Experimental Study on the Effect of Flow Rate on the Performance of Horizontal Ground Heat Exchangers in Sand Soil during Hot Climates

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***Abstract*—Ground heat exchangers are extensively utilized in geothermal heating and cooling systems due to their efficiency and sustainability. This research presents an experimental study on the effect of flow rate on the performance of horizontal ground heat exchangers in sand soil. The study investigates how varying flow rates impact heat exchange efficiency, soil temperature distribution, and thermal performance during hot climates. A laboratory setup was developed to simulate real-world conditions, incorporating a spiral coil heat exchanger buried in sand soil. Experiments were conducted at different flow rates (5 L/min, 6 L/min, and 7 L/min), while monitoring temperature variations in both the soil and circulating fluid. The results indicate that increasing the flow rate enhances convective heat transfer, leading to a 31.8% improvement in heat exchange rate when increasing from 5 L/min to 7 L/min. However, the benefits diminish over time, with heat exchange rate decreasing by approximately 55% within the first three hours as thermal equilibrium is approached.**

In terms of soil temperature distribution, the study found that heat dissipation in the horizontal direction becomes negligible beyond 0.4 meters, while in the vertical direction, temperature influence fades beyond 0.4 meters. At lower flow rates, soil temperature gain increased by up to 38% compared to higher flow rates, due to prolonged heat retention. This study focuses the importance of optimizing flow rates to balance energy efficiency and thermal performance in ground heat exchangers

Keywords— Flow rate; Ground Heat Exchanger; Heat Exchange Efficiency; Soil Temperature Gain; Thermal Performance

I. INTRODUCTION

Rising carbon dioxide (CO_2) emissions from burning fossil fuels have greatly hastened climate change in recent years. Rising world average temperatures, melting polar ice, and more frequent extreme weather events [1]are outcomes of this change. This is a result of residential building sector energy use for heating and cooling, which makes about forty percent of world CO_2 emissions [2]. Thus, offering systems supporting environmental sustainability and energy economy is essential. As a result, geothermal energy exchange systems [3], among other renewable energy sources, are in more and more demand. One widely used geothermal heating and cooling system is the horizontal ground heat exchanger (HGHE). Using the somewhat constant temperature of the earth to permit sustained heat transmission, HGHEs are reliable, cost-effective, and efficient [4]. These systems consist of a network of pipes buried underground, through which a fluid is pumped. Seasonal temperature fluctuations allow the fluid to either absorb or release heat, hence maximizing thermal transfer [5]. Several elements influence their performance, including ambient temperature [5, 6], pipe size and form, and soil thermal characteristics [6]. They are beneficial because HGHEs lower carbon and greenhouse gas emissions, improve thermal efficiency, and cut power use [7].

Though their initial outlay is considerable, they save a lot of money throughout operations and maintenance [8]. Their adaptability also enables application in industrial, commercial, and residential buildings, therefore providing a scalable and versatile solution [9]. HGHE efficiency is affected by multiple factors, such as soil thermal properties, pipe depth and arrangement, flow rate, and environmental conditions. Several configurations of horizontal heat exchangers exist, including the straight horizontal heat exchanger, the spiral coil heat exchanger, the mat-type heat exchanger, and the multi-pipe horizontal heat exchanger [10].

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A straight horizontal heat exchanger is simplest and most traditional, where pipes are laid horizontally in long trenches at sufficient depth.

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
Q	Heat exchange rate (W)
Symbols	
m	Mass flow rate of the circulating fluid inside the coil ($Kg.s^{-1}$)
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 ($m^2\ s^{-1}$)
θ	soil excess temperature (°C)

It is cost-effective and easy to install but requires large land area for optimal heat transfer [11]. The performance is enhanced in moist soils due to their higher heat capacity. The spiral coil heat exchanger is a contemporary design with pipes arranged in the spiral pattern, having advantages in increasing the heat exchange surface area while minimizing excavated soil requirements [12]. Research shows that this configuration presents quite a considerable enhancement in thermal efficiency compared to straight pipe designs by creating a better thermal contact between pipes and soil, which in turn, leads to enhanced heat pump performance [13].

Mat-type heat exchangers consist of horizontally arranged tubes so that heat can be transferred evenly into the ground. Usually, they are employed in commercial and industrial cooling systems [14]. Studies indicate that mat-type exchangers ensure more uniform cooling with better thermal performance than straight types due to the large area of coverage offered by the pipes [15]. The multi-pipe horizontal heat exchanger is an improved design incorporating deeper layers of pipes at different depths, thus improving heat exchange without excessive excavation costs [16]. This system works well in space-limited conditions where high thermal efficiency is required [17]. Studies have also verified the benefits of multi-pipe systems on geothermal heat pump efficiency, particularly in warmer climates [18]. Of these types, the spiral coil heat exchanger is sometimes regarded as the most practical, because it combines thermal effectiveness with simplicity of installation and minimum excavation requirements; hence the system is applicable for a wider range [19]. The flow rate is an essential parameter affecting the thermal behavior of the HGHE as it influences heat transfer between the working fluid and the surrounding soil [20]. Heat transfer is better in soils with high thermal conductivity than in soils with high organic content [21]. Burial depth also affects temperature stability, as deeper pipes experience lesser temperature fluctuations [22]. Pipe arrangement, in turn, affects heat transfer either in horizontal, serpentine, or parallel configuration [23]. The optimization of flow rate is directly proportional to performance, whereas very low flow rates result in prolonged ground heat exchange with excessive heat loss, while very high flow rates account for hydrodynamic resistance and increased energy costs for pumping [24]. Other factors like seasonal variations, ambient temperature, and humidity also influence heat exchange capacity [25].

Choosing the optimum flow rate, which will serve as the key in optimizing efficiency in heat transfer and energy consumption, is an important part of the optimization of HGHE performance [26]. In other studies, it was shown that increasing flow rates improve thermal performance to some threshold; further increases elevate energy use while the thermal gains do not significantly improve [27]. Thus, balance is necessary between soil, fluid properties, and system requirements for optimal performance in these renewable thermal systems.

The aim of this research is to find out experimentally the effect of varying flow rates on horizontal ground heat exchanger (HGHE) performance laid within a sandy soil. The issue of flow rates that affect heat transfer efficiency, soil temperature distribution, and overall system performance are being discussed here. This study improves the thermal efficiency of HGHEs while essentially promoting sustainable, energy-efficient geothermal systems by optimizing flow rates. One of the notable contributions of this research is in improving cooling efficiency through use of ground as a natural heat sink. It investigates how high-temperature water, similar to that passing through condensers in cooling systems, can be effectively cooled through underground pipes in sandy soil. The lesser dependency on mechanical cooling systems reflects in lower energy consumption and reduced operational costs and improved efficiency of a system. Thermal balance in ground heat exchangers is important for their long-term efficiencies. This study endeavours to determine the most appropriate flow rate that would prevent high thermal accumulation in soil, and thus ensure stable system performance. In addition, it would highlight the thermal characteristics of sandy soil, which has moderate thermal conductivity, thus improving heat dissipation and facilitating good cooling

II. MATERIAL AND METHODS

A. *Laboratory Setup for HGHE Testing*

Fig.1(a-d) illustrates a laboratory setup for a horizontal ground heat exchanger (HGHE) for evaluating the flow and temperature performance of an HGHE spiral tube during summer climates. It features a wooden box (2000 × 1200 ×1000 mm) as shown in Fig. 1(d), a data acquisition system, a thermal water tank equipped with a temperature control unit (Fig. 1(c)), a pump for circulating water within the tank, a flow meter, and a tent above the apparatus that contains quartz heating tubes (Fig. 1(b)), a spiral tube, and a water pump to circulate water within the spiral tube. A spiral tube made of high-density polyethylene (inner/ outer diameter 14mm/16mm) will be used as HGHE. The diameter of the spiral ring was 20 cm, and the distance between the rings was 10 cm, as shown in **Fig. 1(a).**

The HSGHE, with a length of 1.80 meters, were installed at a depth of 90 cm below the soil surface and positioned 30 cm above the base of the box.

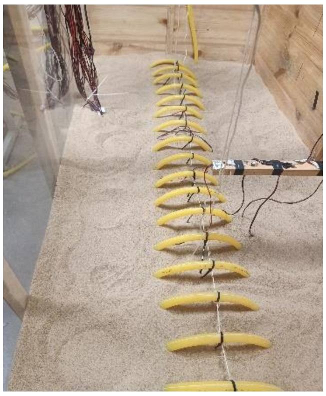
The sand was used as backfill material for the experiments. The sand has been spread on the ground and air-dried for four weeks, being turned over regularly to speed up the drying process. After sieving backfilling material (sieve size 2.36 mm), the soil within the wooden box was compacted down to a specific density. The wooden box was filled with dry sand with a density of 1677 kg/m3. The thermal properties of the sand utilized as a backfill material were determined using a KD2 Pro thermal properties analyzer.

The measured values indicated a thermal conductivity of 1.1 W/m·K, a specific heat capacity of 912.04 J/kg·K, and a thermal diffusivity of 7.2×10^{-7} m²/s. A tent was assembled above the soil with heaters to simulate hot climates and ensure the stability of the temperature on the soil surface. This ensures that study of the flow rate's effect under constant climatic conditions throughout the experiment and at a constant soil surface temperature equal to 45˚C (Fig. 1(b)).

B. *Temperature Monitoring System*

Twenty-seven thermistors were used to monitor soil temperatures around the HSGHE during the test, as shown in **Fig. 2 (a, b)**. Five of these thermistors (#1 to #5) were evenly distributed along the axial centerline of the HSGHE to track soil temperature variations along its axis, as shown in **Fig. 2(a).**

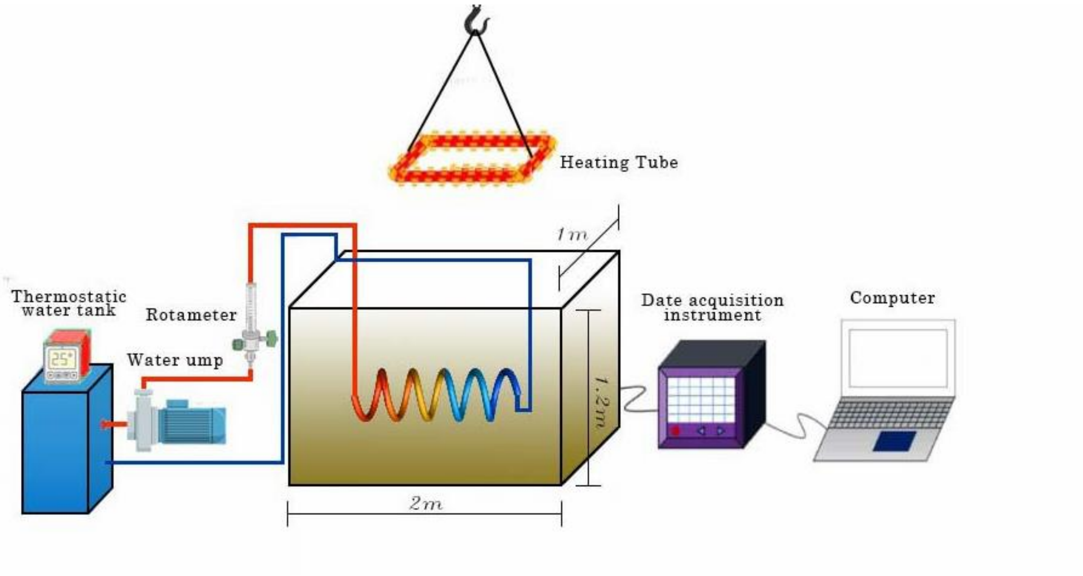
Additionally, 20 thermistors (#6 to #15 and #23 to #32) were positioned around the system to monitor soil temperature distribution at various distances and directions from the spiral tube (Fig. 2(a)). To further analyze water temperature variations, measurements were also taken at five test stations along the exterior surface of the HSGHE (#16 to #22) as shown in **Fig.2 (b)**.



(a) Installation of spiral tube

(b) Tent with heaters inside it

(c) Control of inlet and surface temperature



(d) Experimental schematic diagram

Fig.1. A laboratory setup for a horizontal GHE

Thermistors #33 and #34, respectively, were particularly specified for measuring 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.

All thermistors were connected to a data acquisition system, which recorded temperature readings at regular 20-second intervals. This comprehensive sensor arrangement ensured accurate monitoring of heat transfer dynamics in the soil and water surrounding the heat exchanger.

C. Methodology for Testing the HSGHE System emperature Monitoring System

Table 1 represents the experimental program adopted to indicate the efficiency of the HSGHE system as related to different flow rates with a total number of the 3 experiment programs.

Four quartz heaters were activated inside a 2m × 1m × 1m tent to regulate and maintain the soil surface temperature during each test. The inlet and soil surface temperatures were maintained at 45°C.

Each experiment was conducted in a 24-hour cycle, consisting of 6 hours of operation run and 18 hours of operation stop [28].

D. Methodology for Testing the HSGHE System Emperature Monitoring System

Testing data, including temperatures and flow rate, were used to evaluate the HSGHE's heat exchange efficiency (ε), soil excess temperature (θ), and heat exchange rate (Q).

Heat exchange rate (Q) is defined by eq. (1) as:

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

Where Q is the heat exchange rate of the HSGHE, which considered an indicator of heat exchange performance, *m* is the mass flow rate of the circulating fluid inside coil, $\mathbf{C_p}$ is the specific heat of the circulating fluid inside coil, $\mathbf{T_{in}}$ and $\mathbf{T_{out}}$ are the inlet and outlet fluid temperature of the HSGHE, respectively.

As seen in equation (2), the temperature variation around the HSGHE throughout the heat exchange process is indicated by the soil excess temperature, which is defined as the difference between the measured temperature and the initial soil temperature.

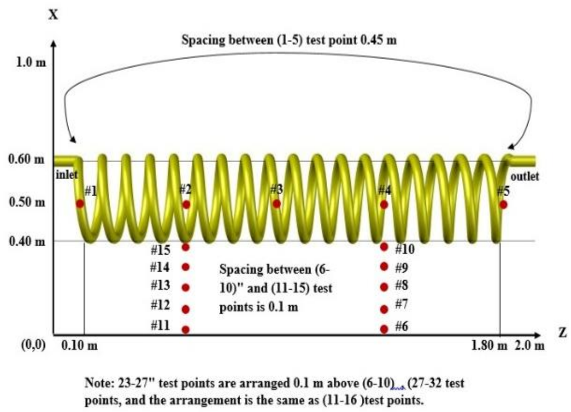
$$\theta = |T_c - T_o| \quad (2)$$

Where θ is the soil excess temperature, T_c is measured soil temperature, and T_o is initial soil temperature.

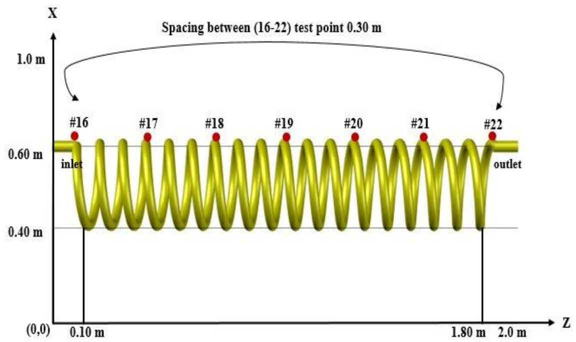
Heat transfer efficiency is the ratio of the actual heat exchange rate, HER, (Q_a) to the maximum possible HER (Q_m). This study used Eq. (3) to explore how factors affect HSGHE heat exchange efficiency[29].

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

Where ε is the heat transfer efficiency of HSGHE, Q_a is the current HER, Q_m is the maximum achievable.



(a) Soil thermal sensor array surrounding a spiral tube



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

Fig. 2. Layout of the sandbox's measuring points in plan view

TABLE 1. DETAILED EXPERIMENTAL PROCEDURES

Test	Material	Inlet temperature (°C)	Flow rate (l/min)	Surface temperature (°C)
1	Dry sand	45	5	45
2	Dry sand	45	6	45
3	Dry sand	45	7	45

III. Results and Discussion

A. Effect of Flow Rate on Temperature Difference in the HSGHE

Fig. 3 illustrates the time variation of the fluid temperature difference (ΔT = Tin - Tout) per unit length of the HSGHE (°C/m) for different flow rates of 5, 6, and 7 L/min; the HSGHE buried in the sand soil. A general trend observed in **Fig. 3** is the gradual decrease in ΔT over time, indicating that the system is approaching thermal equilibrium. Initially, the temperature difference is at its peak due to the significant contrast between the inlet water temperature and the surrounding soil. However, as heat is transferred from the circulating water to the soil, the temperature gradient diminishes, leading to a reduction in the heat exchange rate over time.

Based on Fig. 3, one can predict the required heat exchanger length to satisfy a certain temperature difference for the working fluid.

The impact of flow rate on temperature difference per unit length is evident in **Fig. 3**. The lowest flow rate of 5 L/min consistently exhibits the highest (ΔT/L) throughout the experiment. This can be attributed to the slower-moving water having more time to exchange heat with the surrounding soil, allowing it to cool more effectively before exiting the system. In contrast, the highest flow rate of 7 L/min exhibits the lowest ΔT/L values, as the water travels rapidly through the heat exchanger, reducing its exposure time for thermal exchange. The intermediate flow rate of 6 L/min follows a similar trend, producing results that fall between the two extremes.

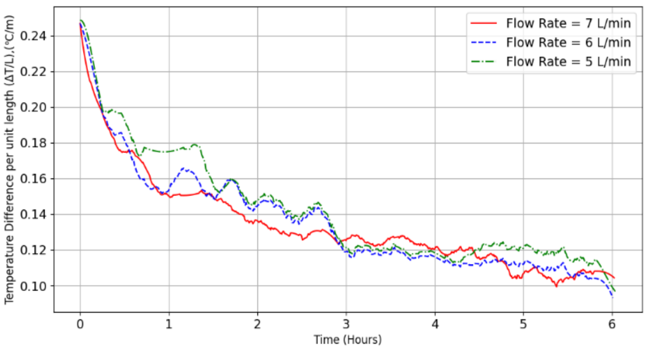


Fig. 3. Temperature Difference per unit length Over Time for Different Flow Rates in a HSGHE

From a heat transfer perspective, a lower flow rate is advantageous when the goal is to maximize the temperature reduction of the fluid before reuse. However, if the objective is to achieve the highest total heat extraction from the system, a higher flow rate is more efficient, as it ensures a greater volume of water is cooled per unit of time, even if each unit experiences a smaller temperature drop. **Fig. 3** also suggests that after approximately three hours, all flow rates exhibit stabilization with minor fluctuations, implying that the system is reaching a steady-state condition where the heat transfer rate balances with the thermal properties of the surrounding soil

B. Effect of Flow rate on HER

While maintaining a constant inlet and surface temperature of 45℃, the heat exchange rate per unit length (W/m) was tested with three distinct flow rates of 5, 6, and 7 l/min of water. Dry sandy soil was used for all experiments.

Fig. 4 illustrated the relation between HER, per unit length of HSGHE, over time during six hours of operation. At the beginning of the experiment, the HER experienced a rapid drop, particularly within the first three hours. Initially, the heat exchange process was efficient due to the substantial temperature difference between the soil and the water inside the spiral tube. However, as heat transfer progressed, the temperature differential decreased, leading to a reduction in HER. The data indicate that HER decreased by approximately 55% across all three flow rates throughout the experiment.

An evaluation of the flow rates highlights the impact of fluid velocity on heat transfer rendering efficiency. At the start of the experiment, at a flow rate of 7 L/min, a reduction to 6 L/min resulted in an 18.2% drop in HER, whereas a reduction from 7 L/min to 5 L/min showed even larger drops of 31.8%. The interpretation is that perhaps an increased flow rate lifts convective heat transfer as a direct consequence and therefore the less inefficient energy system performance. However, as the experiment progressed, a decreasing trend in HER due to diminished flow rates became less significant. By the end of the experiment, there was a 10% drop in HER when the flow rate decreased from 7 L/min to 6 L/min, as opposed to a 20% drop recorded when reducing from 7 L/min to 5 L/min. This indicates that benefits of higher flow rates are reduced as time passes due to thermal saturation.

The overall trend suggests that while higher flow rates contribute to greater heat exchange, their effectiveness is constrained by the system's thermal equilibrium. In the early stages, high flow rates are advantageous as they maximize heat transfer when the temperature differential is significant. However, as the system stabilizes, the impact of flow rate variations diminishes. This highlights a nonlinear relationship between flow rate and heat exchange efficiency, where the benefits of increased flow diminish as the heat exchanger approaches steady-state conditions.

Finally, if the objective is to achieve maximum heat transfer efficiency, operating at 7 L/min is the most effective. However, if energy conservation and operational cost efficiency are priorities, a moderate flow rate of 6 L/min may provide an optimal balance. The lowest flow rate, 5 L/min, results in the least heat exchange, making it less desirable unless energy savings are a critical factor.

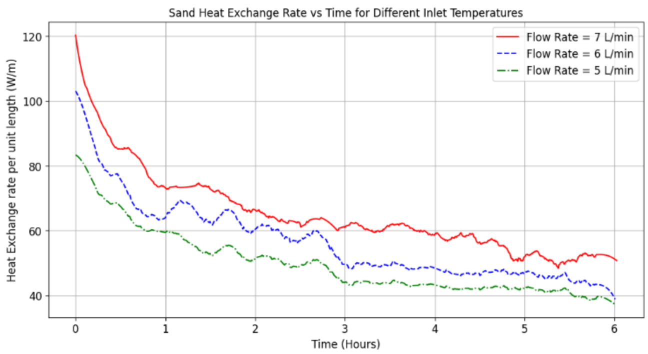


Fig. 4. HER per unit length values of the HSGHE in relation to operational time across various flow rates.

C. Impact of Flow Rate on Soil Temperature Gain in Horizontal Distance

Figs.5 and 6 show that the relationship between soil temperature gain and horizontal distance (z) from the center of the spiral tube to the box wall at different flow rates is illustrated. Near the heat exchanger, at z = 0.1 m, the soil temperature gain is highest due to direct exposure to the thermal energy of the circulating fluid. However, as the horizontal distance increases, the soil temperature gradually decreases and approaches zero at approximately 0.4 m for all flow rates. This indicates that the heat transfer effect is confined to a specific range, beyond which the thermal influence becomes negligible.

The effect of flow rate on soil temperature gain is clearly demonstrated in **Fig.5.** A higher flow rate (7 L/min) results in a lower soil temperature gain, while a lower flow rate (5 L/min) increases soil temperature gain. At the center of the spiral tube, increasing the flow rate from 5 L/min to 6 L/min leads to an 11% decrease in soil temperature gain, while increasing it to 7 L/min results in a 38% reduction. This trend is explained by the water residence time effect—at lower flow rates, the water remains in the exchanger for a longer duration, allowing more heat to be transferred to the surrounding soil. Conversely, at higher flow rates, water moves faster through the exchanger, reducing the time available for heat transfer, thereby lowering the soil temperature gain. This cause-effect relationship is a key finding, providing insights into the balance between flow rate, soil heating, and heat exchange efficiency.

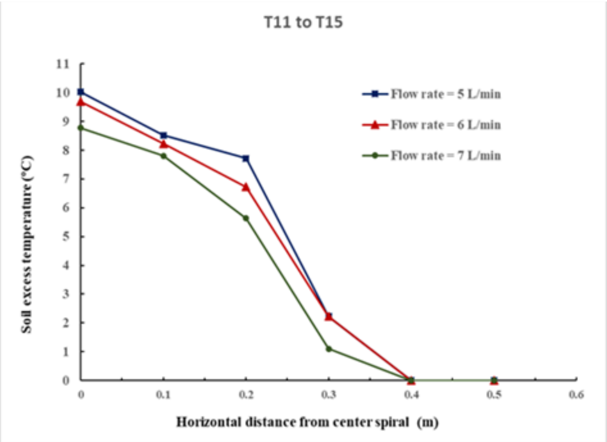


Fig. 5. Temperature changes at the measuring points (at z=0.55 m and y=0.9 m) at different flow rates

A comparative analysis of **Fig.5** and **Fig.6** (T11 to T15 and T6 to T10) further highlights the influence of horizontal distance (x) from the inlet on soil temperature gain. In Fig.4 (T6 to T10, farther from the inlet), the soil temperature decline is more abrupt, with the temperature dropping sharply beyond x = 0.2 m and approaching zero at x = 0.4 m. This suggests that heat transfer effectiveness diminishes rapidly as water moves further from the inlet, indicating that much of the heat is lost within the initial sections of the exchanger. In contrast, in the Fig.5 (T11 to T15, closer to the inlet), the temperature decline is more gradual, suggesting a more uniform heat distribution. This is likely due to the proximity of sensors (T11–T15) to the water inlet at z = 0.55 m, where the fluid is at its highest temperature, ensuring consistent heat transfer over a longer horizontal distance.

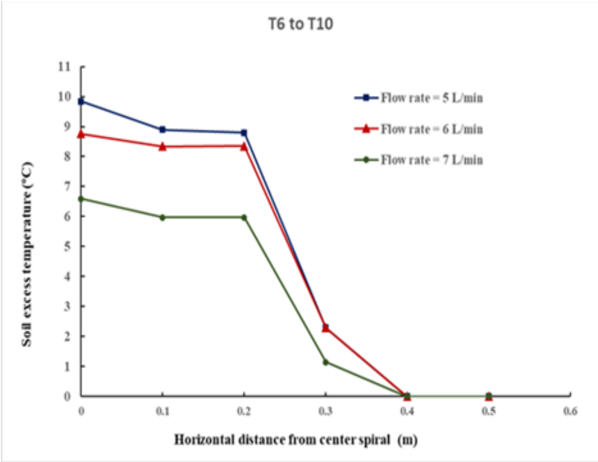


Fig. 6. Temperature changes at the measuring points (at z=1.45 m and y=0.9 m) at different flow rates.

Fig.7 illustrates the soil excess temperature variations at a depth of y = 0.5 m and a horizontal distance of z = 1.45 m from the water inlet for different flow rates (5 L/min, 6 L/min, and 7 L/min). Unlike the previous cases, the soil temperature gain in these measurement points is nearly negligible, remaining close to zero across all measurement points. This indicates that at this specific depth (y = 0.5 m), horizontal distance (z = 1.45 m) a distance of 0.4 meters from SGHE in the vertical direction, the heat transfer effect is minimal, suggesting a weak thermal influence of the heat exchanger in this region.

Additionally, the overall trend confirms that higher flowrates increase the heat exchange rate (HER) but reduce soil temperature gain. Since the 7 L/min flow rate yielded the highest HER, further experimental tests on backfilling materials will be conducted at this optimized flow rate to enhance the thermal performance of the system. This research underscores the need for a strategic balance between flow rate and residence time to optimize both soil heating and heat extraction efficiency in ground heat exchangers.

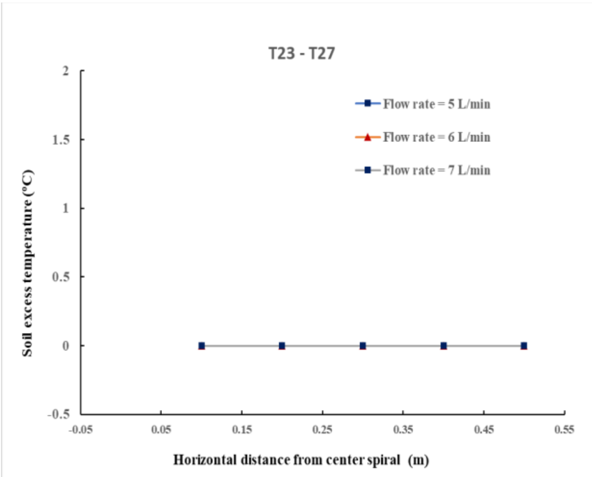


Fig. 7. Temperature changes at the measuring points (at z=1.45 m and y=0.5 m) at different flow rates.

CONCLUSION

This study experimentally investigated the effect of flow rate on the performance of horizontal spiral ground heat exchangers (HSGHE) in sand soil during hot climates. The results demonstrated that flow rate plays a crucial role in determining heat exchange rate (HER), soil temperature distribution, and overall system performance.

The results show that for the case when the flow rate is from 5 L/min to 7 L/min, HER improves with 31.8% gained from the increase in convective heat transfer. Afterward, efficiency gain becomes smaller and even negative after 55% decrease of HER over the first three hours of testing which is actually the approach for thermal equilibrium of the design. This shows that increase flow rates would decrease returns in thermal gains because of the nonlinearity of flow rate in performance of exchanging heat..

Regarding heat dissipation, the study revealed that the thermal influence becomes negligible beyond 0.4 meters in the horizontal and the vertical direction. This suggests that additional heat exchangers should be placed beyond these distances to avoid thermal interference and optimize energy transfer.

The effect of flow rate on soil temperature gain was also evident, with the lowest flow rate (5 L/min) leading to 38% higher soil temperature retention compared to the highest flow rate of 7 L/min. This is due to the prolonged residence time of the circulating fluid, which allows more heat to be transferred to the surrounding soil.

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