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Numerical Analysis of Horizontal Geothermal Heat Exchanger at Various Burial Depths for Solar PV/T Cooling in South Iraq Weather

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ABSTRACT

It can be described that high solar radiation intensity is the basis for the performance of solar photovoltaic modules. Therefore, it causes a decrease in the efficiency of the panel due to the increase in its surface temperature and thus affects its lifespan due to periodic thermal effects. This paper presents an analysis of the PV panel performance and thermal problems and attempts to solve them by cooling it during the day using water circulation in a heat exchanger embedded in the ground. The present work aims to analyze the thermal exchange process of geothermal heat exchangers by computational simulation approach. The research parameters included changing the depth of the copper pipe loop in the soil at 0.5, 1.0, and 1.5 m, and water flow rate of 0.0278 kg/s, copper pipe length, and thermal conductivity of soil in steady conditions employing the yearly weather data of southern desert in Iraq. The computational simulation results manifested that during the solar day, the fluctuations of outlet water temperature are diminished when the burial depth of the heat exchanger is around 2.0 m due to the soil's elevated thermal inertia. In addition, the temperature of the ground is comparatively stable and these values are higher than the inlet water temperature in winter with low values in summer.

1. INTRODUCTION

The desert climate presents a difficult barrier to the use of solar PV and a ground exchanger is one of the cooling systems utilized to treat this problem. Ground heat exchangers are comprehensively utilized in a wide range of industrial applications, including cooling and heating water, and solar heat collector systems. The optimization of heat transfer play's important role in reducing energy wastage across different applications. The importance of energy conservation has led examiners to concentrate on heat transfer improvement, as an enhanced heat transfer rate leads to augmented system performance, which is principal for thermal application systems [1]. A ground heat exchanger (GHE) offers a practical option to reduce the consumption of energy in thermal systems, utilizing the stored heat in the soil of the ground. Stored heat in the soil allows heat absorption in the daytime, and heat supply in the night. Dorobantu et al. [2] experimentally examined two ground coils and aluminum oxide nano-fluid in ethylene glycol increased heat transfer rates by up to 9%. Coil with varying nanofluid concentrations improved thermal performance by up to 5%. The study found no significant difference in thermal performance factors across Reynolds numbers. Go et al. [3] studied water flow and heat transfer by using a ground exchanger design with a linear coil and found that structural changes increased heat transfer, but also increased pressure drop, indicating a direct impact on the thermal performance of the devices.

In their comprehensive study on the dynamics of heat transfer within turbo-tube configurations, Bansal et al. [4] meticulously examined the efficacy of helical coil heat exchangers compared to their cylindrical counterparts. The research specifically focused on helical coils with two distinct bend ratios of 0.114 and 0.078, assessing their performance under a range of flow rates from 1.89×10^{-4} to 6.31×10^{-4} m^3/sec. The investigation also included a thorough analysis of temperature variations at the outlet, ranging from 92°C to 149°C. The findings revealed that helical coil heat exchangers exhibit significantly enhanced heat transfer capabilities. This improvement is primarily attributed to the direct-turbulent flow mechanisms that are more effectively facilitated in the helical structure as opposed to straight tubular designs. The overall heat transfer coefficient in helix configurations was observed to be substantially higher, underscoring the potential benefits of employing helical designs in applications where efficient heat transfer is crucial. This research not only highlights the superior performance of helical coils in managing thermal energy but also provides critical insight into the optimization of heat exchanger designs for industrial applications.

Ground exchanger devices like linear coils are widely used. Numerical investigations show that linear and circler coils and slotted net enhance Nusselt number and friction factor. Solid copper coil achieves the highest hydraulic performance [5]. Jakhar et al. [6] examined flow characteristics, friction factor, and the heat performance factor of fluid flow through linear circler coil heat exchangers, finding a 35.48% and 88.06% decrease in these factors. They have detail described the helical design in U-heat exchangers at different conditions compared the helical model with straight models in heat exchangers, and studied all factors that affect the performance.

Shallal et al. [7] investigated a new type of heat exchanger that depends on a double tube to produce hot and cold air in industrial applications. So, they displayed how use to double-pipe evaporate and condenser in the air-cooling system, while 45 m^3 cooled region at a heat load of 2.24 kW. The study utilized a CFD model to compute outcomes for a linear ground coil with various dimensions and heat exchanger effectiveness. They examined the impact of pipe surface roughness, length, and heights in soil on heat transmission and pressure drops [8]. Found that increasing surface roughness enhanced heat transfer rate and pressure drops. Thermal performance improved by about 35% with linear shape. Reduced flow rate led to higher heat transfer rates and pressure drops. Increasing height burial in the soil proved more effective than ΔT in increasing heat transfer rates [9, 10].

In their analysis, Magazoni et al. [11] delved into the complexities of crossflow heat exchangers, focusing on the derivation of outlet temperatures via the ε-NTU method. They segmented the pipe fluid path to explore how different arrangements influenced the heat capacity ratio (C_{min}/C_{max}), discovering that as this ratio trends toward zero, the accuracy of the ε-NTU curves in predicting the performance of the heat exchanger significantly improves. Despite the detailed structural considerations, they concluded that the installation depth had minimal influence on performance, a finding that emphasizes the paramount importance of flow rate and fluid type in determining heat exchanger efficiency [12, 13]. Expanding on related research, Hongbing et al. [14] conducted a detailed study on the effects of spring-type turbulators inside the internal pipe of a twin-pipe heat exchanger. They meticulously measured the rates of energy transfer and the corresponding changes in the Nusselt number, focusing on the performance enhancements brought about by these modifications. Their experimental results showed that inserting a linear coil not only increased the heat transfer rate (HTR) but also led to higher pressure drops compared to those observed in smooth ground heat exchangers. As they extended the length of the coil, they documented increases of 16.6% in the Nusselt number and 14.6% in the friction factor, demonstrating a significant augmentation in energy transfer efficiency. This enhancement is particularly notable when contrasted with the outcomes from smooth, unmodified tubes, indicating a profound effect of spring-type modifications on the overall energy dynamics within heat exchangers

Some investigations on PV/T cooling integrated with GHEs using nanofluids as thermal fluids have been reported. Abbas et al. [15] reviewed the application of nanofluids in PV/T systems and concluded that maximum efficiency can be obtained at higher velocity laminar flows. Increasing the velocity to higher ranges of turbulent flow does not allow proper time for heat transfer and can cause the clustering of nanoparticles Sangeetha et al. [16] used nanofluid in experiments of a based PV/T for increasing the electrical efficiency of the system. The addition of nanofluids appeared enhancement in electrical production, thermal efficiency, and overall performance.

Also, the main factor in the system's performance is the intensity of solar irradiance. All used nanofluids, TiO_2, Al_2O_3, and MWCNT resulted in potential enhancement with 25%, 36%, and 45% increase in electrical power and 27% 33%, and 47% improvement in electrical performance, respectively. Margoum et al. [17] Studied Effect of Nanofluids on the Performance Enhancement of PV/T system. Pure water, Al_2O_3/water, and Cu/water were simulated in MATLAB and studied as coolants to reduce the temperature of the PV panel. Numerical results show that the use of Al_2O_3, and Cu with water as nanofluids enhances the thermal and electrical efficiency if it was compared to using pure water in a PV/T system. Results showed adding a 2% vol. of Cu and Al_2O_3 nanoparticles in water increased the electrical and thermal efficiency of the PV/T system by 0.99 and 10.33% for Al_2O_3/water and 1.24 and 26% for Cu/water, respectively.

Imran et al. [18] evaluated the cooling of low-cost residential buildings in Sarawak – Malaysia, by air circulation in the ground as a heat sink source to cool down up to a thermally acceptable level. They reported internal temperature reduction inside the building from 33℃ to 29.5℃ due to the ground air circulation. Jakhar et al. [19] evaluated the thermal performance of an Earth air tunnel heat exchanger with a solar air heating duct for the arid climate of Ajmer City, India, during the winter season. They studied the thermal effects of this system. While many researchers experimentally studied the thermal performance of earth-water heat exchangers. In contrast, other researchers have studied solar air heating ducts for different locations during winter and summer seasons [20, 21].

There are several PV/T cooling techniques to mitigate the accumulated heat in the modules. However, cooling by ground-embedded heat exchangers is newly proposed and studied in the current paper. This paper introduces a design of horizontal geothermal heat exchangers (HGHE) for heat extraction from solar PV. The investigation, through computational simulation, focused on the system performance when HGHE is buried at various depths in the ground. The proposed design uses forced convection by pump water circulation between the HGHE and the backside water tank of the PV module. Soil and weather conditions have been selected in the south region of Iraq, while the depth was selected at 0.5, 1.0, and 1.5 m. This approach is particularly interesting in applications for keeping thermal equilibrium in solar PV/T systems, with fewer costs, and with short water pipe loops.

2. COMPUTATIONAL SIMULATION

2.1 Model generation

The simulation is performed by using the CFD software ANSYS Fluent. In the case of ground exchanger geometry, an automatic mesh was applied, while for water ground exchanger mesh was used to provide accurate temperature distribution as shown in Figure 1. In normal conditions, the ground exchanger consists of seven linear coils with a total length of 22 m; it is buried at a proper depth. These analyses used three depths of 0.5, 1.0, and 1.5 m. Further, the solid and fluid domains in the present computational fluid analysis have been coupled in such a way that the transported thermal characteristics at the interfaces will hit the bull's eye.

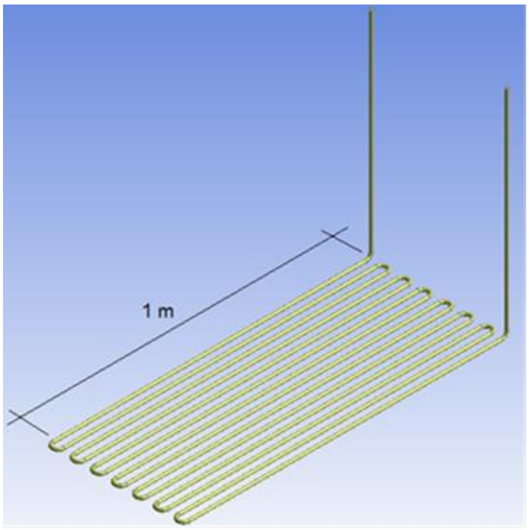
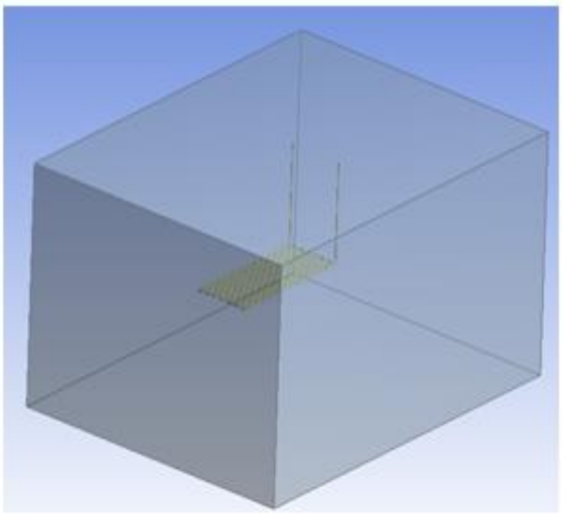


Figure 1. Horizontal ground heat exchanger

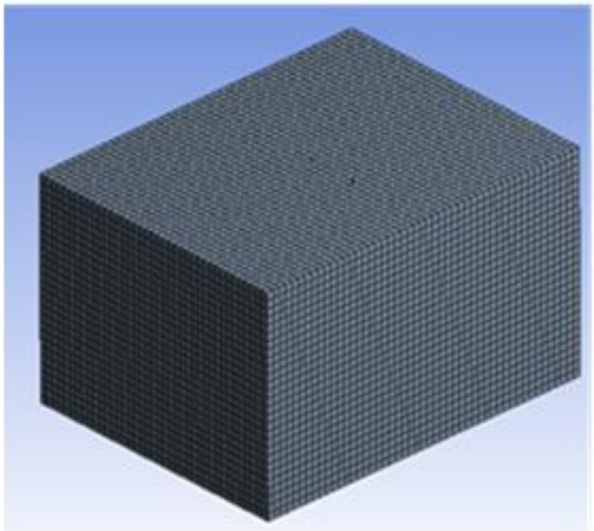
2.2 Computational grid

The computational grid step is one of the main steps in any numerical analysis; it includes specified structures and shapes of cells. While computational cells were analyzed by a list of the governing equations. The ANSYS software was used to create the mesh for two domains; the soil pile and the copper pipe loops. The meshing methods used were mainly made to let the number of cells' limited value to a minimum while letting heat transfer in and around the fluid domain be known. First, the soil pile domain is $2\times3\times2$ m^3. Second, the pipe loops diameter of 0.015 with 22 m length meshed using a hex type to get a perfect number of cells in the domain. On the other hand, the soil domain was designed with big dimensions to let it be enough that the heat transfer effects are limited far away from the wall's domain. While the cells in the pipe loops domain were meshed with the size of 0.2 cm. The maximum size of the cells is limited to ensure good accuracy of the simulation results.

A grid independence test was performed to evaluate the accuracy of the simulation results, showing an average variation of 0.06% from the obtained results. The numerical simulation appears in Figure 2. The soil domain is a cube and linear ground exchanger in Figure 2 (a), while the mesh of this model can be seen in Figure 2 (b).



(a)



(b)

Figure 2. The soil domain and the copper pipe loops domain, (a) geometry, and (b) mesh

The simulation was conducted utilizing the ANSYS FLUENT version 15.0 by solving Reynolds-Averaged Navier-Stokes as governing equations of the Thermofluids process in the system. In the thermodynamic model of study, potential and kinetic energy changes, the pressure drop between cells, heat loss to the environment, and phase changes in fluids are ignored. In addition, temperatures are evenly distributed in each cell, and fluids fill the cells. Thermophysical properties such as heat conductivity, specific heat, dynamic viscosity, density, and Prandtl number are simultaneously calculated for differing temperatures across the heat exchanger using the thermophysical properties versus temperature variation supplied by Ajel et al. [22] inserted into the model. Table 1 presents the CFD code set-up factors. Furthermore, the numerical investigation was achieved in stable circumstances with a three-dimensional structured mesh via the preceding analysis. The geometry-independent factors were similar for the whole layouts.

Table 1. Details of the computational simulation setting

Parameter	Description
Mesh elements	3D Structured mesh, hex-dominant elements
Numbers of elements/nodes	228390/289388
Solver	3D steady
Numerical scheme	Segregated
Pressure velocity coupling	SIMPLE
Fluid	Water
Turbulence model	Realizable k-ε

2.3 Governing equations

The ground temperature profile at transient ambient and solar conditions has been predicted using the empirical model suggested by Reda et al. [23]. The weather data for the southern desert in Iraq have been used to solve Eq. (1) including the soil properties, solar irradiation, wind, and temperature of air throughout the whole year.

$$T(z,t) = T_i + A.e^{-z\sqrt{\frac{\omega}{2d}}} \sin\left(\omega t - z\sqrt{\frac{\omega}{2d}} + B\right) \quad (1)$$

And, $\omega = 2\pi/\tau$, $B = (\tau - 4t_i)\pi/2\tau$.

The predicted temperatures of the ground at various depths are documented in Figure 3. Those results have been then utilized for setting the ground boundary conditions in the simulation setup for HGHEs' thermofluids process simulations, The simulation has been performed under 0.5 m, 1.0 m, and 1.5 m burial depths of the HGHE. The illustration via an easy yearly cycle harmonic of the soil monthly average temperature is adequately exact, as revealed via preceding in-depth scrutiny. Also, in Eq. (1), the average temperature in the climatic region year is Ti; A is the half discrepancy between the max. and min. temperatures upon the surface of soil into the year; τ is the regarded duration; t_i is the time if the max. Temperature upon the ground surface takes place; d is the regarded soil's thermal diffusivity. Additionally, the chief assumption for such an equation is that the physical characteristics mentioned in the soil are fixed in time and space. Therefore, uniform soil is deemed at the whole depths. Furthermore, this isn't very remote from the real hypothesis due to a maximum burial depth of 2 m, as well as the climate of the southern desert in Iraq is a temperate climate.

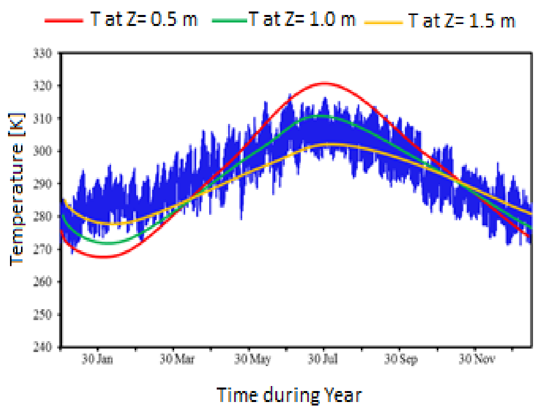


Figure 3. The ground temperature distribution predictions by the use of the first equation while calculating under the southern desert in Iraq's weather

The governing equations represented by mass, momentum and energy conservations are adopted and solved numerically using ANSYS commercial software, following the suggestions of the studies [24-26]. The equations have been manipulated to meet the steady, incompressible, viscous, 3D fluid flow.

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

Momentum equation in x- y, and z- directions are given by Eq. (3), Eq. (4), and Eq. (5), respectively:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \quad (3)$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \quad (4)$$

$$\rho\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \quad (5)$$

where, *u*, *v*, and *w* are the velocity components in *x*, *y*, and *z*, respectively. The gravitational acceleration applies in the *y*-direction only. Density, ρ is constant as the assumption is incompressible fluid flow, which is true for any liquid under moderate pressure. The fluid viscosity, μ is Newtonian and constant as the temperature change is within a small range. The viscosity could not be neglected as the flow inside a relatively long conduit.

The energy equation is:

$$\rho\, Cp\frac{DT}{Dx} = \nabla.\mathrm{k}\nabla T + \beta T\frac{DP}{Dx} + \mu\emptyset \quad (6)$$

where, β is the coefficient of thermal expansion, defined as:

$$\beta = -\frac{1}{\rho}\left[\frac{\partial\rho}{\partial T}\right]_p \quad (7)$$

Cp and k are the heat capacity and thermal conductivity of water, assumed constant as no large change in the temperature during the heat transfer process.

$$\emptyset = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left[\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2\right] - \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)^2 \quad (8)$$

2.4 Boundary conditions

The HGHE was simulated under different operating conditions. Material properties and inlet conditions (turbulent flow) used in the simulations are shown in Table 2 and Table 3, respectively. The properties of soil have been lab-tested and measured.

Table 2. Properties of materials included in the computational simulations

Variable	Pipe (Copper)	Ground (Soil)	Fluid (Water)
Density (kg/m^3)	8.94×10^3	1555	1000
Conductivity (W/m·K)	355	0.8	0.6
Cp (J/kg·K)	385	875	4184
Viscosity (kg/m·s)	-	-	0.001003

Table 3. Inlet boundary conditions

Parameter	Value
Water mass flow rate	0.0278 kg/s
Water inlet temperature	313 K
Soil thermal diffusivity	1×10^{-6} m^2/s [21]
Depth	0.5 m, 1.0 m, 1.5 m

3. RESULTS AND DISCUSSION

The results computed through simulation for the 22 m long buried copper pipe HGHE at variance depths for differing weather have been thoroughly validated and analyzed. The performances of the HGHE concerning various environmental parameters, such as temperature fluctuations, moisture, and seasonal changes, have been evaluated in the research. The major factors considered for the buried pipe included depth, which determined the efficiency of heat transfer from the surrounding ground. When laid deeper, the thermal performance became more consistent because the earth's temperature was stable; shallower depths were more directly affected by weather changes. Various weather conditions, therefore, affect the ability of the system to maintain consistency in output temperature, again emphasizing the dependence on the factors of depth and soil thermal conductivity. The validation of computational results by comparing them with experimental data and analytical models provides the basis for the accuracy of the same.

3.1 Simulation results of soil temperature distribution

Figures 4 and 5 elucidate the contours of temperature distribution for the soil pile at three different depths, 0.5, 1.0, and 1.5 m, at 12:00 PM. The behavior of the temperature distribution into the ground at various depths, z was simulated in Figure 4. It was utilized as boundary conditions of the ground around the HGHE, and thus, uniform heat transfer occurs at different conditions. The ground is at 1.0 m and 1.5 m, and consequently, any lower depth is far from the ground surface's high temperature.

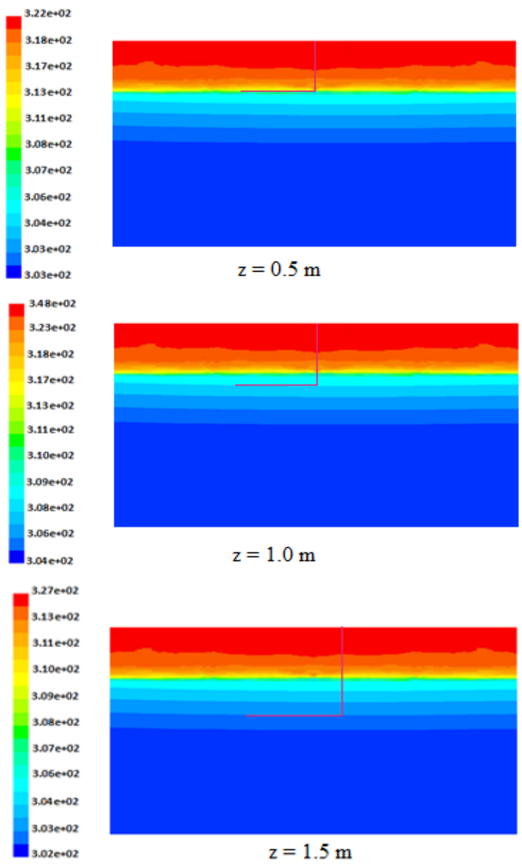


Figure 4. Contours of temperature distribution for the soil pile at 12:00 PM

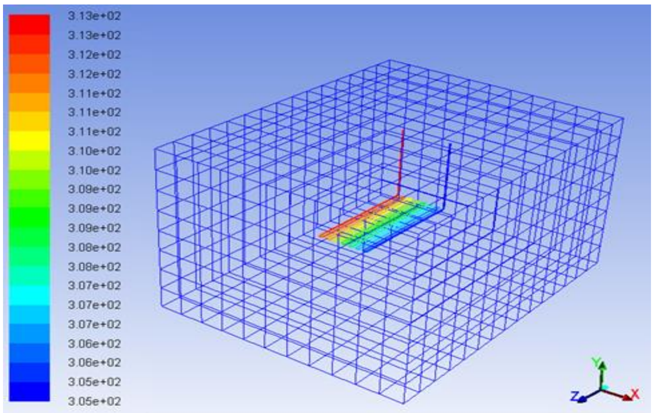


Figure 5. Contours of temperature distribution for the pipe loops, water mass flow rate equal to 0.0278 kg/s, in a 1.0 m depth, at 12:00 PM

The research utilized the outlet temperature of water as a primary metric to evaluate the impact of varying burial depths on heat transfer efficiency. This comparison was visually represented in Figure 6, which illustrates the relationship between the outlet temperature of water and time for burial depths of 0.5, 1.0, and 1.5 meters. The results indicated that deeper burial of the copper pipe loops in the soil pile significantly hastened the reduction of the outlet water temperature over a shorter pipe length, suggesting enhanced thermal conductivity at increased depths. The experimental setup achieved a state of thermal equilibrium between the water and the surrounding ground, which was maintained throughout the operation of the thermal system. This equilibrium was successfully simulated using Computational Fluid Dynamics (CFD) code, under conditions that ensured a constant water flow rate. Furthermore, the heat flux measurements corroborated the baseline assumption of zero thermal flux, meaning there was no net heat gain or loss under stable conditions. Additionally, the analysis clarified that the heat flux concerns the entire pipe system rather than just a portion of it. In cases where the circulating water in the horizontal ground heat exchanger (HGHE) system removes heat from the pipe to the ground, the heat flux is expected to be negative, indicating effective heat transfer from the water to the surrounding soil.

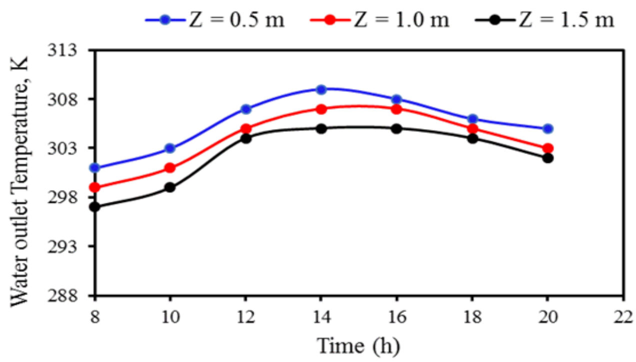


Figure 6. Water outlet temperature as a function of time of the day for different depths, on 11 July

The performance of water heating and cooling using an HGHE is governed by the temperature difference between the outlet water and the surrounding soil. This difference is remarkably larger in summer than in winter for the southern desert of Iraq. Thus, the HGHE will have a higher performance during the summer period. Therefore, the larger summer discrepancy in temperature has a considerable effect on enhancing the HGHE's capability for heat transfer and supports the HGHE to operate actively and efficiently. In warmer climates, the system's specific advantages go toward an extreme in summer when there is a substantial difference between ground temperatures and solar collector water temperature because it enables the HGHE to cool the water by several degrees effectively as agreed with [27]. In winter, with a small temperature difference, the operating hours of the HGHE in a day are fewer and work with very low efficiency. Therefore, this system can take a major role during summer and cool the water in solar collector systems more efficiently with higher temperature gradient as explained in Figure 7.

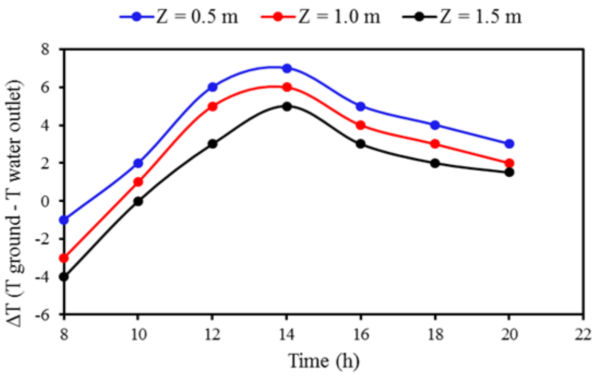


Figure 7. Temperature difference between the ground and the output water on 11 July

4. CONCLUSION

The present computational simulation aims to investigate the HGHE performance to dissipate the generated heat and cool the PV during the solar daytime and warm the PV in the night utilizing the thermal energy stored into the ground. The selected pipes' horizontal geometry ensures a virtuous heat transfer between the ground and flowing water as well as a beneficial steadiness of the temperature of the water. Also, the simulations elucidated important HGHE advantages through the summer. This exchanger can cool the water from the solar plant through the entire day. The reduction of the temperature of outlet water is within 4°C to 8°C. Furthermore, this provides a virtuous likelihood for using HGHE for a solar thermal system's pre-treatment. Certainly, this regime depicts a satisfactory performance in terms of efficacy as well as the ecological influence when coupled with the working climate zone conditions.

Future studies are recommended to evaluate the thermal performance of ground heat exchangers buried in the wet and dry soil of the geothermal reservoir. Also, the influence of the ground coil diameter and configuration on HGHE performance is a matter of interest to investigate.

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