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RESEARCH ARTICLE

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Geothermal cooling solutions for rural communities at Homa Bay, Kenya: a CFD modelling study

Mamdud Hossain[a], Mailys Lassale[b], Stephen Vertigans[c], Gokay Deveci[d], Eyad Elyan[a], Katherine Burgess[e] and Mark Okowa[f]

[a]School of Computing, Engineering and Technology, Robert Gordon University, Aberdeen, UK; [b]ENSEIRB-MATMECA, Bordeaux Graduate School of Engineering, Bordeaux, France; [c]School of Law and Social Sciences, Robert Gordon University, Aberdeen, UK; [d]The Scott Sutherland School of Architecture & Built Environment, Robert Gordon University, Aberdeen, UK; [e]School of Pharmacy, Applied Sciences and Public Health, Robert Gordon University, Aberdeen, UK; [f]Department of Arts and Social Sciences, Tom Mboya University, Homa Bay, Kenya

ABSTRACT

A Computational Fluid Dynamics (CFD) modelling study has been presented to analyse the cooling impact of a geothermal cooling system based on the Earth-Air-Tunnel-Heat-Exchanger (EATHE) concept to provide passive cooling to heat-stressed vulnerable people in Homa Bay, Kenya. Like many places on earth, Homa Bay is experiencing extreme environmental heat. The novelty and significance of the present work lies in demonstrating the effectiveness of the technology for a field application using real-world data. Two different pipe arrangement designs, a straight pipe and a serpentine pipe, were investigated for their cooling effect. The inlet and boundary conditions were set using the air and ground surface temperature data available from the NASA Satellite for Homa Bay, Kenya. The simulation results show that the lower the air velocity the better the cooling effect and a 40 m long straight or serpentine pipe with a 0.1 m internal diameter and 1.0 m/s air velocity can provide a 3°C cooling on the hottest days of the year. The performance difference between a straight pipe and a serpentine pipe is negligible, and owing to the lower space requirements, a serpentine design is recommended.

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KEYWORDS
Geothermal cooling; climate change; CFD; EATHE; UNSDG

1. Introduction

As the world warms up owing to climate change, the demand for cooling is growing rapidly (UN Environmental Programme n.d.). People need cooling to protect themselves from extreme heat and to remain productive. Temperature plays a crucial role in human health, with thermoregulation of the body constantly occurring with the aim of maintaining a constant core body temperature, typically between 36°C and 37°C (Cramer et al. 2022). An acute increase in core body temperature causes the clinical syndromes of heat cramps, heat syncope, heat exhaustion, and heat stroke (Kovats and Hajat 2008). Symptoms range from extremity swelling, muscle spasms, light-headedness, fatigue, headache, and nausea, to hypotension, hyperventilation, tachycardia, seizures, coma, and ultimately death (Gauer and Meyers 2019). An acute increase in core body temperature is more likely to occur when exposure to temperatures higher than usual is prolonged (such as during heat waves), when the humidity is also high, and when individuals lack access to water (Gauer and Meyers 2019). In addition to the aforementioned clinical heat-related syndromes, elevated temperatures have negative effects on human populations. A recent systematic review by Chevance et al. (Chevance et al. 2024) showed that higher temperatures are associated with poorer sleep outcomes. Poor sleep is associated with the development of cardiovascular and metabolic diseases, cancer, mental health disorders, and accidents (Chevance et al. 2024). Increased temperatures reduce physiological capacity, leading to lower productivity, higher workplace injury, higher worker attrition, loss of income, and greater reliance on younger workers in indoor factories (Bach et al. 2023). In dwellings, hot nights result in a lack of sleep, with everyday activities affected by daytime temperatures, impacting both health and well-being. Conventional cooling using fans or air conditioning uses extensive electrical energy, leading to emissions and global warming. Passive cooling can be an effective solution for providing a cooler environment. Passive cooling strategies, where the building envelope elements are modified for cooler designs such as retrofitting buildings with green roofs, rooftop shading, painted roofs or insulated roofs, evaporative cooling (Sadineni, Madala, and Boehm 2011), and geothermal cooling, could be possible solutions to the heat stress problem (Agrawal et al. 2019). The effectiveness of passive cooling systems in improving heat conditions in less-developed countries under the threat of climate change needs to be investigated using local data.

One of the geothermal cooling systems is the Earth-Air-Tunnel-Heat Exchanger (EATHE) system, where atmospheric hot air is drawn through an underground pipe, which cools down the air, and the cool air is then released inside the home. The EATHE works on the principle that although the air temperature varies over the year, the soil temperature 2–3 m

CONTACT Mamdud Hossain M.Hossain@rgu.ac.uk School of Computing, Engineering and Technology, Robert Gordon University, Aberdeen, UK

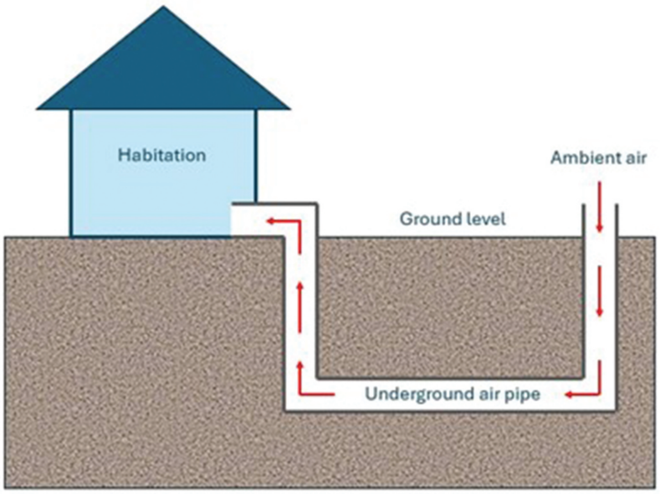

Figure 1. Schematic drawing of an earth-air-tunnel-heat exchanger (EATHE) system.

underground remains constant at an average yearly temperature, and this constant ground temperature can be used for cooling. Figure 1 shows the schematic of a typical EATHE system. Goswami and Dhaliwal (1985) developed a transient two-dimensional heat transfer equation and applied it to determine the exit temperature of air from a ground pipe. They used this equation to compare the temperature profile along the length of the buried pipe with their own experimental data. Their model was shown to underpredict experimental temperature data along the length of the pipe. Chel and Tiwari (2009) developed a comprehensive mathematical model to determine the air tunnel exit temperature and the mixing temperature within rooms throughout the year. In addition, they performed a life cycle analysis of the system. Their analysis shows that the total energy saving potential of a six-bed adobe home in New Delhi is 10,321 kWh/year. Su et al. (2012) developed a one-dimensional transient implicit finite difference equation considering a convection-diffusion sub-model for air temperature and an explicit 1-D transient sub-model for earth temperature calculation. Their model shows a maximum error in the temperature calculation of 1.4°C. Benhammou and Draoui (2015) developed an analytical model to provide a parametric study on the thermal performance of an earth-to-air heat exchanger for cooling buildings. They investigated the impact of length, diameter, and air velocity, and reported that there is an optimum pipe length of 40 m to get the highest efficiency. They also reported that a pipe with a smaller diameter and lower air velocity produced better performance. Krarti and Kreider (1996) developed an analytical equation (an algebraic equation) that can be used to predict temperature variation over a day. Their study also confirmed that the smaller the pipe diameter, the lower the exit temperature, and an optimum pipe length of approximately 40 m yields a better performance. A comprehensive design layout for underground piping for air tunnel heat exchangers was provided by Agrawal et al. (2019). Another comprehensive review of air tunnel heat exchangers was provided by (Singh et al. 2018). (Agrawal et al. 2018) applied CFD modelling to optimise the operating and design parameters of an earth air tunnel heat exchanger for space cooling using the Taguchi method. Their simulation results indicated that the highest air temperature drop inside the pipeline was influenced by the inlet air temperature, pipe diameter, pipe length and air velocity. Mathur et al. (2015) has applied CFD modelling to investigate the EATHE system under intermittent running over 12 hr by operating in cycle of 60 min on and 20 min off and 60 min on and 40 min off. They have also investigated three different soil conditions. Their simulations show that intermittent running gives 1.81% improvement in cooling than continuous operation over 12 hr. However, there simulations have shortcomings of keeping the inlet temperature constant over 12 hours, while the air temperature should vary continuously.

In the context of Kenya, an emphasis to revise the building code to make passive cooling mainstream only occurred in 2022 with the drafting of a national cooling action plan. In this respect, academic research and published articles are very scare. Ishugah et al. (2024) conducted an experimental study using a direct evaporative cooler for a classroom in Nairobi whereby the cooling system on average provided a 2.71°C drop of room air temperature. However, the relative humidity level in the supply air increased to 87% indicating the characteristics of the direct evaporative cooling adding moisture content in air. High humidity could reduce comfortability of occupants reducing its evaporation rate of moisture from the body. Moreover, the evaporative colling system needs water, which might not be readily available in drier areas and informal settlements. Olawale-Johnson et al. (2021) created a model box of 1 m × 1 m x 2 m to perform an experiment and simulation study to understand the impact of passive cooling namely: wall coating, roof coating, green roof and floor insulation and showed a 3.9°C cooling in room temperature, for Kiambu, Kenya. Samani et al. (2016) has applied four passive cooling systems (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) to a prefabricated 30 m^2 house located in rural areas of Nairobi, Kenya. All exterior and interior walls, floors and roofs are made of a composite sandwich panel consisting of two-glass fibre reinforced-laminates sandwiching an extruded polystyrene core. Their analytical calculations show that the natural ventilation is the most effective, followed by exterior shading, cool painting and thicker side wall plaster. Moreover, it was calculated that there would be an 84.7% reduction in cooling demand by combining all these techniques.

In this study, an Earth-Air-Tunnel-Heat Exchanger was designed for a tin-made building in Homa Bay, Kenya, using real-world data. Homa Bay is the capital town of Homa Bay County in Western Kenya, on the bank of Lake Victoria. Homa Bay faces several hazards owing to climate change, including drought, flooding, rainstorms, and extreme heat. While temperatures vary across Kenya, a distinct warming trend is evident, and the annual mean temperature has increased by approximately 1°C since the 1960s (Mathur et al. 2015). Temperatures in Kenya are projected to continue to rise by 1.7°C by 2050 and by approximately 3.5°C by 2100 (The World Bank Group 2021). The Homa Bay County Integrated Development Plan (CIDP) 2018–2022 reveals that the county is focused on reducing vulnerability to climate change through

Figure 2. A tin-built house at Homa Bay Town (taken by the author).

several initiatives, including the development of green building guides (CGHB 2018). Figure 2 shows a typical rented housing in Homa Bay for daily labourers, farm workers, fishermen, and small traders who are subjected to extremely high temperatures.

The aim of this study is to demonstrate that geothermal cooling can be a solution to the extreme heat problem. The novelty of the present work lies in using the real-world data to demonstrate the effectiveness the geothermal cooling for a particular location. The air temperature data gathered by a satellite were analysed and used to design the EATHE system, and a parametric study was performed to optimise the design. The project directly contributes to UNSDG 13 (Climate Action) by helping to meet the aspirations of Target 13.1, to strengthen the resilience and adaptive capacity of vulnerable populations, particularly as it relates to Indicator 13.1.1, which aims to reduce the number of deaths and people directly affected by climate-related hazards, and Target 13.3, by improving the capacity of target populations to mitigate and adapt to climate emergencies.

2. Methodology

A Computational Fluid Dynamics (CFD) model was used to design the EATHE system using temperature data available from Homa Bay. CFD modelling is the method of simulating the temperature, velocity, and turbulence parameters of a fluid flow system. In this method, a set of governing partial differential equations is solved using the control volume method. The governing equations used for the flow simulation were as follows:

Continuity:

$$\frac{\partial \rho \bar{u}_j}{\partial x_j} = 0 \tag{1}$$

Momentum:

$$\frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{u}_j\bar{u}_i\right) = -\frac{\partial P}{\partial x_i} + \mu_{eff}\frac{\partial}{\partial x_j}\left(\frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j}\right) \tag{2}$$

where μ_{eff} is the effective viscosity considering the viscosity of the fluid and the viscosity generated by turbulence, $\mu_{eff} = \mu + \mu_t$.

In the present study, the STT $k-\omega$ model (Menter 1994) was used to represent the turbulence in the flow. This two-equation eddy viscosity model has the advantage of capturing turbulence all the way down to the wall without using any special wall treatment. According to the model,

Kinematic eddy viscosity:

$$\nu_t = \frac{a_1 k}{\max(a_1\omega, SF_2)} \tag{3}$$

Turbulence Kinetic Energy:

$$\frac{\partial k}{\partial t} + U_j\frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_T)\frac{\partial k}{\partial x_j}\right] \tag{4}$$

Specific dissipation rate

$$\frac{\partial \omega}{\partial t} + U_j\frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_T)\frac{\partial \omega}{\partial x_j}\right. + 2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \tag{5}$$

Closure coefficients and auxiliary relations according to (Menter 1994) are:

$$F_2 = \tanh\left[\left[\max\left(\frac{2\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right)\right]^2\right] \tag{6}$$

$$P_k = \min\left(\tau_{ij}\frac{\partial U_i}{\partial x_j}, 10\beta^* k\omega\right) \tag{7}$$

$$F_1 = \tanh\left\{\left\{\min\left[\max\left[\left(\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right), \frac{4\sigma_{\omega 2}k}{CD_{k\omega}y^2}\right]\right\}^4\right\} \tag{8}$$

$$CD_{k\omega} = \max\left(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}, 10^{-10}\right) \tag{9}$$

$$\phi = \phi_1 F_1 + \phi_2(1 - F_1) \tag{10}$$

$$\alpha_1 = \frac{5}{9}, \alpha_2 = 0.44 \tag{11}$$

$$\beta_1 = \frac{3}{40}, \beta_2 = 0.0828 \tag{12}$$

$$\beta^* = \frac{9}{100} \tag{13}$$

$$\sigma_{k1} = 0.85, \sigma_{k2} = 1 \tag{14}$$

$$\sigma_{\omega 1} = 0.5, \sigma_{\omega 2} = 0.856 \tag{15}$$

Heat Transfer:

$$\frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{u}_j\bar{T}\right) = \Gamma_{eff}\frac{\partial}{\partial x_j}\left(\frac{\partial \bar{T}}{\partial x_i} + \frac{\partial \bar{T}}{\partial x_j}\right) \tag{16}$$

where Γ_{eff} is the turbulent diffusion coefficient, $\Gamma_{eff} = \frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}$; Pr and Pr_t are the laminar and turbulent Prandtl numbers, respectively.

Following assumptions are made in the CFD simulation:

- Flow is incompressible and steady state
- Conservation of mass, momentum and energy is achieved after the convergence of iterative solutions
- Fluid, pipe and soil properties are uniform

2.1. Solution techniques

The set of governing equations was solved using the SIMPLE algorithm within ANSYS Fluent CFD software. Two different geometries were used: a straight pipe and a serpentine pipe, as shown in Figure 3. A combination of hexahedral and tetrahedral meshes was used in the simulation, and an extensive mesh independence test was performed. A second-order upwind scheme was implemented to discretise the momentum terms in all governing equations. In the transient solutions for the verification cases, a time step of 60 s was used.

2.2. Boundary conditions

The inlet velocity condition was imposed at the inlet of the pipe, whereas the pressure boundary condition was imposed at the exit. The inlet boundary temperature was applied based on temperature data from Homa Bay. The temperature at the top surface of the ground was set according to the Homa Bay ground surface temperature, whereas all other earth boundaries were set at a zero gradient.

2.3. Material properties

The thermophysical properties of the earth, air, and pipe materials used in the simulation are listed in Table 1.

3. Results

3.1. Validation

The developed CFD model was validated against two test cases by (Agrawal et al. 2018) and (Mathur et al. 2015). For both cases, the EATHE system is made of a 40 m straight pipe, with a pipe diameter of 0.1 m, initial soil and pipe temperatures were set at 27°C, air inlet velocity and temperature were set at 5 m/s and 46.2°C respectively. Figure 4 shows the temperature of flowing air along the length of the pipe after 1 and 12 h. The results show that air drawn through the pipe cools down due to convective heat transfer from the air to the pipe's inner surface and then conducted through the pipe material and to the soil. The atmospheric air at 46.2°C cools down to approximately 30°C. The present simulation reproduces their simulated temperature profiles well. After 1 hr of cooling, Figure 4a, the mean absolute percentage error (MAPE) between the (Mathur et al. 2015) and the present prediction is 2.14% and the MAPE between the (Agrawal et al. 2018) and the present prediction is 0.98%. After 12 hr of cooling, the MAPE for the two cases are, Figure 4b, 2.88% and 1.63%, respectively. Thus,

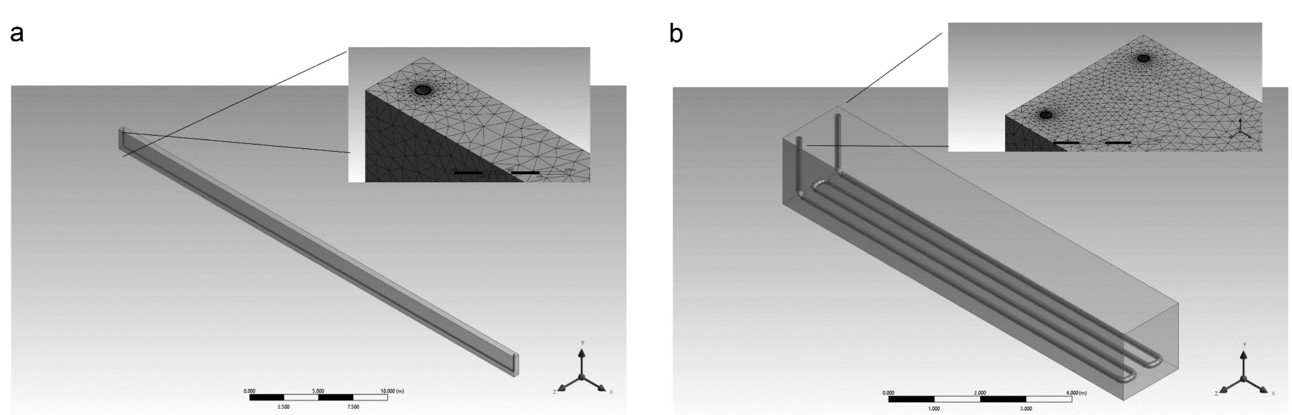

Figure 3. Geometries and meshes used in the simulation.

Table 1. Material properties used in simulations.

Material	Density (kg/m^3)	Specific heat (J-kg/K)	Thermal conductivity (W/mK)
Air	1.22	1006	0.02
Earth	2050	1840	0.52
Pipe (PVC)	1380	900	0.16

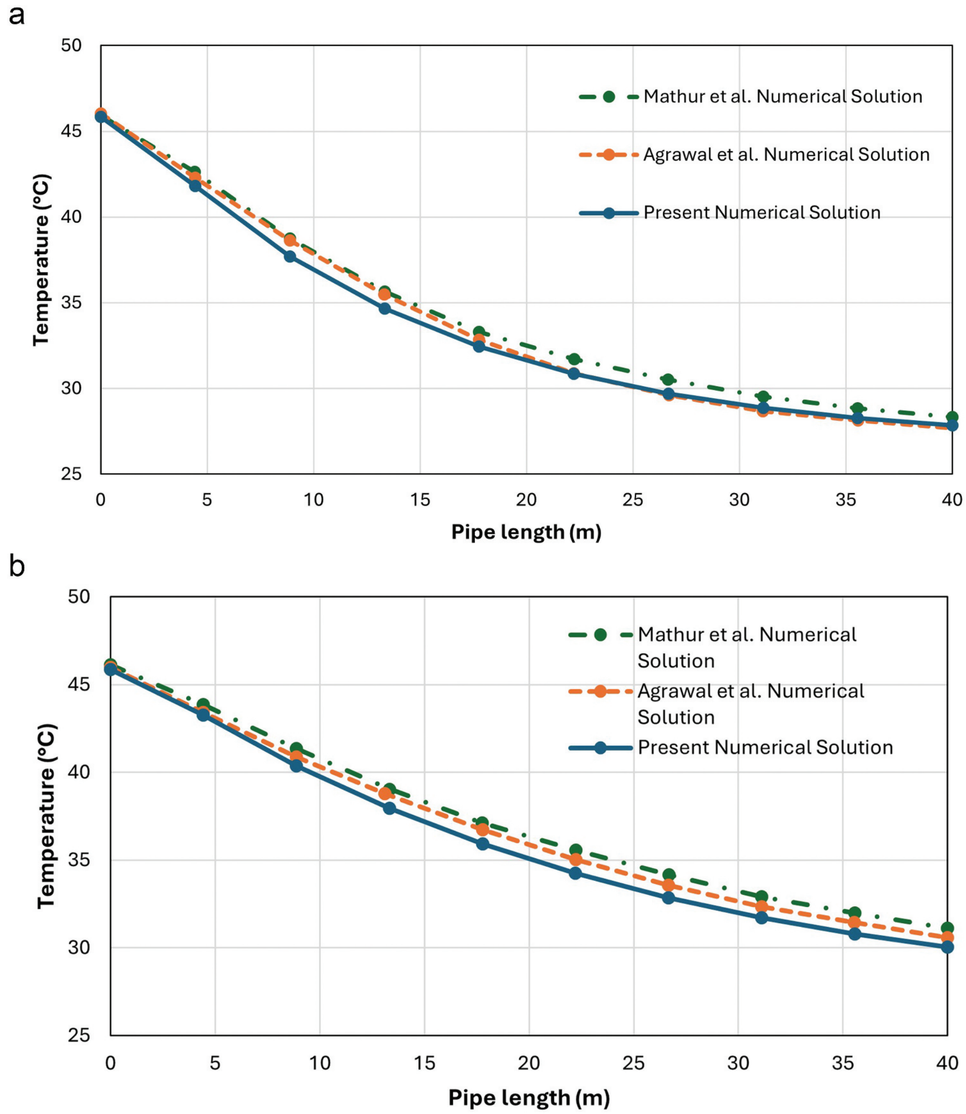

Figure 4. Comparison of temperature profile along the length of the pipe after a) after 1 hr and b) after 12 hr.

it can be concluded that the proposed CFD model was validated.

3.2. Homa Bay temperature analysis

Figure 5 shows the daily average air temperature variations at Homa Bay 2 m above ground level and the ground surface temperature from 1 July 2023, to 1 July 2024, from the satellite data (NASA 2024). The surface-based measurements are generally considered more accurate than the satellite-derived data (NASA 2024). However, the NASA Power Project (The World Bank Group 2021) provided an extensive validation and their hourly surface temperature data has a root mean square error (RSME) of 3.32% and daily average surface temperature has a RSME of 2.10%, while hourly dry bulb temperature and daily average dry bulb temperature have RMSEs of 3.32% and 2.4%, respectively. Daily average air temperature variation over a year can be approximated by a sinusoidal curve, as shown in these figures. The temperature variations showed that the seasonal variations in Homa Bay were relatively small, varying by approximately 4°C. The ground surface temperature is 2–3°C higher than the air temperature because it receives more intense radiation from the sun throughout the year. The warmer seasons in Homa Bay are January to March and September to November. The daily or diurnal temperature variation was approximately 12°C as shown in Figure 6, for the two hottest days. Figure 6 also shows the calculated temperature at 1.5 m depth. The seasonal temperature variations do not penetrate deeper than 1.5 m and the subsoil temperature at 1.5 m is uniform throughout the year. The subsoil temperature at a 1.5 m depth was calculated using (Kasuda and Bean 1965):

$$T(z,t) = T_m - A_s e^{-z\left(\frac{\pi}{365\alpha}\right)^{\frac{1}{2}}} \cos\left[\frac{2\pi}{365}(t - t_o) - \frac{z}{2}\left(\frac{365}{\pi\alpha}\right)^{\frac{1}{2}}\right] \quad (17)$$

where T_m is the annual mean ground surface temperature, A_s is the amplitude of temperature fluctuation, t_o the phase lag, α is the soil thermal diffusivity.

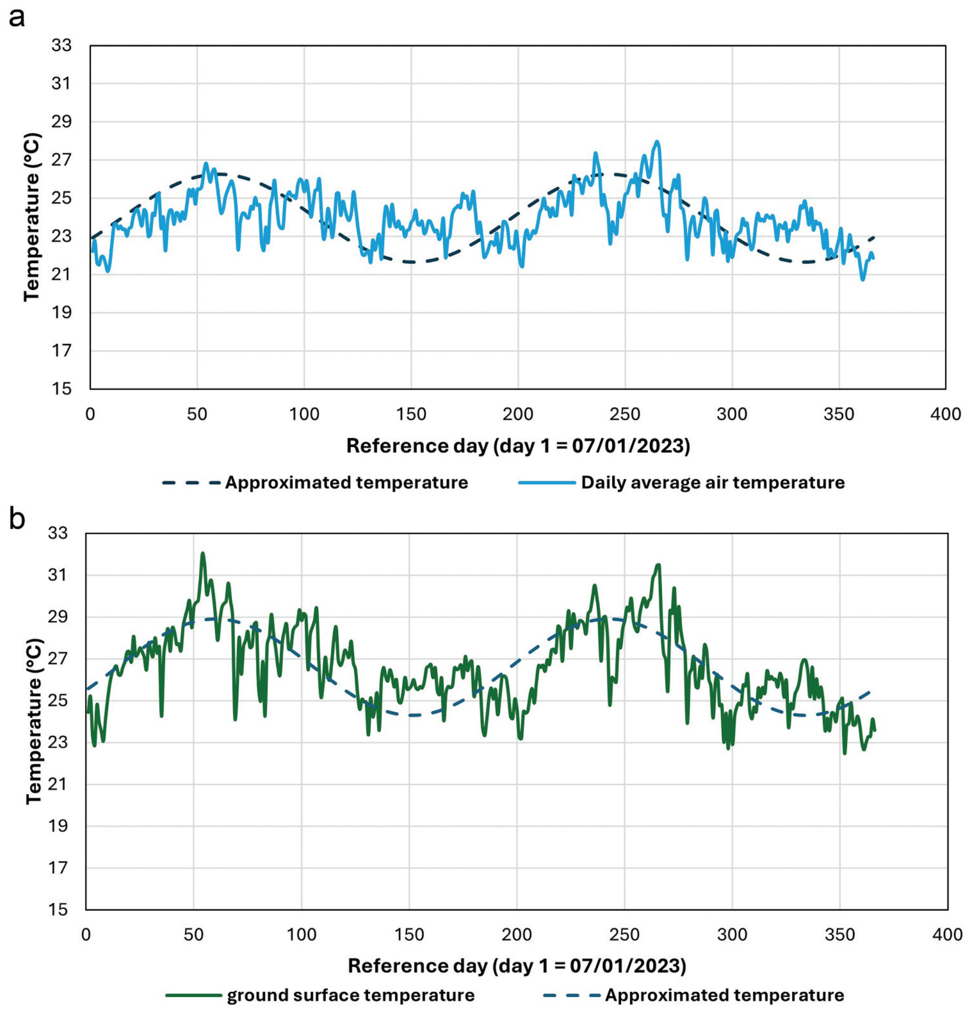

Figure 5. Daily average temperature variations in Homa Bay.

3.3. Geothermal cooling design for Homa Bay

CFD simulations were carried out for the hottest two days of the year between 1 July 2023, and 1 July 2024, for Homa Bay. The geothermal cooling system was designed using a PVC pipe having 0.1 m internal diameter of 40 m length. Two different arrangements were investigated: a straight pipe and a serpentine pipe, and the air velocity was varied between 1 and 5 m/s. In the serpentine pipe arrangement, the distance between the parallel pipes is kept at 0.4 m. Literature shows that PVC is a common material for use in the EATHE system (Agrawal et al. 2019; Benhammou and Draoui 2015; Chel and Tiwari 2009), possibly because it is durable, corrosion resistance, affordable and easy to instal. It is readily available in Homa Bay, Kenya for implementation. Previous studies have shown that 0.1 m diameter and 40 m length PVC pipe provided the optimum system design (Agrawal et al. 2018; Benhammou and Draoui 2015) and have been used in the present study. Once a geothermal system is designed and installed, the only way the performance can be influenced is by adjusting the velocity of air movement through the pipe (using a fan) and thus, a parametric study of geometric factors such as pipe length and diameter has not been caried out but was obtained from literature (Agrawal et al. 2018; Benhammou and Draoui 2015)

Extensive mesh independency tests have been carried out and 747,324 tetrahedral cells for straight pipe and 887,324 tetrahedral cells for serpentine pipe. Figure 7 shows the simulated steady-state temperatures of air and soil at 2 pm on 20 March 2024 for the straight pipe arrangement through a vertical central section for 1 m/s and 5 m/s air velocity. Since the air temperature is hotter than the soil temperature, the air moving through the pipe releases heat to the cold soil through convection to the inner wall of the pipe and the conduction though pipe material and soil materials. As the air flows through the pipe, it gradually cools down, whereas the ground soil around the pipe heats up owing to conduction heat transfer. Figure 7 (b) shows that at an air velocity of 5 m/s, the soil temperature is higher around the pipe, i.e. soil was heating up reducing the heat transfer between the flowing air and ground soil.

Figure 8 shows the simulated temperature contour on a horizontal section for the serpentine arrangement of the cooling pipe. These simulation results corresponded to the air temperature at 2 pm on 20 March 2024. Figure 8 (a) shows that the soil temperature remained cooler to provide cooling effects at 1 m/s and the gaps between the serpentine pipe of 0.4 m are adequate to keep the soil cold. On the other hand, it is evident from the simulation results that an air

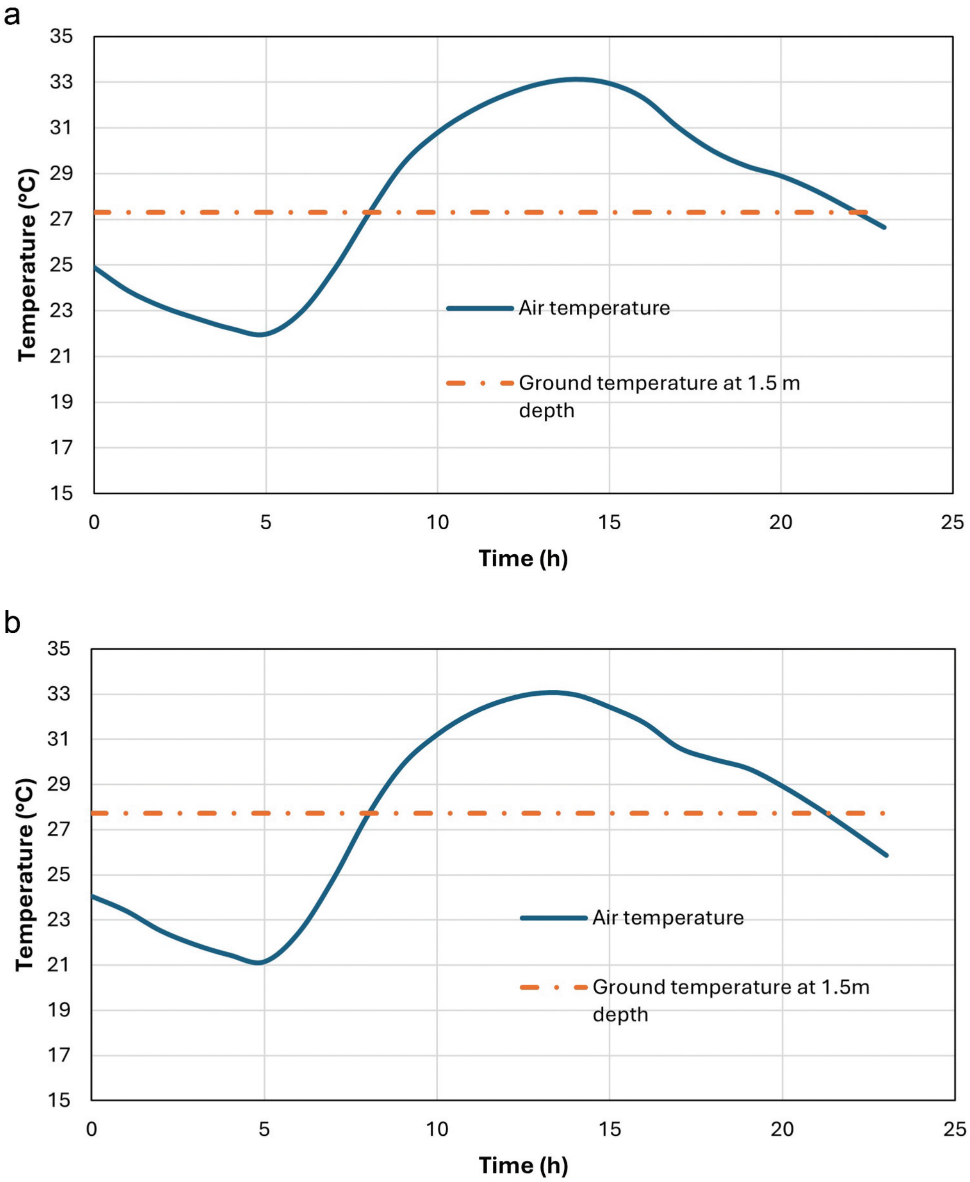

Figure 6. Daily temperatures variations of hourly average at hottest and coldest days a) 20/3/2024 b) 21/3/2024.

velocity of 5 m/s heated up the surrounding soil and, as a result, provided hotter air at the pipe exit.

Figure 9 shows the effects of air velocity on the delivery temperature over a 24-hour period for a straight pipe for two days (a and b). These figures also show the hourly average air temperature and the surface temperature. The hourly average air temperature on 20/3/24 on varies approximately from 21°C to 33°C and these temperatures are used as the inlet boundary conditions for air temperature for CFD simulation, while the ground soil temperature in the simulation are fixed at an average ground temperature of 27.7°C, which is not affected by the seasonal or the daily variation of air temperature. The simulation results over 24 h show that the geothermal system can provide heating at night, when the soil temperature is higher than the ambient temperature and cooling can be provided during the day when the soil temperature is less than the ambient temperature. The simulation results show that air velocity has significant effects on the cooling or heating. The lower the air velocity, the better the cooling or heating effect. If heating is not required at night, airflow can be blocked. Figure 10 shows the delivery temperature for the serpentine flow arrangement; the delivery temperatures were very similar to those of the straight pipe.

4. Discussions

The present simulations have used air temperatures for the two hottest days in the year in Homa Bay, Kenya. Other days will have less cooling effects, although the seasonal temperature variation for Homa Bay is small (approximately 3°C). Geothermal cooling will be more effective at places where the seasonal temperature variations are very large and more than 10–15°C such as in India, and consequently the difference between soil and ambient temperatures will be enhanced (Chel and Tiwari 2009). Moreover, the impact of humidity has not been considered in the simulation, humid air may provide reduced cooling by condensing water vapour and releasing heat condensation into the air.

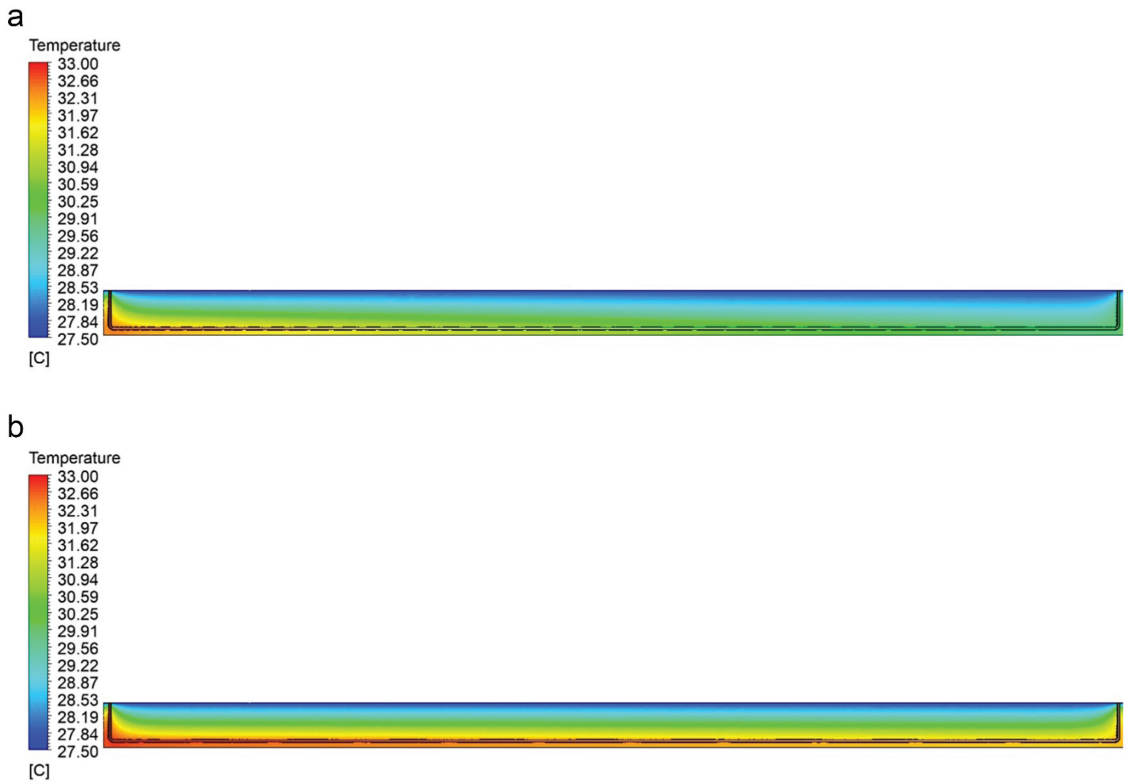

Figure 7. Contour plots of temperature on 20/3/24 at 2 pm a) 1 m/s b) 5 m/s.

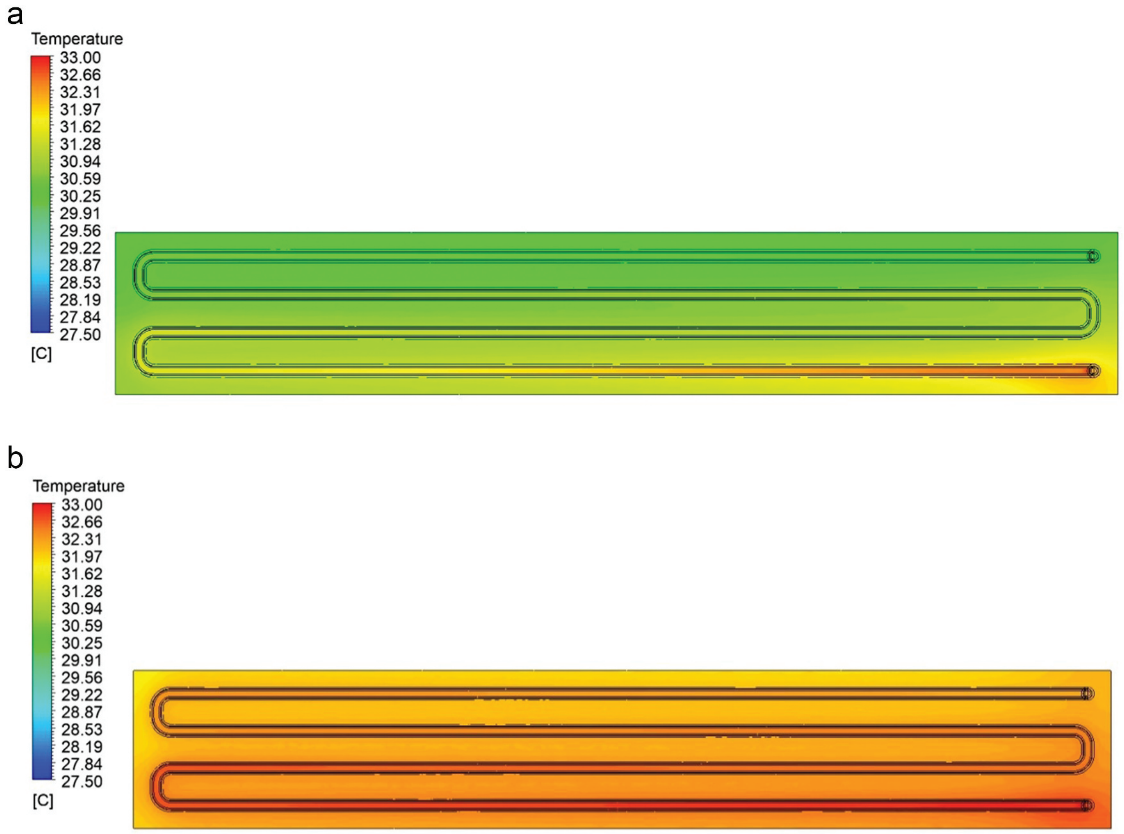

Figure 8. Contour plots of temperature on 20/3/24 at 2 pm a) 1 m/s b) 2 m/s.

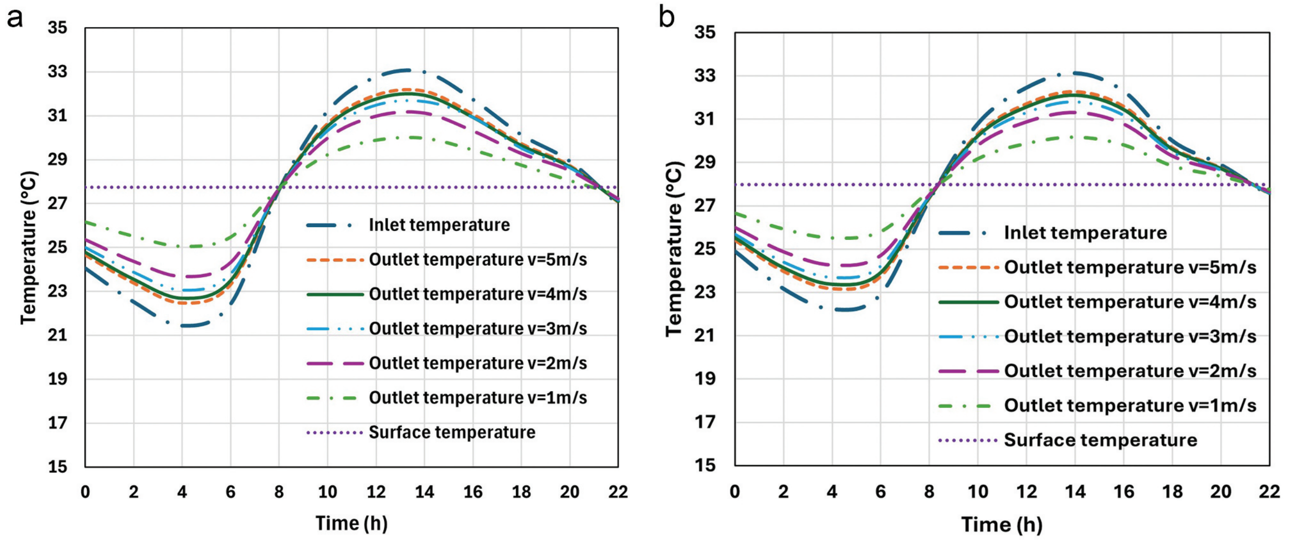

Figure 9. Delivery temperature as a function of air velocity over 24 hours time period for the straight pipe arrangement a) 20/3/2024 b) 21/3/2024.

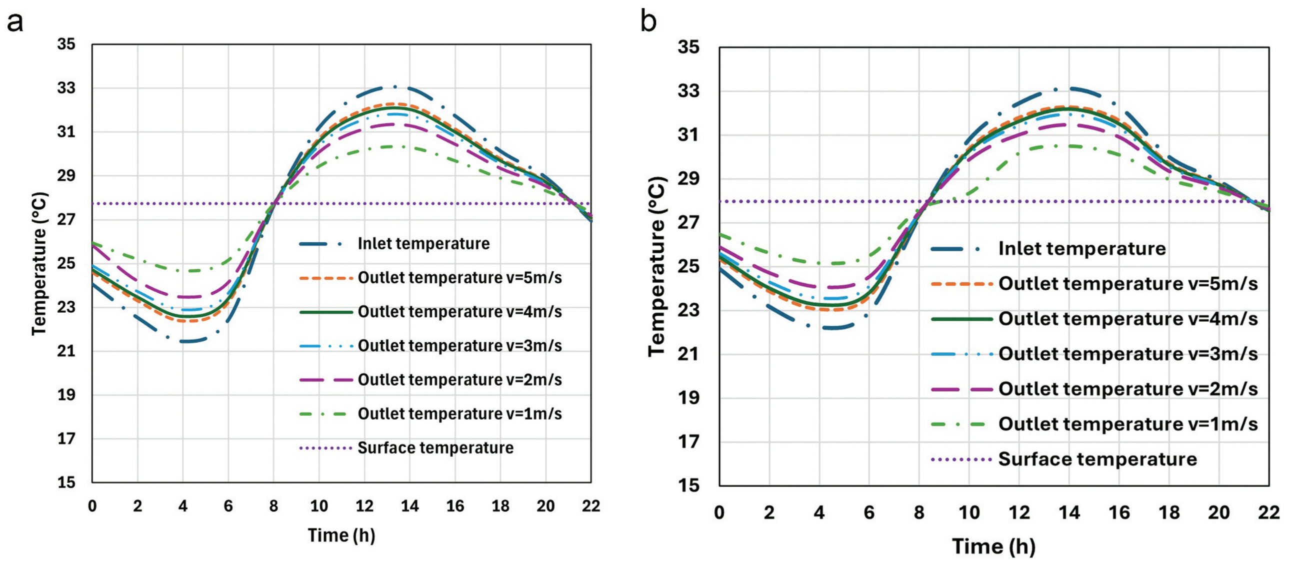

Figure 10. Delivery temperature as a function of air velocity over 24 hour time period for the serpentine pipe arrangement a) 20/3/2024 b) 21/3/2024.

However, the NASA Power Project data (The World Bank Group 2021) shows that the relative humidity was 54.74% and the dew point temperature was 16.74°C on 20 March 2024 at Homa Bay and the geothermal cooling temperature is above the dewpoint temperature and thus the condensation would not occur. Humidity levels should be considered when considering the transferability of the simulation to other locations.

Figures 7 and 8 show that the soil is warmed by the heat released from the air during the daytime as the air within the pipe gets cooled. However, at night-time, the soil temperature will be above the air temperature and will be cooled down to its original temperature. This is also evident in an experiment by (Goswami and Dhaliwal 1985). Rain can also influence the soil temperature and thus, in practical applications, it is very important to know the soil's thermal properties and the bulk soil temperatures at the location where this system is considered.

Since the serpentine design provides the same cooling as the straight pipe, the installation of the serpentine design is preferable to the straight pipe, due to the smaller length of the space required next to the building. Many low-cost buildings in Homa Bay have the 4 m x 10 m space needed next to the house for serpentine pipe installation (see Figure 2). Further multiple serpentine pipes arrangement can be made within a single hole supplying cooling air to several houses. PVC piping is widely available, it is lightweight and easy to transport. Simple tools like a pipe cutter and glue would be needed to assemble a geothermal cooling system. PVC piping can last up to 100 years buried underground and thus no maintenance will be required. The airflow is driven by a solar fan which also does not require regular maintenance. To prevent debris entering the pipe, the pipe entrance will have a filter or strainer attached to it.

The cost of PVC pipes, elbows, vent caps, plugs, glues was quoted from a local vendor in Homa Bay was £177.00

and the cost for hiring a digger, diesel and labour cost for installation was quoted as £126.0. The price of a solar driven fan with lithium-ion battery for storage is £30.0. Therefore, the total cost of geothermal cooling installation for a single house is estimated to be £333.0. It is predicted that the PVC pipe will last more than 50 years and with the economy of scale, the cost can be reduced. This price is comparable to the similar cost estimation provided by Chel and Tiwari (10) for a house in Delhi, India, to €314.17.

The outcomes of the present study show that geothermal cooling can provide a passive cooling solution for heat stressed communities in Homa Bay Kenya. Thus, this article evidences a solution to climate adaptation and improving rural living conditions addressing the UN Sustainable Development Goals Challenge 13 Climate Action.

5. Conclusion

A geothermal cooling system based on an Earth-Air-Tunnel-Heat exchanger (EATHE) was designed for Homa Bay Kenya. The Computational Fluid Dynamics (CFD) modelling study was conducted using the inlet air temperature and ground earth temperature available from NASA Satellite data. The geothermal cooling system is based on the concept of the subsoil temperature remaining constant throughout the year without seasonal variation. In Homa Bay, the seasonal temperature variation was small, and the ground surface temperature was higher than the air temperature. During the hottest days, the diurnal or daily temperature variations are very high; thus, the EATHE can provide up to a 3°C cooling effect. The impact of the air velocity was investigated, and it was shown that the lower the air velocity, the better the cooling. Furthermore, both straight pipe and the serpentine pipe arrangements provide a similar cooling effect, and because of the lower space requirement, a serpentine design is recommended.

Following the design work based on simulations presented here, the recommended geothermal cooling system has been installed in six houses in Homa Bay, Kenya, with an additional two houses selected as control houses. Temperature sensors have been installed inside and outside houses as well body activities tracker has been given to participants to monitor temperature, heart rate, sleeping patterns to establish the impact of geothermal cooling on improvement in living conditions. The outcomes of the implementation phase will be published towards the end of 2025.

Highlights

- A CFD modelling study has been carried out to predict the suitability of a geothermal cooling system for a remote area of Kenya
- A real-world data set has been used for the investigation
- The present study shows that the geothermal cooling can be effective in providing passive cooling at Homa Bay, Kenya

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Notes on contributors

Professor Mamdud Hossain is an expert in energy transition with extensive collaborative research with Bangladesh, India, Kenya, Brazil and Bolivia. His research has been funded by EPSRC, NetZero Technology Centre, Innovate UK, GCRF and industry.

Mailys Lassale was a placement student at RGU for three months. She is expert in High Performance Computing and CFD modelling.

Professor Stephen Vertigans is a sociologist with considerable experience of working in ‘slums’ within the global south. His research projects within these locations include resilience, peacebuilding, everyday life, climate change prevention, livelihoods and he is in the midst of completing research into the health and livelihood experiences of older people.

Professor Gokay Deveci is a chartered architect and holds a professorial chair at the School of Architecture & Built Environment at Robert Gordon University. He has an international reputation for his expertise in affordable and sustainable low-energy housing.

Professor Eyad Elyan’s expertise lies in machine learning, ensemble-based learning, and learning from unstructured and imbalanced datasets. He has attracted support for his research from various public funding bodies like Innovate UK, the Data Lab Innovation Centre, NetZero Technology Centre (NZTC), and more.

Dr Katherine Burgess is a BASES accredited sport and exercise scientist based in the School of Health Sciences. She has a range of experience in monitoring health, wellbeing and physical performance and the influence of interventions.

Dr. Mark Okowa is a distinguished academic and project development expert with a robust background in political studies, research, and project management. Holding a PhD in Political Studies from the University of Aberdeen, Dr. Okowa specializes in transitional justice, conflict transformation, and public policy. His career is marked by significant contributions to strategic planning and the execution of donor-funded projects, as well as impactful academic supervision and teaching.

CRediT Authorship

All authors have read and approved the final version of the manuscript

Mamdud Hossain: Conceptualisation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – Original Draft

Mailys Lassale: Data Curation, Investigation, Software, Validation, Visualization

Stephen Vertigans: Funding acquisition, resources, supervision, writing – review and editing

Gokay Deveci: Funding acquisition, supervision, writing – review and editing

Eyad Elyan: Funding acquisition, supervision, writing – review and editing

Katherine Burgess: Funding acquisition, supervision, writing – review and editing

Mark Okowa: Funding acquisition, supervision, writing – review and editing

Data availability statement

The data supporting the findings of this study are available from the corresponding author, MH, upon reasonable request.

Nomenclature

Roman	
A_s	amplitude of daily average temperature variation over a year (^{O}C)
k	turbulence kinetic energy (m^2/s^2)
P	pressure (Pa)
Pr	Prandlt number
s	soil thermal diffusivity (m^2/s)
T	Temperature (K, ^{O}C)
t	time (s)
u	velocity (m/s)
x	location (m)
Z	depth (m)
Greek	
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
Γ	diffusivity (m^2/s)
ρ	density (kg/m^3)
ω	specific rate of dissipation of turbulence kinetic energy (1/s)

Abbreviations

CFD	Computational Fluid Dynamics
EATHE	Earth-Air-Tunnel-Heat-Exchanger
PVC	Poly vinyl chloride

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