Journal of Kyzylorda Scholarly Review

P-ISSN:3006-0265 | E-ISSN:3007-4681. Published by the Open University of Kyzylorda

https://bulletin.ouk.kz/index.php/bulletin/index

THERMAL PERFORMANCE EVALUATION OF GROUND HEAT EXCHANGERS WITH NANO FLUIDS AND DIFFERENT PIPING SYSTEMS: EXPERIMENTAL STUDY IN IRAQ

Firas Ahmed Mohammed
Department of Mechanical Engineering, College of Engineering, Tikrit University, Iraq
Salah Al-Din Governorate,
Corresponding author: frasa0528@gmail.com

Prof. Dr. Fayyadh Mohammed Abed
Department of Mechanical Engineering, College of Engineering, Tikrit University, Iraq
Salah Al-Din Governorate,

Prof. Dr. Raaid Rashad Jassem
Department of Mechanical Engineering, College of Engineering, Tikrit University, Iraq
Salah Al-Din Governorate,

Abstract. This study presents an advanced experimental evaluation of the thermal and hydraulic performance of a vertical Ground Heat Exchanger (GHE) system designed for heating and cooling applications. The field experiments were conducted in Al-Shirqat district, Saladin Governorate, Iraq, a region characterized by specific soil properties and climatic conditions that represent a significant challenge for renewable energy systems. The system was implemented using two separate metal networks; the first consists of copper pipes and the second of aluminum pipes, with each network installed at a total length of 30 meters at a depth of 3.5 meters. This configuration aims to conduct a precise physical comparison of the thermal conductivity efficiency of each metal with the surrounding medium and evaluate their environmental durability. The research results indicated that copper pipes slightly outperformed aluminum by approximately 2–3%, suggesting concluding that soil thermal resistance is the dominant factor. To enhance efficiency, a Nano fluid was employed, leading to an increase in heat transfer rate by 19% for copper and 12% for aluminum, due to improved thermo physical properties and nanoparticle dispersion, despite the flow regime remaining within the Laminar phase according to analytical calculations (Re = 1231). In-depth analysis demonstrated that the structural innovation of the "Combined System" (hybrid connection) with the Nano fluid was the most effective method. At an optimal flow rate of 1 L/min, the system reached its peak performance with a heat transfer rate (Q) of 821.24 W, effectively covering a significant portion of the 900 W design load, while achieving the highest

Coefficient of Performance (COP) of 6.84. Conversely, increasing the flow rate to 2 L/min led to a marked decline in thermal feasibility; the high velocity reduced the residence time, causing the temperature difference (ΔT) to drop to only 2.7 °C, while friction losses surged beyond 3600 Pa. The study concludes that operating the system at 1 L/min represents the "Optimal Operating Condition," ensuring a precise balance between maximum thermal absorption and minimized pumping costs, providing a pioneering engineering model for sustainable energy applications in harsh environments.

Keywords: Water Ground heat exchanger; Nano fluid; piping systems; Under Ground Thermal energy; Heating performance, Iraq

1. Introduction

Low-carbon renewable energy technologies, particularly Ground Heat Exchanger (GHE) systems, represent a fundamental pillar in the strategic transition toward sustainable and eco-friendly buildings. These systems rely on exploiting the physical properties of soil and its thermal inertia, where researchers such as [1] have confirmed that the earth acts as an ideal thermal reservoir—serving as a heat source in winter and a heat sink in summer. Amidst the escalating global energy crisis, recent studies [2] have highlighted the necessity of developing advanced heat exchange systems to reduce reliance on fossil fuels and lower carbon emissions. In the context of harsh continental climates, such as that of Al-Shirqat District in Saladin Governorate, Iraq, the urgent need for these technologies becomes evident; the sharp seasonal temperature fluctuations impose a significant technical and economic burden on conventional air-conditioning systems, making the stable ground temperature in this region a vital, yet underutilized, energy resource [3]. The significance of this study lies in providing the first comprehensive and direct experimental evaluation of a GHE system under the actual climatic and geological conditions of Saladin, a field that still lacks robust field data in local scientific literature [4].Reviewing the applied aspects of system design, the selection of operating depth is a critical factor for performance stability. Previous research [5] has indicated that depths exceeding 3 meters provide total thermal insulation from surface weather fluctuations and direct solar radiation. Accordingly, this study was designed to meet the thermal requirements of a model room with dimensions of (4*2*2) meters and a design thermal load of 900 W, with the system implemented at a depth of 3.5 meters to ensure access to soil layers with relatively constant temperatures throughout the year. The core objective of this engineering precision in calculating pipe network lengths and diameters is to overcome the limitations observed in some previous experiments [6] regarding heat exchange efficiency in semi-arid regions and to establish an experimental database that contributes to the development of design standards for sustainable energy systems in Iraq. In pursuit of enhancing performance efficiency, this research extends beyond traditional materials to include a physical analytical comparison between copper and aluminum pipes, aiming to identify the metal most compatible with the chemical and physical conditions of local soil. Furthermore, a "dual copper-aluminum system" was innovated to integrate both metals, maximizing the heat exchange area and reducing the thermal resistance of pipe walls without excessive costs—an approach supported by several researchers [7] as a promising technical and economic solution for increasing thermal absorption efficiency. Additionally, performance was bolstered by integrating Nano fluid technology using Aluminum Oxide (Al_2O_3); a qualitative addition aimed at addressing the limited thermal conductivity of conventional water.

This aligns with global research trends [8] that have proven the ability of nanoparticles to improve the thermo physical properties and heat dispersion of fluids, even in laminar flow conditions, which was analytically verified in this study at a Reynolds number of (Re = 1231).The added scientific value of this research lies in its precise balance between the thermal aspect and the hydraulic aspect (pressure drop). While reference studies [9] have often focused on increasing thermal absorption in isolation from pumping costs, this experiment tested the system under three flow rates (0.5, 1, and 2 L/min) via continuous 24-hour monitoring. This comprehensive analysis aims to identify the "Optimal Operating Point" that ensures covering the 900 W load with the highest Coefficient of Performance (COP) and minimum electrical consumption for the pumps, thereby providing an integrated engineering roadmap for building sustainability in harsh environments and similar semi-arid regions The importance of this study lies in the fact that it provides a direct experimental evaluation of a ground heat exchanger system under real Iraqi climatic and soil conditions, which is still a limited area in local studies. It also aims to determine the best engineering and operational configuration in terms of pipe material, working fluid type, and flow rate in order to achieve the highest thermal efficiency and the best practical performance. The results of this study therefore represent a scientific basis that can be relied upon for the development of sustainable geothermal energy applications in Iraq and in similar semi-arid regions. [10]

2. Theoretical and Mathematical Analysis

The thermal and hydraulic performance of the ground heat exchanger system was evaluated using the governing equations of internal flow and heat transfer [15].

The mass flow rate ($\dot{m}$) .[9].

$$\dot{m} = \rho \dot{V} \qquad \dot{m}_{total} = 2\rho \dot{V}$$

The Reynolds number, and Prandtl number which characterizes the flow regime inside the pipe, is expressed as: [12].

$$Re = \frac{\rho\, u\, D}{\mu} \qquad Pr = \frac{\mu\, C_p}{k}$$

Based on the values of the Reynolds and Prandtl numbers, the Nusselt number is determined. For fully developed laminar flow in a circular pipe with constant wall temperature, the Nusselt number is assumed constant and equal to 3.66, a value widely adopted in internal flow heat transfer analysis [16].

Hausen Correlation (Laminar Flow in a Circular Tube with Thermal Entrance Region)

The Hausen correlation for laminar flow inside a circular tube accounting for the thermal entrance region is given by:

$$Nu = 3.66 + \frac{0.0668 G_z}{1 + 0.04 {G_z}^{2/3}} \qquad (3\text{-}7)$$

Grates Number .The Grates number (G_z) is defined as:

$$G_z = Re \ \ Pr \ \frac{D}{L}$$

This is the most widely used correlation for fully developed turbulent flow in smooth pipes. It is simple but effective for fluids with moderate property variations. [10,17].

Conditions: Re_ > 10,000, and 0.6≤ P_r ≤ 160

Nu = 0.023 $Re^{0.8}$ Pr^{n}

- n = 0.4 for heating of the fluid (wall is hotter than fluid).
- n = 0.3 for cooling of the fluid (wall is colder than fluid).
- Nu = $\frac{(\frac{f}{8})(Re-1000)\mathrm{Pr}}{1+12.7\,(\frac{f}{8})^{0.5}(\mathrm{Pr}^{\frac{2}{3}}-1)}$

From the definition of the Nusselt number, the internal convective heat transfer coefficient is obtained as: [18].

$$\mathrm{Nu}=\frac{hD}{K} \quad \Rightarrow \quad h=\frac{Nu\,k}{D}$$

The total thermal resistance (R_total) is the sum of convective, pipe wall, and soil resistances:

$$Rconv=\frac{1}{\pi Dh} \qquad R_{pipe}=\frac{Ln(\frac{ro}{ri})}{2\pi K}=\frac{Ln(\frac{Do}{Di})}{2\pi K_{pipe}} \qquad R_{soil}=\frac{1}{S\,k_{soil}}$$

$$S=\frac{2\pi}{Ln\left(\left(\frac{2d}{D_0}\right)+\sqrt{\left(\frac{2d}{D_0}\right)^{2}-1}\right)}$$

$$R_{total}=R_{conv}+R_{pipe}+R_{soil}$$

The overall linear heat transfer coefficient is defined as: [17,22].

$$U=\frac{1}{R_{total}A_0}$$

The length of the tube

$$Q=UA\Delta T \quad ,,,, \quad A=\pi DL$$

$$L=\frac{Q}{U*\pi*D*\Delta T} \quad \text{or} \quad L=\frac{\mathbf{Q_{design}}*R_{total}}{\Delta T_{LMTD}}$$

$$\Delta T_{LMTD}=\frac{(T_{in,w}-T_{SOIL})-(T_{out,}w-T_{SOIL})}{\mathrm{Ln}(\frac{(T_{in,w}-T_{SOIL})}{(T_{out,}w-T_{SOIL})})} \quad ,,,, \quad Tb=T_f=\frac{T_{out+}T_{in}}{2}$$

In horizontal systems the spacing is usually Z from 0.5m to 1m

Let z = 0.9m ,,, $A_e = \frac{L}{Z}$

Pressure Drop and Performance Evaluation

For laminar flow: $f = \frac{64}{R}$

For smooth turbulent flow (Blasius correlation): $f = 0.3164\, Re^{-0.25}$

The pressure drop is calculated using the Darcy–Weisbach equation:

$$\Delta P = f \frac{L}{D} \frac{\rho^2 u}{2}$$

a soil correction factor was applied: [,2123]

$C_f \approx 0.2 - 0.35$

Consumed Power and Coefficient of Performance

The hydraulic power required to circulate the fluid inside the pipe was calculated from the relation: [,1318].

$$Power_{pump} = \frac{\Delta P V^{\cdot}}{\eta_{pump}}$$

where η_pump represents the pump efficiency, which is defined as the ratio between the useful hydraulic power and the electrical power supplied to the pump.

After that, the coefficient of performance of the ground heat exchanger loop was defined as: [19,20]

COP_loop= Q/Power_(pump)

3. Experimental Work

3.1 System Description

The experimental ground heat exchanger (GHE) system was designed and implemented in Al-Shirqat, Saladin Governorate, Iraq. to exploit the thermal stability of the ground for heating and cooling applications. The setup consists of two independent pipe networks buried within a 30 m² (5 m × 6 m) experimental field:

1. Copper Network: 0.5-inch diameter, buried at a depth of 3.5 meters.
2. Aluminum Network: 0.5-inch diameter, buried at a depth of 3.0 meters.

A stacked horizontal configuration was adopted with a 50 cm vertical spacing to minimize thermal interference and maximize heat exchange density within the available surface area.

3.2 System Components

The closed-loop thermal system comprises the following primary components:

- Water Tank: A 10-liter thermally insulated tank serving as a collection and storage point to ensure fluid temperature stability.
- Circulation Pump: A low-power centrifugal pump designed to overcome hydraulic losses (friction in pipes, valves, and flow meters).
- Indoor Split Unit: A 2-ton capacity unit acting as the heat exchanger between the ground-source fluid and the indoor air.
- Control Valves & Manifold: Manual ball valves to regulate flow across three modes (copper only, aluminum only, or combined) and a return manifold to mix and stabilize the return flow.

3.3 Instrumentation and Measurements

- Water Flow Meters: Installed on each loop to monitor volumetric flow rates ranging from 0.5 to 3 L/min.
- Temperature Sensors: High-precision sensors installed at the inlets and outlets of the ground loops and the split unit to determine the temperature difference (ΔT).

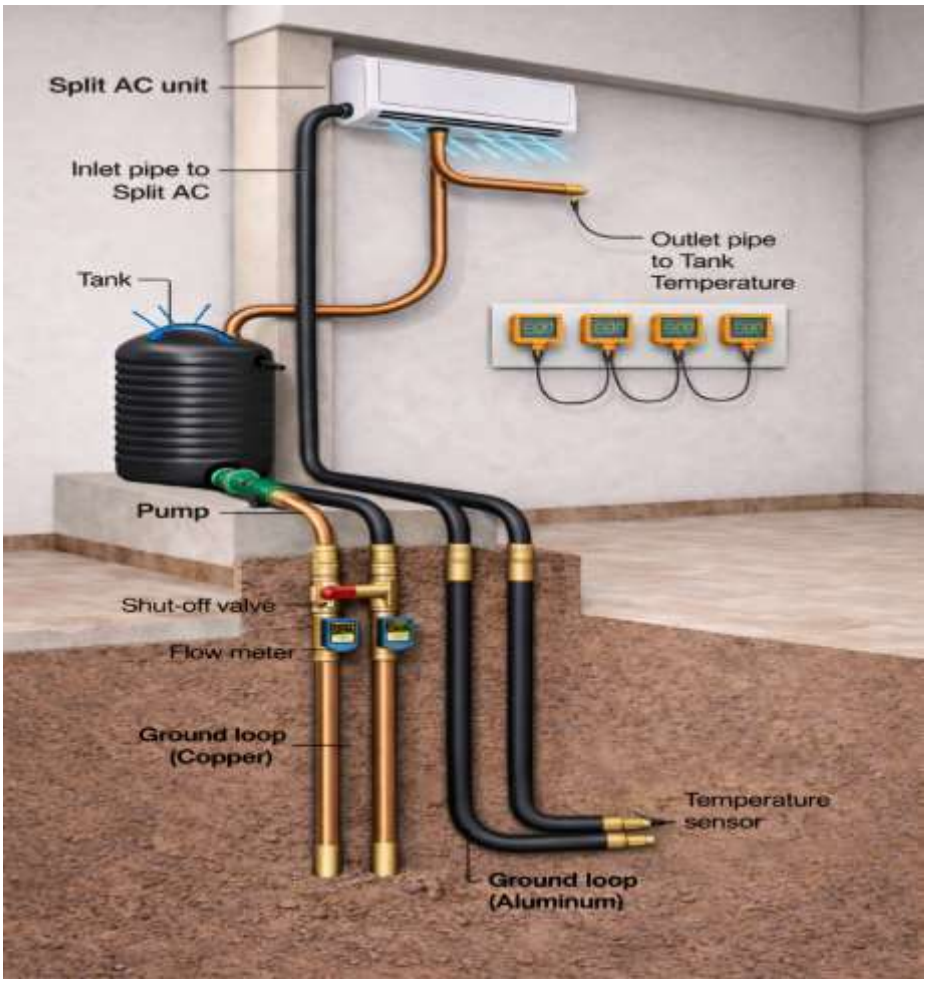


Figure 1. A three – dimensional model illustrating the Earth system and its components

3.4 Operating Procedure

The experimental operation was conducted in three distinct stages, each lasting 24 hours with measurements recorded every two hours to reach quasi-steady-state conditions:

1. Stage 1: Operating the copper loop individually using pure water.
2. Stage 2: Operating the aluminum loop individually under identical conditions for comparative analysis.
3. Stage 3: Combined operation of both networks to evaluate the total thermal capacity.

- Working Fluids: All experiments were repeated using an Al_2O_3-based Nano fluid, prepared by dispersing 80 grams of aluminum oxide nanoparticles in 20 liters of water to enhance the fluid's thermal conductivity.

4. Results and Discussion

4.1 Thermal Behavior of the Hybrid Nano fluid System

This section presents the performance analysis of the ground heat exchanger (GHE) system under the identified optimal operating conditions: the operation of the hybrid pipe network (copper-aluminum) using an aluminum oxide Al_2O_3 Nano fluid at a flow rate of 1 L/min. This configuration achieved the most efficient balance between heat transfer enhancement and the system's hydraulic requirements.

4.2 Combined system with Nano fluid at a low flow rate (1 L/min for each network)

Table 1 represents the operating results of the combined copper–aluminum system under simultaneous operation after adding aluminum oxide (Al_2O_3) nanoparticles at a flow rate of 1 L/min for each network. It shows the transition of the system from a "low-flow" condition to a more active operating state in terms of forced convection, while the flow remains within the advanced laminar regime. The Reynolds number values range approximately between (1232–1367), indicating that velocity increased compared with the 0.5 L/min case, while the Nano fluid properties (particularly the higher viscosity) remain an influential factor in controlling the Reynolds number and associated losses.

Table 1. Thermal and hydraulic parameters of the combined copper–aluminum system using Al_2O_3 Nano fluid at a flow rate of 1L/min for each network

TimeTin

Time	Tin °C	Tout °C	ΔT °C	μ (Pa ·s)	Re	P_r	Nu	ΔP (Pa)	Q (W)	COP
8:00	8.1	13.6	5.5	0.001355	1231.92	9.85	3.66	1061.10	765.57	6.38
10:00	8.6	14.4	5.8	0.001332	1253.19	9.66	3.66	1043.08	807.33	6.73
12:00	11.0	17.0	6.0	0.001247	1338.61	8.97	3.66	976.52	835.16	6.96
14:00	11.6	18.0	6.4	0.001221	1367.11	8.76	3.66	956.16	890.84	7.42

16:00	11.7	17.8	6.1	0.001224	1363.76	8.79	3.66	958.51	849.08	7.08
18:00	11.1	16.9	5.8	0.001246	1339.68	8.96	3.66	975.74	807.33	6.73
20:00	10.7	16.4	5.7	0.001263	1321.65	9.10	3.66	989.05	793.41	6.61
22:00	10.1	15.7	5.6	0.001283	1301.05	9.27	3.66	1004.71	779.49	6.50
00:00	9.6	15.0	5.4	0.001303	1281.08	9.43	3.66	1020.37	751.65	6.26
02:00	8.9	14.2	5.3	0.001329	1256.02	9.63	3.66	1040.74	737.73	6.15
04:00	9.1	14.4	5.3	0.001320	1264.58	9.56	3.66	1033.69	737.73	6.15
06:00	9.8	15.4	5.6	0.001292	1291.99	9.32	3.66	1011.76	779.49	6.50
08:00+1	10.6	16.5	5.9	0.001267	1317.48	9.12	3.66	992.18	821.24	6.84

In Figure (4.1), which presents the variation of the temperature difference ΔT with time, ΔT ranges between (5.3–6.4 °C). The 1 L/min curve appears lower than the 0.5 L/min curve because increasing the flow rate reduces residence time inside the pipes, thereby decreasing the temperature rise per unit mass. Nevertheless, the ΔT peak at 14:00 remains evident, reflecting the continued influence of midday conditions on increasing the thermal gradient. The attainment of ΔT = 6.4 °C indicates that the improved fluid properties still allow a considerable temperature difference even at higher flow rate.

Despite the reduction in ΔT compared with the 0.5 L/min case, the actual thermal performance is clearly reflected in Figure (4.3), where the heat transfer rate Q ranges between (738–891 W), reaching its maximum at 14:00. This significant increase in Q demonstrates that increasing the flow rate in combined operation raises the amount of fluid exchanged per unit time, and with the presence of Nano fluid, heat transfer inside both networks is enhanced simultaneously. As a result, the overall level of the Q curve increases markedly compared with the 0.5 L/min case and even more clearly compared with single operation. The difference between the peak and the remaining hours of the day also reflects the system's sensitivity to daily thermal variations, while the nanoparticle addition amplifies the benefit of favorable thermal periods.

From the hydraulic perspective, Figure (4.2) shows that the pressure drop ΔP ranges between (956–1061 Pa), which is higher than the 0.5 L/min case due to increased velocity. However, these values remain significantly lower than those of the 2 L/min case, indicating that the hydraulic burden at 1 L/min remains relatively moderate compared with the substantial thermal gains achieved. It is also observed that ΔP is higher during colder periods (early hours of the day) when viscosity is higher, and decreases relatively around midday.

In Figure (4.4), which represents the coefficient of performance COP, the values range between (6.15–7.42), which are higher than those of the 0.5 L/min combined operation with Nano fluid. The highest value occurs at 14:00 in coincidence with the highest Q, indicating that the increase in heat transfer rate exceeded the increase in pressure losses, thus improving the net system performance. Achieving a COP of 7.42 clearly indicates that this flow rate provides the best balance between the benefits of combined operation and nanoparticle enhancement and the associated pumping cost within the scope of the data.

Overall, the figures associated with Table (4.1) show that combined operation after adding Al_2O_3 at 1 L/min reduces ΔT compared with 0.5 L/min as shown in Figure (4.1), significantly increases Q as shown in Figure (4.3), increases ΔP to a noticeable but acceptable level as shown in Figure (4.2), and achieves the highest COP as shown in Figure (4.4). Accordingly, 1 L/min can be considered one of the best operating conditions for combined operation with Nano fluid within the scope of the study, as it provides substantial thermal gains while maintaining hydraulic losses under control.

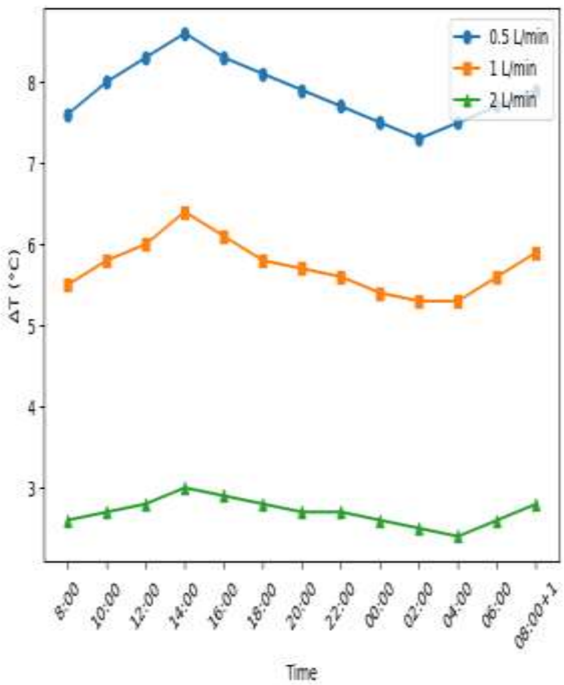


Figure 2. Temperature (ΔT) With time

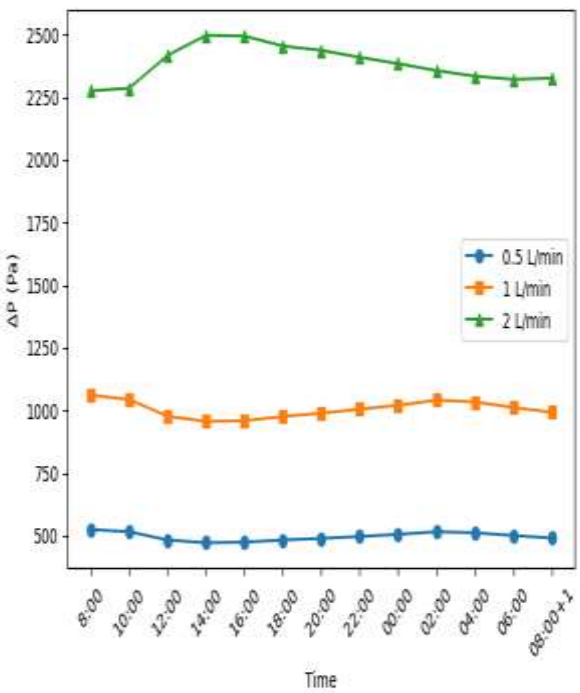
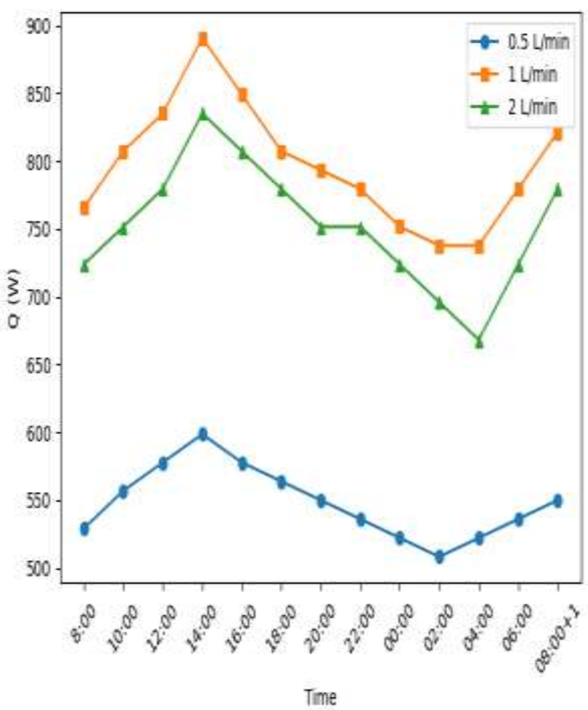


Figure 3. Pressure drop (ΔP) With time



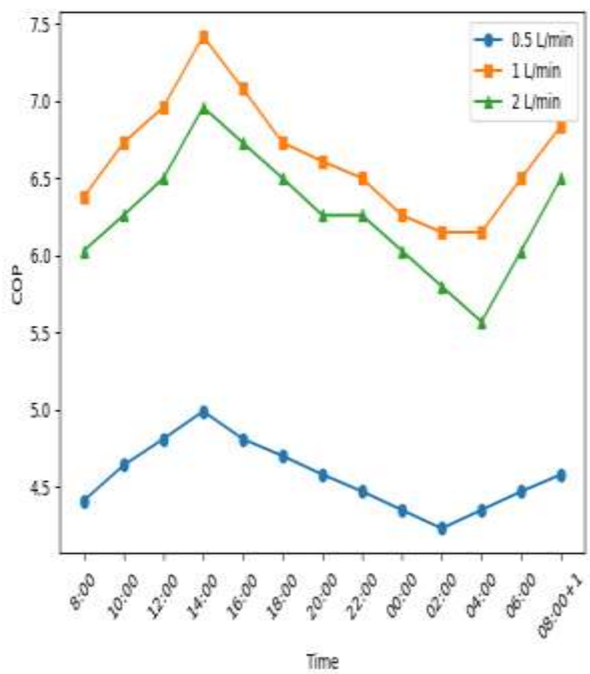


Figure 4. Heat transfer rate (Q) With time **Figure 5.** Coefficient of performance (COP) versus time

4.3 Overall Comparison of Heating Performance

A final comparison of all tested heating conditions showed that the thermal performance depended strongly on pipe material, working fluid type, and flow rate.

At 1 L/min with pure water, the copper system produced 357.23 W with a coefficient of performance of 2.98, compared with 347.98 W and 2.90 for the aluminum system. The hybrid copper–aluminum system nearly doubled the thermal performance, reaching 709.89 W with a coefficient of performance of 5.92.

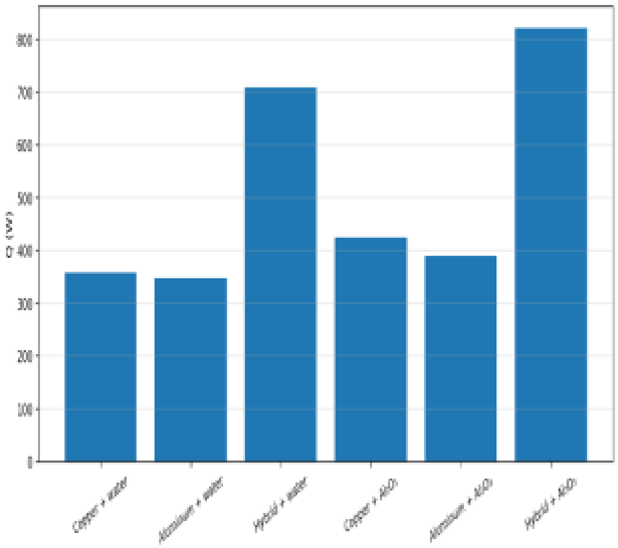
When Al_2O_3 Nano fluid was used at the same flow rate, the copper system improved to 424.54 W and a coefficient of performance of 3.54, whereas the aluminum system reached 389.74 W and 3.25. The hybrid system showed the highest performance, reaching 821.24 W and 6.84.

Regarding the effect of flow rate, the results showed that 0.5 L/min produced higher temperature differences but lower total heat transfer, whereas 2 L/min increased the pressure drop significantly without proportional thermal benefit. Therefore, 1 L/min was identified as the optimum operating flow rate.

Table 2. Final comparison of all heating operating conditions

Operating condition	Flow rate	ΔT (°C)	Q (W)	COP	ΔP (Pa)
Copper + water	1 L/min	5.1	357.23	2.98	944.50
Aluminum + water	1 L/min	5.0	347.98	2.90	945.11
Hybrid + water	1 L/min	5.1	709.89	5.92	944.41
Copper + Al_2O_3	1 L/min	6.1	424.54	3.54	1000.80
Aluminum + Al_2O_3	1 L/min	5.6	389.74	3.25	1000.80
Hybrid + Al_2O_3	1 L/min	5.9	821.24	6.84	992.18

The results confirm that the hybrid copper–aluminum system with Al_2O_3 Nano fluid at 1 L/min provides the best overall heating performance under the present experimental conditions.



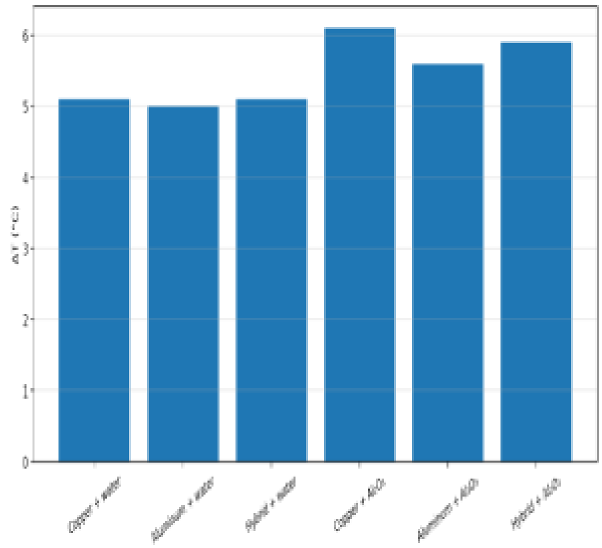
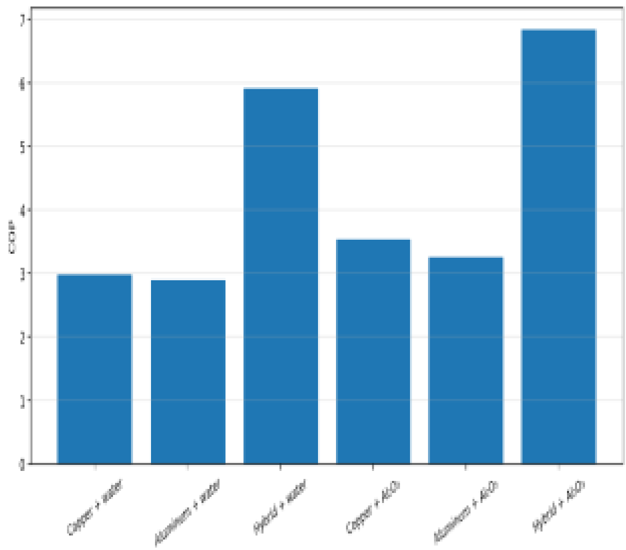


Figure 6. ΔT comparison

Figure 7. Q comparison



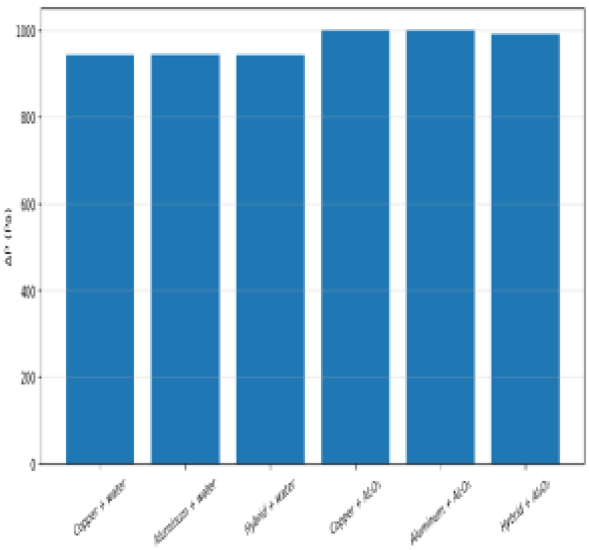


Figure 8. COP comparison

Figure 9. ΔP comparison

5. Conclusions

The experimental investigation and comprehensive analysis of the vertical ground heat exchanger system, utilizing a dual copper–aluminum network and Al_2O_3 Nano fluid, led to several scientific conclusions that directly address the research objectives. The field results confirmed the high technical feasibility of exploiting shallow geothermal energy in the Al-Shirqat region, Saladin Governorate, for heating applications. The system successfully overcame harsh continental climatic challenges by relying on stable ground temperatures at a depth of 3.5 meters, providing a reliable energy source isolated from surface weather fluctuations. Regarding material performance, physical evaluation revealed that copper pipes slightly outperformed aluminum by approximately 2–3% in thermal conductivity; however, the analysis indicated that soil thermal resistance remains the dominant factor limiting the overall heat exchange rate.

The innovation of the "dual copper–aluminum pipe system" proved significantly effective in maximizing the heat exchange surface area and improving the total heat transfer rate compared to individual pipe systems, while maintaining an economically and engineering-balanced design. This efficiency was further bolstered by the integration of 〖Al〗_2 O_3 Nano fluid, which fundamentally enhanced the system's thermo physical properties. Despite the flow remaining in the laminar regime (Re = 1231), the nanoparticles increased the heat transfer rate by 19% for the copper network and 12% for the aluminum network compared to pure water, highlighting the importance of nanotechnology in enhancing shallow ground exchanger performance.

Operationally, the research identified a flow rate of 1 L/min as the "Optimal Operating Condition," providing the most precise balance between thermal absorption and hydraulic losses. At this rate, the system achieved a maximum thermal capacity of 821.24 W, covering over 91% of the 900 W design load, with a peak Coefficient of Performance (COP) of 6.84. Conversely, increasing the flow rate to 2 L/min yielded counterproductive thermal and economic results; the high velocity reduced thermal residence time, dropping the temperature difference (ΔT) to only 2.7 °C, while friction losses surged beyond 3600 Pa. Consequently, this study establishes a robust experimental database and an engineering roadmap for developing sustainable energy systems in Iraq and similar semi-arid regions, providing a scientific basis for selecting materials, fluids, and operating conditions that ensure maximum efficiency and minimum energy consumption.

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