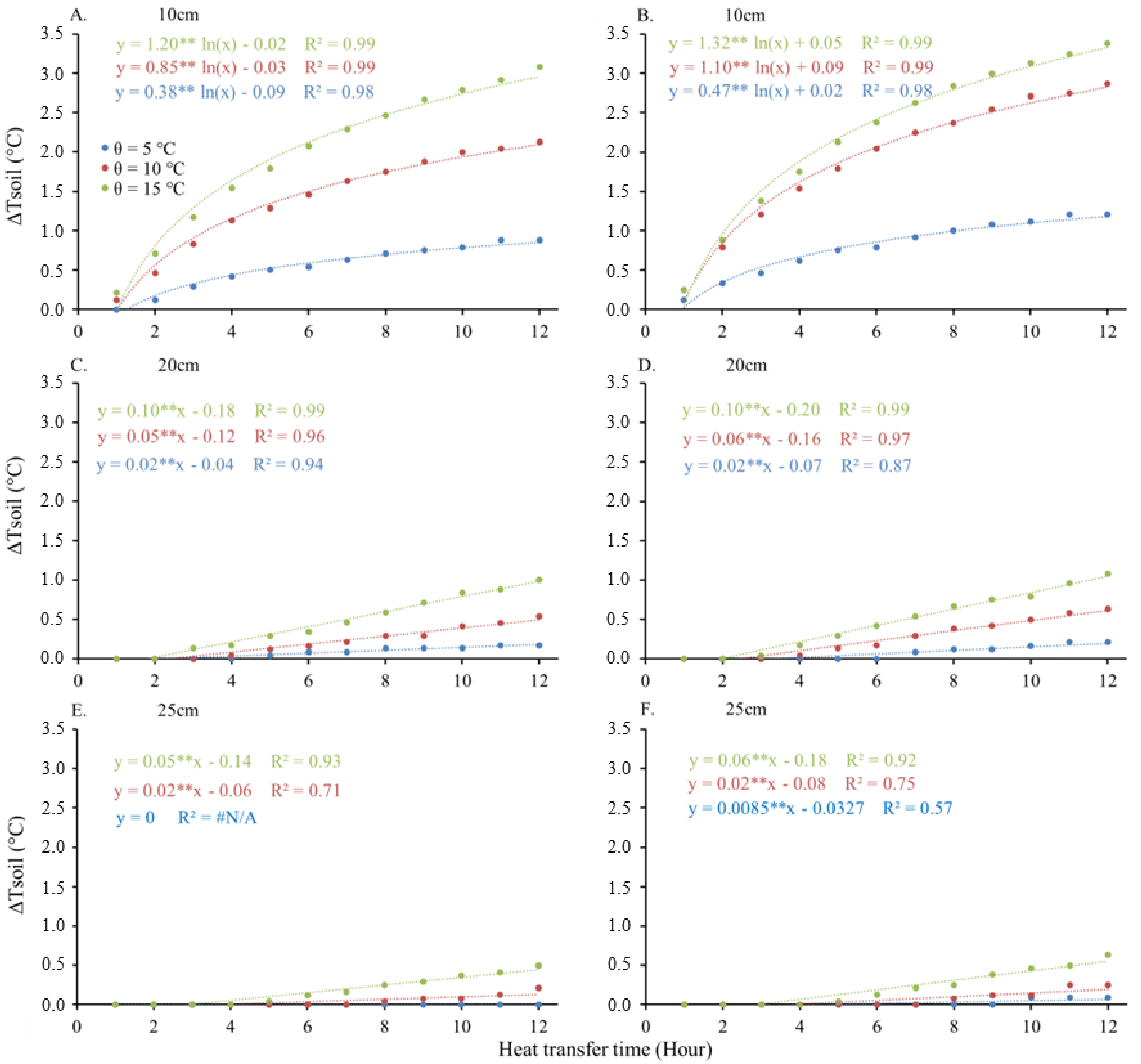
It can be observed that the radial distance closest to the pipe was the one with the highest temperature variation for both materials and that this variation was oriented over time following a logarithmic behavior, with R^2 greater than 0.98 (Figures 6A and B). This behavior indicates that soil temperature variation increases gradually over time during the heat storage process. This result is explained by the fact that the advance of the heat front contributes to a gradual reduction in the temperature differential between water and soil around the exchanger. According to Xu et al. (2022), soil temperature variation around an exchanger is higher in the first 15 cm from its axis.

Radial distances of 20 cm and 25 cm showed linear temperature variation with a maximum R^2 of 0.99 for 20 cm and 0.93 for 25 cm (Figures 6C to 6F). However, the radial distance of 25 cm, referring to the temperature differential between soil and water (θ) of 5 °C, did not vary. Figure 6 also



CV - Coefficient of Variation; ΔTsoil - Soil temperature variation: P= PVC (P10 at 10cm; P20 at 20cm; and P25 at 25cm); C= copper (C10 at 10cm; C20 at 20cm; and C25 at 25cm)

Figure 5. Soil temperature variation (ΔTsoil) and ambient temperature, as a function of time of day (hour). (A) PVC and (B) copper



CV - Coefficient of Variation; ** Significant at p ≤ 0.01, respectively, by the F test. ΔTsoil - Soil temperature variation; and, θ - Temperature differential between soil and water; #N/A - not applicable (y=0)

Figure 6. Soil temperature variation (ΔTsoil) as a function of the heat transfer time for section 1 of PVC (3.0 m) and copper (2.5 m)

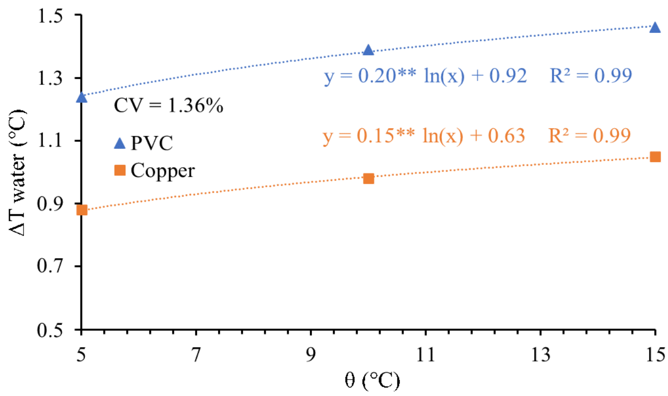
shows that an increase in the temperature differential between soil and water (θ) results in greater soil temperature variations, regardless of radial distance and material. Indeed, according to He et al. (2022), the analysis of two temperature differentials between the soil and the fluid (θ) will be more relevant when there is a difference of at least 5 °C between the two.

Soil temperature variation tends to increase with a linear behavior when the temperature differential (θ) is increased, regardless of the radial distance, with similar angular coefficients for both heat exchangers (Figure 7). There was reduction in the angular coefficients with increasing distance from the heat exchanger, that is, a slower thermal change of the soil in the layers that are most radially distant from the pipe, regardless of the material. These results corroborate those obtained by Huang et al. (2020).

Soil temperature variation (ΔTsoil) in the radial direction is reduced logarithmically (R^2 greater than 0.98), that is, with increasing distance from the pipe there is a reduction in the thermal disturbance of the soil, regardless of the material and temperature differential between soil and water (θ) (Figure 8). This occurs because the very soil around the pipe behaves as a resistive medium to heat transfer. Wen et al. (2020) observed the same behavior.

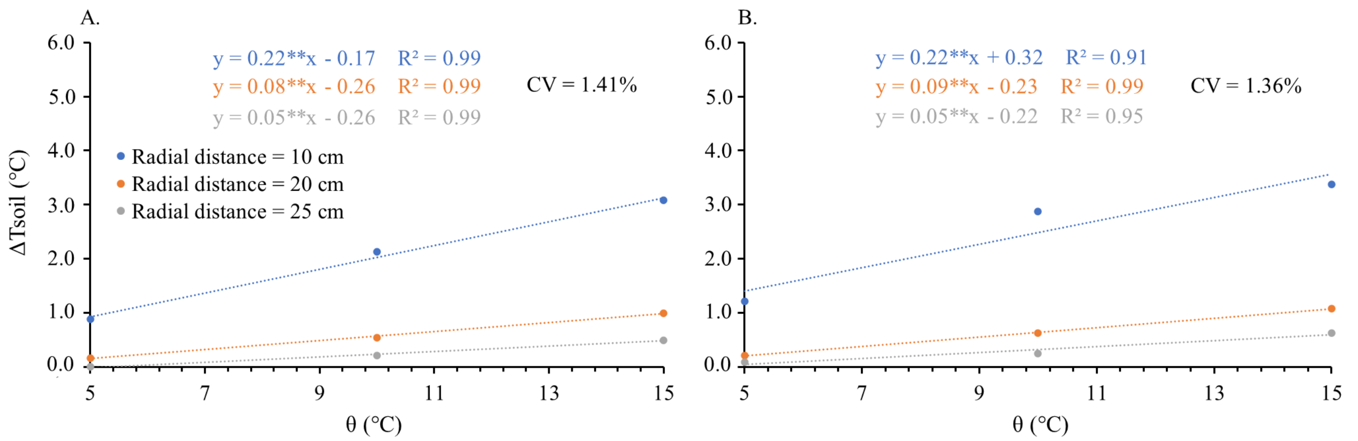
The existence of minimal thermal variations for the radial distance of 25 cm allows suggesting that the pipes in geothermal systems should be installed at least 50 cm apart. The coefficients of variation (CV) were below 2.55%, and the F test at a 1% significance level indicates good experimental accuracy.

With regard to water, there was a gradual increase in the difference between the inlet and outlet temperatures (ΔTWater) as the temperature differential between soil and water (θ) increased, for both PVC and copper pipes (Figure 9). This behavior occurred according to a logarithmic trend, so there



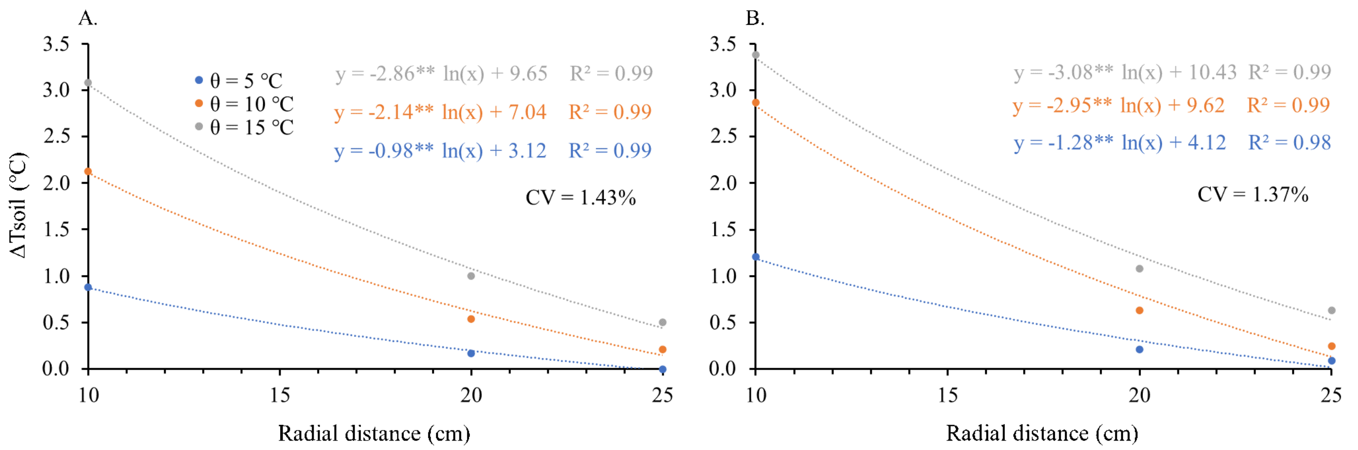
CV - Coefficient of Variation; ** Significant at p ≤ 0.0, respectively, by the F test

Figure 9. Difference between inlet and outlet water temperatures (ΔTwater) in the two heat exchangers as a function of temperature differential between soil and water (θ)



CV - Coefficient of Variation; ** Significant at p ≤ 0.01, respectively, by the F test

Figure 7. Soil temperature variation (ΔTsoil) as a function of θ (temperature differential between soil and water) for Section 1. (A) PVC-3.0 m and (B) copper-2.5 m



CV - Coefficient of Variation; ** Significant at p ≤ 0.01, respectively, by the F test

Figure 8. Soil temperature variation (ΔTsoil) as a function of radial distance for Section 1. (A) PVC-3.0 m and (B) copper-2.5 m

was a non-proportional gain in heat exchange when θ increased from 5 to 15 °C.

The difference in water temperature variation for the two materials can be explained by the length of the heat exchanger used, since the PVC pipe was 10 m long and the copper pipe was 8 m long. The heat loss per linear meter of pipe showed similar values: 0.12, 0.14 and 0.15 °C m^{-1} for the PVC pipe and 0.11, 0.12 and 0.13 °C m^{-1} for the copper pipe, both with θ of 5, 10 and 15 °C, respectively. The coefficient of variation (CV) was 1.36, indicating good experimental accuracy.

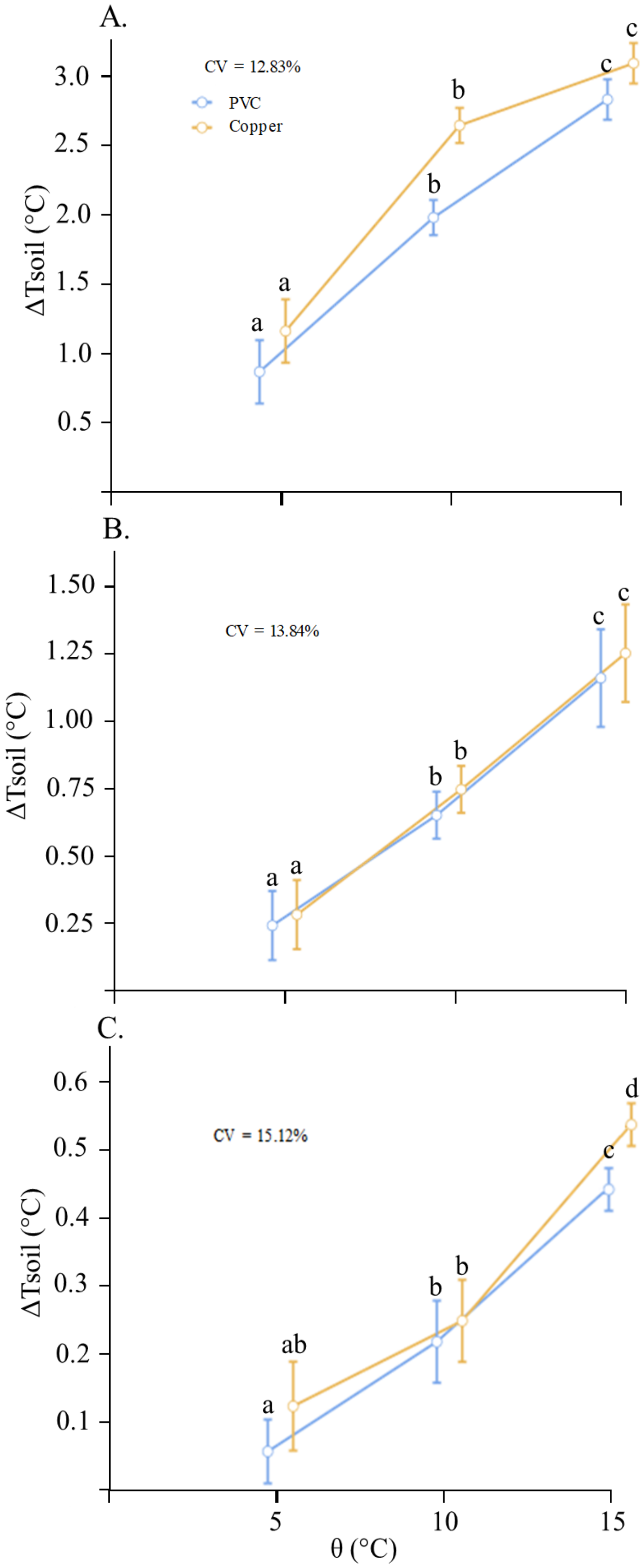
Figure 10 shows the estimated marginal means of soil temperature variation (ΔTsoil) as a function of the temperature differential between soil and water (θ), referring to radial distances of 10, 20 and 25 cm (Figures 10A, B and C, respectively). It is observed that each material, at the three levels of temperature differential between soil and water (θ), showed a significant difference in soil temperature variation (ΔTsoil), given its trend of increase with the increase in temperature differential between soil and water (θ) ($P_{tukey} \leq 0.05$).

The PVC x copper interaction, whose temperature differential between soil and water (θ) is different, also showed a significant difference in soil temperature variation (ΔTsoil). These results indicate that the most significant factor in soil temperature variation (ΔTsoil) was the temperature differential between soil and water (θ). Although the thermal energy of the system is stored in the pipe, as demonstrated by Wehbi et al. (2022), the piping material, statistically, did not have a significant influence on this variation, even with their coefficients of variation (CV) reaching 15.12, as $F_{calculated} > 0.01$, indicating that the F test is not significant.

This result reinforces the recommendation for using PVC pipes made by Souza & Gomes (2003) when they stated that these pipes are recommended for solar collectors because they have adequate characteristics for heating and drainage and are economically viable, besides being easy to assemble and maintain.

It is also observed that, in the PVC x copper interaction, for the temperature differential (θ) of 10 °C at the radial distance of 10 cm (Figure 10A), the material factor contributed significantly to soil temperature variation (ΔTsoil) ($P_{tukey} \leq 0.05$). However, based on the experimental analysis, the variation recorded for PVC and copper was 2.13 and 2.87 °C, respectively, i.e., a difference of only 0.74 °C. The same is true for the temperature differential (θ) of 15 °C at the radial distance of 25 cm ($P_{tukey} \leq 0.05$), in this case with a difference of 0.13 °C (0.50 and 0.63 °C for PVC and copper, respectively) obtained experimentally.

The existence of three independent variables (factors) affecting soil temperature distribution (ΔT_{soil}) required a regression analysis to determine an equation for the thermal behavior of the soil in the radial direction of the pipe. The three independent variables are: temperature differential between soil and water (θ, corresponding to 5, 10 and 15 °C), radial distance (r, corresponding to values of 10, 20 and 25 cm) and test time (t, corresponding to values from 0 to 12 hours). The values obtained for the coefficients, after applying this regression, are presented in Table 2. The length of heat exchangers was not added to the model, since it did not provide improvement in the adjusted R^2.



The values represented by the same letter in Figures A, B, and C separately do not differ from each other by Tukey's test at p ≤ 0.05

Figure 10. Estimated marginal means for three radial distances. (A) 10 cm, (B) 20 cm and (C) 25 cm

The obtained fit had an R^2 of 0.85 and a coefficient of variation of 2.31%, indicating that the proposed model provides coherent and accurate results compared to the experimental values. The equation obtained showed coefficients that were

Table 2. Results of the regression analysis

Predictors	Coefficients	Adjusted R²	CV (%)
Intercept	2.67*	0.85	2.31
Temp diff.	0.76*		
Radial distance	-2.27*		
Time	0.63*		

*Significant at $p \leq 0.01$ by F test; CV - Coefficient of variation

close to those obtained by Zhu et al. (2021). The general equation referring to the radial thermal behavior of both heat exchangers is presented below:

$$\Delta\theta = 14.44 \cdot \theta^{0.76} \cdot r^{-2.27} \cdot t^{0.63} \qquad (6)$$

Conclusions

1. The minimum distance between heat exchangers must be greater than 50 cm.
2. Heat exchangers are not influenced by the material used in their construction, whether copper or PVC.
3. The greater the variation in soil temperature, the more accurate the estimate of heat transfer between soil and water.
4. Considering soil and water temperature variation and the piping material, PVC pipes proved to be more attractive for uses involving thermal exchange with the soil.

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