Evaluation of Inlet Temperature Impacts on Heat Transfer and Soil Thermal Behavior in Horizontal Spiral Ground Heat Exchangers

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***Abstract*— This study investigates the thermal performance of a Horizontal Spiral Ground Heat Exchanger (HSGHE) under varying inlet temperatures in hot climates, with a focus on ground source heat pumps (GSHPs) as a sustainable energy solution. The experimental setup utilized a spiral tube embedded in dry sand placed within a controlled environment. The results indicated that inlet temperature significantly influences heat exchange rates (HER). Higher inlet temperatures initially resulted in higher HER, but these values declined over time due to the diminishing temperature gradient between the circulating fluid and surrounding soil. For an inlet temperature of 50°C, reductions in HER of approximately 40% and 63% were observed at 45°C and 40°C, respectively. After six hours, HER decreased by 58%, 50%, and 36% for 50°C, 45°C, and 40°C, respectively. These findings highlight the long-term impact of inlet temperature on system efficiency, where higher initial HER does not always correlate with sustained high performance.**

The study also assessed soil thermal dispersion and found that heat dissipation was highly localized. For 50°C, the thermal effect extended up to 0.4 meters, while at 45°C, it diminished to 0.3 meters, and at 40°C, the effect was minimal beyond a short distance. Based on these results, an optimal spacing of 0.8 meters between exchangers is recommended to minimize thermal interference and maximize system efficiency. These findings underscore the importance of temperature gradients and operational parameters in optimizing ground heat exchanger performance in hot climates.

Keywords*— *Geothermal Cooling; Ground Source Heat Pump (GSHP); Heat Exchange Rate (HER); Thermal performance; Soil Heat Transfer; Spiral Ground Heat Exchanger

I. INTRODUCTION

In the last few decades, growing economic and environmental pressures, particularly fossil fuel price increases and the pressing demand to lower carbon emissions, have intensified the search for alternative energy solutions that may be cleaner and more sustainable for heating and cooling [1]. In this sense, GSHPs are considered remarkable due to the utilization of relative stable underground temperatures, avoiding the performance fluctuations often encountered by air-based heating and cooling systems [2].A GSHP system works either by extracting heat from the ground into the structure in the heating mode or dissipating heat into the ground in the cooling mode by circulating a heat transfer fluid through underground piping. Such buried loops are termed ground heat exchangers (GHEs) [3] and can be provided in a horizontal (HGHE) or vertical (VGHE) arrangement or as a hybrid system, for example, energy piles integrated into building foundations [4]. Each configuration has different implications for excavation depth, land availability, cost, and operational stability [5].

Horizontal ground heat exchangers (HGHEs) are characterized by their low costs as deep drilling and highly specialized equipment are avoided [6]. Such systems are usually constructed to depths of 1–2 m, making excavation easy [7]. CFD simulations show that, while the linear, spiral, and slinky coil set-ups possess different thermal efficiencies, they are still more economical than the vertical types [8]. In exactly the same manner, it was found that less drilling depth is advantageous for lands where space is plenty [9]. Further study on the designs of spiral-coils proved that these arrangements are space efficient and have better thermal performance [10], [11].

Pipe configuration has an important effect on thermal transfer effectiveness as well as thermal interference.

Nomenclature	
Abbreviations	
HSGHE	Horizontal Spiral Ground Heat Exchangers
GSHP	Ground Source Heat Pump
GHE	Ground heat exchanger
HGHEs	horizontal ground heat exchangers
TRT	thermal response test
CFD	computational fluid dynamics
HER	Heat Exchange Rate
SET	Soil Excess Temperature
Symbols	
m	Mass flow rate of the circulating fluid inside the coil ($Kg.s^{-1}$)
Q	Heat exchange rate (W)
c_p	Specific heat of the circulating fluid ($J\ kg^{-1}K^{-1}$)
T_{in}	Inlet fluid temperature (°C)
T_{out}	Outlet fluid temperature (°C)
T_c	Measured soil temperature (°C)
T_o	Initial soil temperature (°C)
Greek symbols	
k	Thermal Conductivity of Backfill Material ($W\ m^{-1}\ K^{-1}$)
α	Thermal Diffusivity ($m^2\ s^{-1}$)
ε	heat exchange efficiency
θ	soil excess temperature (°C)

Experiments on normal U-loop designs, spiral coils and three-pipe cases indicated that the minimized thermal interference between the inlet and outlet lines of three-pipe systems enhanced overall performance [12]. Additional verification proved that horizontal loops enhance feasibility in large-scale applications because they eliminate the need for deep boreholes [13].

Numerical modeling using software such as COMSOL and FEFLOW has been employed to analyze the thermal interactions between GHE pipes and surrounding soil [14].

Simulations underscore the importance of accurate boundary conditions for predicting temperature profiles under various operational phases. Refinements in numerical models have improved predictions of soil temperature behavior, particularly near the exchanger's core [15]. Additionally, combining numerical and analytical models using Green's function techniques has achieved high precision in estimating ground thermal conductivity and system efficiency [16, 17].

Integrating theoretical models with numerical simulations, validated through thermal response tests (TRTs), remains crucial for optimizing GSHP systems [18]. Studies have explored the impact of pipe arrangements on surrounding soil temperatures, demonstrating that optimizing pipe spacing reduces unwanted thermal interference [19]. Research has also reported that decreasing loop pitch increases heat exchange rates but necessitates balancing against material costs [20].

Despite their cost advantages, HGHEs are susceptible to atmospheric temperature fluctuations due to their shallow placement [21]. Early systems often used linear trench layouts, but closely spaced pipes can induce thermal interference [22]. Slinky and spiral designs offer a solution by fitting more piping into limited trench space [23], yet deeper burial to counteract air-temperature influence raises excavation costs. An optimal depth range of 1.5–2.5 meters has been proposed to balance investment and temperature stability [24].

Additionally, ambient temperature variations significantly impact near-surface exchangers, with studies showing that neglecting seasonal cycles can lead to heat transfer underestimations of up to 22% [25, 26]. Enhancing predictive accuracy for slinky coils by incorporating real local temperature data into finite element simulations has been demonstrated [27].

Although significant progress has been made in designing and modeling GHEs, experimental studies remain limited. While analytical and numerical models have been validated through thermal response tests (TRTs), most of these studies have been conducted in cold regions, with limited investigations in hot climates. Therefore, an experimental model will be implemented to study the impact of hot climate conditions during the summer months on the efficiency of horizontal ground heat exchangers, contributing to the improved reliability of geothermal heating and cooling systems in such environments

II. Experimental system description

In the cooling mode of a Ground Heat Exchanger (GHE) system, heat is dissipated from the circulated fluid to the inner surface of the pipe via convective heat transfer, followed by conduction through the pipe material and the surrounding soil. In a conventional GHE system, heat conduction within the soil is the predominant mode of thermal transport, succeeded by conduction through the pipe wall and convective heat transfer within the fluid domain [28]. However, altering the thermal properties of the soil presents significant challenges, and in practical applications, the pipe material is typically high-density polyethylene due to its favorable thermal and mechanical characteristics. To systematically investigate influence of effect of the inlet temperature on the thermal performance of a HSGHE during the hot climates, an advanced experimental platform was developed at Nahda University, Egypt.

A. *Methodology for Testing the HSGHE System emperature Monitoring System*

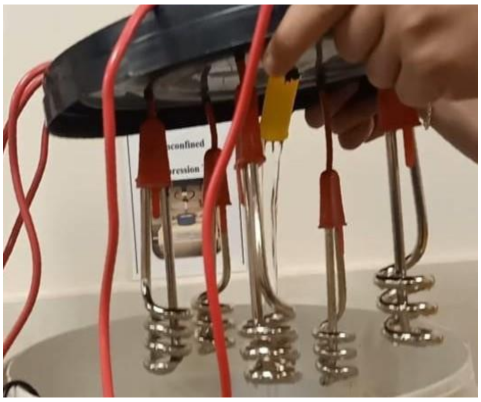
The experimental setup consisted of a wooden box measuring 2 x 1 x 1.2 m, a control unit to control six electric heaters in a thermostatic water tank, a tent measuring 2 x 1 x 1 m within it four quartz heating tubes to simulate the hot climate during summer seasons, a high-density polyethylene spiral tube inside which the fluid was circulated, a water circulation pump to circulate the water inside the spiral tube and a data acquisition system to monitor all temperatures in the wooden box. **Fig.1** illustrates the main components of the system, and the specifications of the measuring devices used in the study are shown in **Table 1**.

The spiral coil had a diameter of 20 cm and a pitch of 10 cm. The HSGHE was constructed using 1.80-meter-long pipes, which were positioned horizontally within the ground and installed at a depth of 90 cm inside the wooden sandbox. The spiral tube was placed 30 cm above the base of the box. Within the sandbox, the spiral tube was placed horizontally and connected with a cord to maintain a constant pitch and spiral diameter. The spiral coil pipe had an inner diameter of 14 mm and an outer diameter of 16 mm.

(a) Installation of spiral tube in wooden box

(b) Installation of tent above the wooden box

(c) Control board



(d) six heating elements inside the thermostatic water tank

Fig. 1. The main components of the system

Table 1

Specification of the measuring devices used in the study

Item	Specification
Thermostatic water tank	Temperature adjustment range: 20 _ 100 °C Accuracy: ±0.5℃
Water circulating pump	Power 100 W ; Lift:20m; Flow:17 L/min
Rotameter	Flow regulation range: 2 _ 18 L/min Accuracy: ±0.1 L/min
Data acquisition	34 channels; Recording interval 20 sec
Quartz heating tubes	Power: 800 W or 400 W
Thermistor sensor	Temperature range: -25 to +100 °C Accuracy: ±0.5℃

To reduce heat loss, 10 mm-thick hardwood boards were used in the construction of the sandbox. To preserve consistent pitch and spiral diameter, in addition to, the spiral tube was horizontally placed and fastened in the sandbox using cord two layers of 10-millimeter-thick glass wool insulation covered the part of the spiral tube reaching beyond the wooden box. Thermistor sensors were installed and fixed using cable ties for accurate positioning.

B. Thermal Monitoring System and Sensor Arrangement

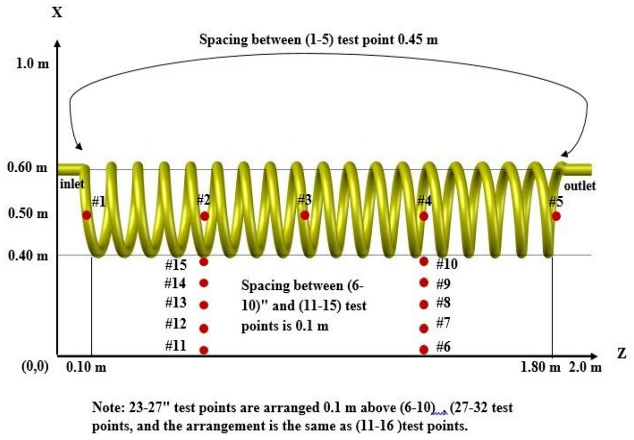
Fig.2 includes the distribution of thermistor locations in the experiment. Thermistors were deliberately arranged at several axial and radial points and at varied depths to track temperature changes precisely. Seven thermal thermistors (#16–#22) were uniformly placed on the outer surface of the spiral tube, with thermistors #33 and #34, respectively, particularly specified to measure the inlet and outlet fluid temperatures to assess fluid temperature variations along the HSGHE. Thermistor #33 was positioned in direct contact with the inlet water, while thermistor #34 was in direct contact with the outlet water, ensuring accurate measurement of temperature variations at these points**.**

Temperature readings taken in several directions and at different distances from the spiral tube produced a complete soil temperature profile. Five thermistors (#1–#5) were equally positioned in the center of the spiral coil to track changes in soil temperature along the axial direction. At varying radial distances, another set of fifteen thermistors (#6–#15, #23–#27) was placed in the wooden box (Fig. 2). Thermistors #11–#15 and #6–#10 were positioned at horizontal distances of 0.55 m and 1.45 m, respectively, from the water inlet, while the thermistors in the #23–#27 group were put directly above the #6–#10 group with a vertical separation of 0.4 m.

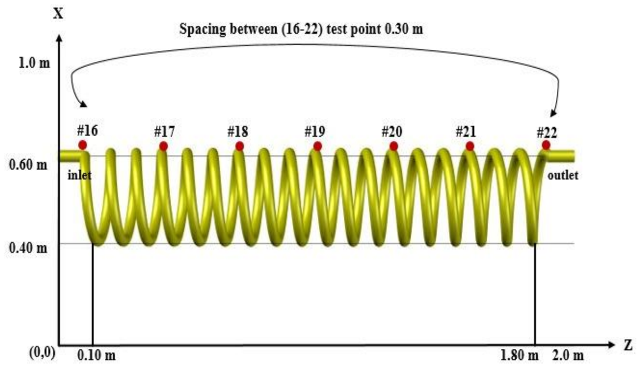
Water and soil temperature data were logged at 20-second intervals using a data capture system to guarantee high resolution thermal monitoring. Inside a controlled tent, a temperature recorder above the sand surface constantly tracked the ambient temperature.

C. The Appropriate Depth for Ground Heat Exchangers

Primary tests were carried out to determine how surface temperatures affect depth and the appropriate depth for the horizontal ground heat exchanger. For 6 hours, surface temperatures of 45℃ affected the sandy soil. Five sensors



(a) Soil thermal sensor array surrounding a spiral tube



(b) Systematization of thermal sensors along the spiral tube's outside

Fig.2 The arrangement of the thermistors within the sandbox from a plan view

(numbered 28# to 32#) were placed parallel to the depth of the box, with a vertical spacing of 30 cm between each sensor to measure changes in temperature.

Fig.3 shows the variation of soil temperature with depth under a surface temperature of 45°C at six hours. The temperature distribution reveals that at the soil surface, the temperature remains constant at 45°C due to the imposed boundary condition.

However, as depth increases, the temperature gradually decreases, demonstrating the process of heat dissipation through soil layers. The initial temperature profile at t = 0h exhibits a steep gradient in the upper soil layers, indicating a rapid decrease in temperature with depth. In contrast, after 6 hours, the soil temperature increases in the shallow layers (0.1m - 0.3m), indicating the gradual penetration of heat over time.

The results confirm the presence of a appropriate depth, approximately between 0.6m and 0.9m, where temperature variations stabilize.

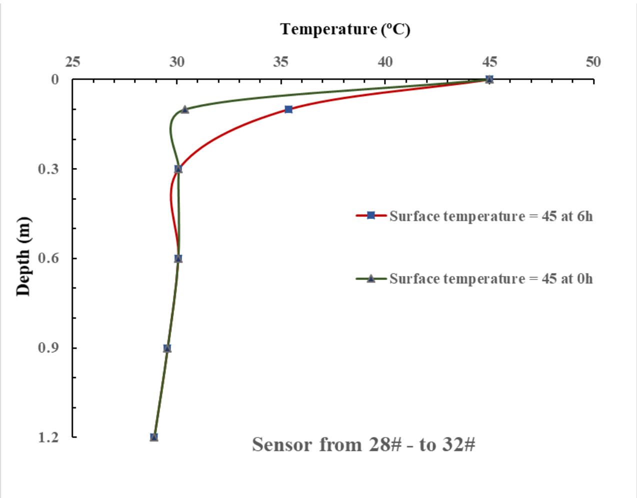


Fig.3 Variations of depth temperatures at different surface temperatures at sand and the sand/limestone powder blend soil after 6 hours

This depth range is particularly relevant for the optimal design and placement of ground heat exchangers (GHEs) to maximize thermal performance and efficiency. Therefore, an appropriate depth of 0.9m is chosen for the ground heat exchanger (GHE).

D. The Backfilling Material and Thermal Properties Measurement

Dry native sand was used as the backfilling material in the experiment. The sand (sieve size: 2.36 mm) was first sieved and then compacted inside the wooden box to achieve a specific density. The thermal properties of the sand were measured using the KD2 Pro thermal properties analyzer, and the measured thermal properties of the sand are presented in **Table 2**. The sand was backfilled with a density of 1677 kg/m³.

E. Experimental Procedure

Experiments were conducted to investigate the impact of different inlet temperatures on the energy efficiency of the HSGHE during the hot and summer climates.

The tests were carried out sequentially from top to bottom, as summarized in **Table 3**. To ensure stable experimental conditions, four quartz heaters were utilized to keep the ambient temperature above the soil surface at 45 ° C throughout the testing period.

The flow rate was maintained at 7 l/min. Each experiment was conducted in a 24-hour cycle, consisting of 6 hours of operation run and 18 hours of operation stop [29]. Then the heat exchange rate (HER) is calculated by eq. (1)

$$Q = C_p m\ (T_{in} - T_{out}) \qquad (1)$$

Where Q is the heat exchange rate of the HSGHE, which is considered an indicator of heat exchange performance, m is the mass flow rate of the circulating fluid inside the coil, Cp is the specific heat of the circulating fluid inside the coil, and Tin and Tout are the inlet and outlet fluid temperatures of the HSGHE, respectively.

As seen in equation (2), the SET, which is defined as the difference between the measured temperature and the initial soil temperature, indicated the temperature variation around

Table 2

Thermal properties of backfill materials

Materials	Thermal conductivity (W/m.K)	Specific heat capacity (J/kg.K)	thermal diffusivity (m2/s)
Sand	1.1	912.04	7.2×10-7

Table 3

Detailed experimental procedures

Test	Material	Inlet temperature (°C)	Flow rate (l/min)	Surface temperature (°C)
1	Dry sand	40	7	45
2	Dry sand	45	7	45
3	Dry sand	50	7	45

the HSGHE throughout the heat exchange process. temperature, and T_o is initial soil temperature

$$\theta = |T_c - T_o| \quad (2)$$

where θ is the soil excess temperature, Tc is measured soil temperature, and To is initial soil temperature**.**

Heat transfer efficiency is the ratio of the present heat exchange rate (HER) to the highest possible HER.

This study used Eq. (3) to explore how factors affect HSGHE heat exchange efficiency.

$$\varepsilon = \frac{Q_a}{Q_m} = \frac{T_{in} - T_{out}}{T_{in} - T_o} \quad (3)$$

Where ε is the heat transfer efficiency of HSGHE, **Qa** is the current HER, **Qm** is the maximum achieve.

F. Experimental uncertainty analysis

An uncertainty analysis determines possible sources of error through experimental manipulation while also assessing the degree of reliability of obtained results. This analysis was, therefore, carried out to confirm the accuracy and credibility of the experimental results.

This study primarily focuses on measuring the water temperature, soil temperature, and the rate of fluid flow. Measurements from these parameters then provide values for heat exchange rate (HER) and soil excess temperature (SET). From the experimental error analysis, there is an evaluation of errors in both directly measured variables and subsequently calculated ones. Relative uncertainties for these parameters were determined using Equations (5) and (6), respectively, as cited in [30].

$$\delta x_i = A.\gamma_i \quad (4)$$

$$\delta R x_i = \frac{\delta x_i}{x_i} \quad (5)$$

$$\delta RF = \frac{\sqrt{\sum_1^n (\frac{\partial F_i}{\partial x_i} \delta x_i)^2}}{F} \quad (6)$$

Where A is the upper limit of the measuring range, γ_i is the accuracy grade of the measuring device.

The function F depends on the measured parameter x_i. **Table 4** presents the error values of main parameter used in this study.

Table 4

Errors of the main parameters used in the study

Parameter	Type of data	Unit	Relative error
Average water temperature	Measured	℃	0.625%
Average Flow rate	Measured	L/min	1.69%
Average heat exchange rate	Calculated	W	1.8%
Average soil excess temperature	Calculated	℃	2.53%

III. RESULTS AND DISCUSSION

A. Effect of Inlet Temperature on Temperature Difference (ΔT) Over Time

Fig.4 shows the relationship between temperature difference (ΔT) and time for different inlet fluid temperatures (50°C, 45°C, and 40°C). In general, the temperature difference (ΔT) decreases over time for all inlet temperatures. At the beginning, the ΔT is relatively high. Then it gradually decreases until it reaches a nearly steady-state condition after several hours. Regarding the effect of inlet temperature, higher inlet temperatures result in a higher temperature difference. This means that the heat exchanger is more effective at transferring heat when the inlet temperature is higher.

The inlet temperature at 50°C shows the highest ΔT, followed by the inlet temperature at 45°C and then at 40°C, confirming this trend. The behavior shown in **Fig. 4** reveals a sharp initial decline in ΔT, indicating rapid heat transfer during the early stage. After this initial phase, the decline becomes more gradual, suggesting that the system is approaching thermal equilibrium with the surrounding soil.

The findings corroborate those of an earlier study by Yang et al. [31], which also reported that the ΔT values are initially high due to the strong thermal transition of the fluid and the soil, and the same gradually decreases as the system approaches thermal equilibrium. This confirms the reproducibility of the observed thermal behavior across different experimental conditions.

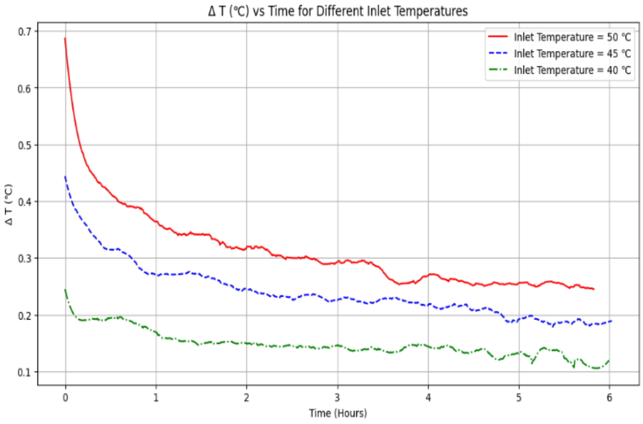


Fig.4 Temperature difference (ΔT) at different inlet temperatures over time

While Yang et al. dealt with moderate and cold climate conditions, the present study confirms the thermal behavior under hot climate environments and thus suggests the thermal behavior to be a robust one across various climatic zones.

B. Effect of inlet temperature on Heat Exchange Performance

The experimental investigations were conducted under meticulously controlled conditions to understand how different inlet temperatures impact the heat exchange rate of horizontal spiral tubes during summer climates. The soil surface temperature was precisely maintained at 45°C, while the fluid flow rate was consistently regulated at 7 l/min throughout the testing period.

The HER with time for different inlet water temperatures, that is 50°C, 45°C, and 40°C, is depicted in **Fig. 5**. All configurations displayed a rapid initial decrease in HER during the first hour of operation, followed by the gradual stabilization of the HER over a 6-hour experiment. Such behavior primarily occurs because of the enormous initial temperature difference between the circulating fluid and the surrounding soil, which encourages enhanced heat transfer at the onset of the process. As the system approaches thermal equilibrium, however, the temperature gradient between the working fluid and the soil diminishes, leading to a progressive reduction in the rate of heat dissipation. The influence of inlet temperature on the heat transfer efficiency is evident from the results.

A higher inlet temperature consistently yields a greater heat exchange rate, with the maximum HER recorded at 50°C, followed by 45°C and 40°C, respectively. This confirms that the temperature gradient between the fluid and the soil is the predominant factor governing heat transfer efficiency.

An increased inlet temperature enhances the thermal driving force, thereby amplifying the heat flux from the fluid to the surrounding soil, in accordance with Fourier’s law of heat conduction.

Initially, the HER at an inlet temperature of 50°C was measured at 320 W, whereas the corresponding values for inlet temperatures of 45°C and 40°C were 210 W and 115 W, respectively. Compared to the HER at 50°C, the values at 45°C and 40°C exhibited a reduction of approximately 40% and 63%, respectively. This variation can be attributed to the substantial temperature difference between the inlet and outlet at higher temperatures, particularly 50°C, which facilitates a more robust heat transfer process. Conversely, at 40°C, the relatively lower temperature differential results in a reduced heat exchange rate.

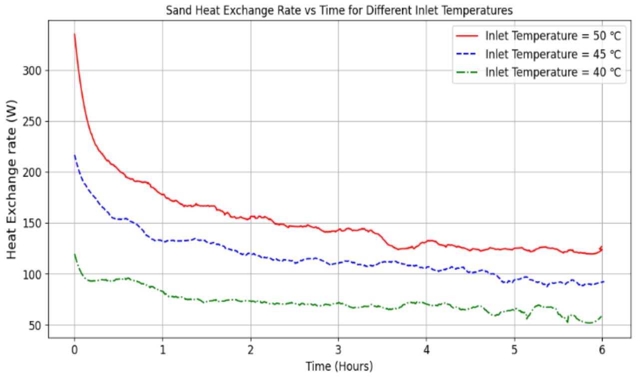


Fig.5 HER values of the HSGHE in relation to operational time across various inlet temperatures

Over time, a noticeable decline in the HER was observed across all test cases. After 6 hours of operation, the HER values had decreased to 125 W, 90 W, and 70 W for inlet temperatures of 50°C, 45°C, and 40°C, respectively. The overall reduction in HER for these cases was 58.3%, 50.0%, and 36.4%, respectively, as illustrated in **Fig.5**. This trend underscores the long-term influence of inlet temperature on system efficiency, where higher initial heat exchange rates do not necessarily translate into sustained high-performance levels over extended operational periods.

A similar trend was reported in the study by Yang *et al.* [31], where numerical and experimental results showed that HER decreases significantly during the first 4–6 hours of operation due to thermal equilibrium with the surrounding soil. The current findings validate that this thermal behavior remains consistent under hot climate conditions, highlighting the importance of intermittent operation or control strategies to mitigate performance degradation.

C. Thermal Dispersion and Optimal Exchanger Spacing

The variation in soil excess temperature as a function of horizontal distance from the center of the spiral heat exchanger for different inlet temperatures (50°C, 45°C, and 40°C) is illustrated in **Figs. 6, 7 and 8**. The temperature distributions were assessed at three distinct positions along the Z-direction (parallel to the spiral tube's length). These include measurements taken at (Z = 0.55 m and Y = 0.9 m), (Z = 1.45 m and Y = 0.9 m), and (Z = 1.45 m and Y = 0.5 m).

At Z = 0.55 m, with a depth of Y = 0.9 m, the maximum soil excess temperature at the center of the spiral coil (horizontal distance = 0 m) reached approximately 10.5°C for an inlet temperature of 50°C, while for 45°C and 40°C, the corresponding values were 7.9°C and 3.2°C, respectively, as shown in **Fig.6**. As the horizontal distance increased, a significant temperature decline was observed. At 0.2 m, the soil temperature dropped to 9.1°C for 50°C, 6.1°C for 45°C, and 2.7°C for 40°C. Beyond 0.4 m, the soil excess temperature approached near-zero values across all cases, indicating a rapid reduction of the thermal effect at larger horizontal distances from the heat exchanger.

At Z = 1.45 m, measured at the same depth (Y = 0.9 m), a similar trend was observed, albeit with slightly lower soil excess temperatures than at Z = 0.55 m. Near the center of the spiral coil, **Fig.7** illustrated that the maximum soil excess temperature reached 9.8°C for an inlet temperature of 50°C, while for 45°C and 40°C, the values were 7.5°C and 3.05°C, respectively.

As the horizontal distance increased to 0.2 m, the excess temperature further decreased to 8.2°C, 5.8°C, and 2.5°C, respectively, for the different inlet conditions. Beyond 0.4 m, the soil temperature became negligible, reinforcing the localized nature of heat dissipation in the surrounding soil.

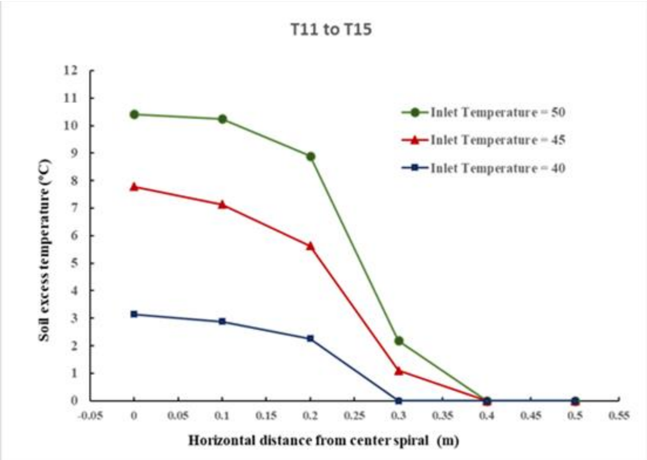


Fig.6 Temperature variations of soil (at z=0.55 m and y=0.9 m) at different inlet temperatures

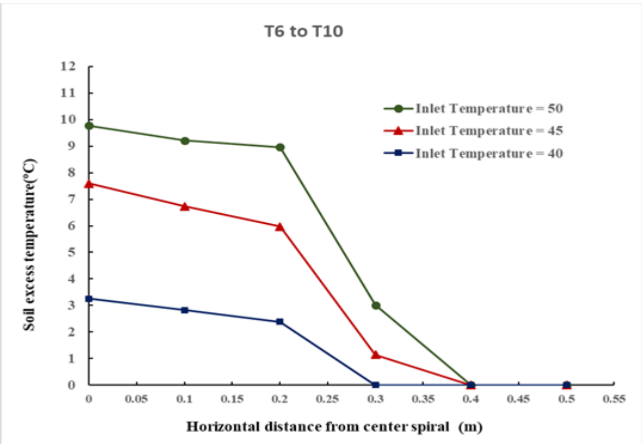


Fig.7 Temperature variations of soil (at z=0.1.45 m and y=0.9 m) at different inlet temperatures

The thermal influence of the spiral heat exchanger was found to vary depending on both the inlet temperature and the horizontal distance from the exchanger. At higher inlet temperatures (50°C and 45°C), the thermal propagation extended up to 0.4 m, whereas for an inlet temperature of 40°C, the thermal effect was negligible beyond 0.3 m. These results align with prior observations that suggest a stronger heat influence at higher temperature gradients, which enhances thermal diffusion in the soil. The observed variation in heat dissipation distances further confirms that the temperature gradient serves as the primary driving force for heat transfer in the soil, with higher inlet temperatures extending the thermal impact over a larger horizontal domain.

Unlike the two previous cases where a significant heat propagation effect was observed, **Fig.8** indicates a negligible impact of the spiral heat exchanger on soil temperature at this location (Z = 1.45 m, y= 0.5m). Across all inlet temperatures, the measured soil excess temperature remains close to zero along the entire horizontal distance from the center of the spiral heat exchanger, suggesting that the thermal influence of the exchanger does not extend to this region due to limited vertical and horizontal heat diffusion. Several factors contribute to this observation, including the distance from the heat source, as the measurement position may be beyond the effective thermal influence zone, preventing significant heat propagation. Moreover, these results reinforce previous findings that the heat exchanger's impact is highly localized, with most heat dissipation occurring near the spiral coil and within a limited horizontal distance (typically ⩽ 0.4 m for higher inlet temperatures and ⩽ 0.3 m for lower inlet temperatures).

Based on the thermal distribution data and observed heat dissipation patterns, placing another heat exchanger at a distance of 0.8 m appears to be a highly feasible approach that minimizes thermal interference between the two systems.

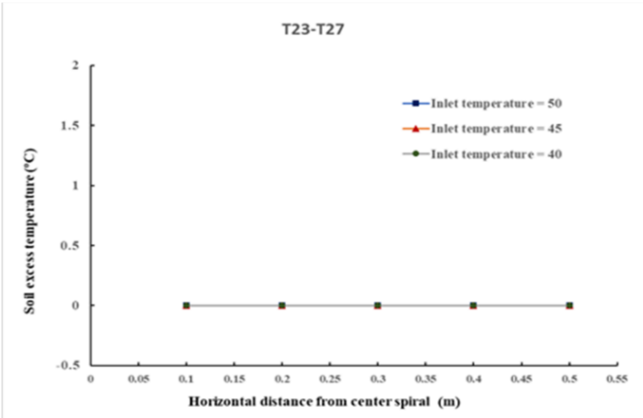


Fig.8 Temperature variations of soil (at z=1.45 m and y=0.5 m) at different inlet temperatures

The results indicate that the thermal influence of the first exchanger becomes negligible beyond 0.4 m, particularly for higher inlet temperatures (50°C and 45°C). By extending the separation distance to 0.8 m, the risk of thermal overlap is further reduced, ensuring that the two exchangers operate independently without significant heat accumulation in the surrounding soil.

These results are consistent with the conclusions of the study by Yang *et al.*, which also highlighted that the thermal effect of a spiral heat exchanger is localized and typically does not extend beyond 0.4 m. That study similarly recommended optimized pipe spacing to reduce thermal overlap and enhance system efficiency—supporting the current recommendation of 0.8 m minimum spacing for hot climate applications.

D. Soil Excess Temperature Variation Over Time

To evaluate these temperature effects further in time, excess soil temperature was observed at a horizontal distance of 0.2 m from the heat exchanger. The main objective is to assess the rate and extent of thermal accumulation in the soil for a 6-hour discharge under three different inlet temperature conditions: 40 °C, 45 °C, and 50 °C.

Fig. 9 indicates that higher inlet temperature would cause a much more rapid increase in the soil excess temperature with time. At 50 °C, therefore, the soil was further subjected to thermal buildup, with a recorded excess temperature of about 9 °C by the end of the testing regime. The gradual upward movement seen in Fig.9 indicates that a certain amount of heat is continuously gaining access to the soil surrounding the heat exchanger. Comparatively, for temperatures of 45 °C and 40 °C, soil temperature increases were relatively slower compared with their peaks of about 6.5 and 3 °C, respectively.

The pervious results demonstrate the strong influence of inlet temperature on soil thermal responses, some of which may yield understanding of how these thermal effects under accumulation vary temporally in the environment surrounding the heat exchanger. The gradual accumulation of heat at the higher inlet temperatures further decreases the temperature differential between the working fluid and the surrounding soil and accounts for the observed reduction in HER over time, as shown in **Fig. 5**.

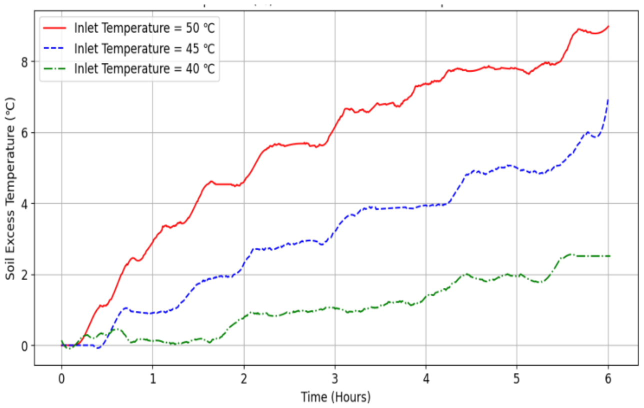


Fig.9 Variation of soil excess temperature over time at x = 0.2 m under different inlet temperatures

These findings confirm the horizontal thermal distributions of **Figs.** 6 and 7, showing that the effects of temperature become more localized with increased duration of high-temperature operation. The restriction of heat flow in this way supports the view of thermal saturation in surrounding soil, especially when an adequate time between cycles to dissipate accumulated heat is lacking.

Upon integrating dynamic thermal dissipation in both time and place, one notes the necessity of having a time management strategy for system operation. Such observations warrant the need to apply an optimized ON/OFF operation cycle in order to avoid permanent thermal saturation in GSHP systems, especially in hot climates where such high inlet temperatures are the norm. This will ensure that the temperature gradient necessary for effective heat transfer is maintained and, thus, the long-term stability and functioning of the system are assured.

Conclusion

This study comprehensively investigated the thermal performance of a Horizontal Spiral Ground Heat Exchanger (HSGHE) under varying inlet temperatures in hot climates. Experimental findings validate the importance of the inlet temperature in determining the heat exchange rate (HER); increased inlet temperatures significantly enhance thermal efficiency. The highest HER was recorded at an inlet temperature of 50°C. If the inlet temperature were changed to 45°C, the HER would decrease drastically by 40%, while at 40°C, the HER would suffer an even higher decline of about 63%. The greater the reductions in HER at the lower inlet temperatures further confirm that the heat transfer efficiency is strongly dependent on the initial thermal gradient between the circulating fluid and the surrounding soil.

The various mechanisms for heat transfer commonly followed a pattern where the heat exchange rate exhibited a sudden drop within the first hour, setting into a more gradual stabilization through the subsequent six hours of testing. This behavior can be explained by the fact that in the initial phase, heat exchange was facilitated rather quickly by the large temperature difference between the working fluid and the surrounding soil, a factor that later got minimized as the system approached thermal equilibrium.

In addition to HER evaluation, soil thermal dispersion was also investigated in this study. The results indicated that for 50°C and 45°C inlet temperatures, heat transfer was observed up to 0.4 m away from the spiral heat exchanger, while for 40°C, the heat dissipation effect was more restricted, approximately limited to 0.3 m. This means that higher inlet temperature not only improves rate of transfer of heat but also increases the zone of influence thermally to the surrounding soil. On the basis of these findings, a minimum spacing of 0.8 m was proposed between different thermal energy exchangers to prevent thermal interference and make sure that the system is functioning optimally.

The conclusion gained from this study contribute to the optimization of HSGHE design and operation, particularly in hot climate regions where efficient cooling systems are essential. By carefully regulating the inlet temperature and maintaining adequate exchanger spacing, it is possible to enhance the long-term efficiency and sustainability of ground heat exchanger systems. These findings can be applied to real-world scenarios where geothermal energy is utilized for cooling applications, supporting the development of more energy-efficient and environmentally sustainable thermal management solutions.

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