



Thermal study of a dry sandy soil in Ouagadougou: Nodal method approach

**Boureima KABORE^{1,2,*}, Wende Pouré Germain OUEDRAOGO^{2,3},
Salifou Cisse², Isidore SODO², Kalizeta SAWADOGO²,
Sié KAM², Dieudonné Joseph BATHIEBO²**

¹*UFR-ST, Laboratoire de Chimie Analytique, Physique spatiale et Energétique (L@CAPSE),
Université Norbert ZONGO, Koudougou, Burkina Faso*

²*Laboratoire d'Energies Thermiques Renouvelables, Université Joseph KI-ZERBO, Burkina Faso.*

³*ESI, Université Yembila Abdoulaye TOGUYENI (UYAT), Burkina Faso*

*Corresponding author, Email address: kaboureim@gmail.com

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Abstract: In Sahelian zone, renewable energies are an alternative in a context of insufficient energy in all its forms. Geothermal energy comes from a source which is the ground. The thermal behavior of a soil depends on several parameters including its nature. In Burkina Faso, the best-known renewable energy source is the sun. Geothermal and geothermal technologies are little known by persons in the energy sector. However, these technologies offer possibilities to users, for example for air conditioning of homes and for energy storage. In this work, we carried out a thermal study of a dry sandy soil in Ouagadougou. We considered a dry sandy soil exposed to solar radiation during the day. There follows a heat exchange between the soil and environment. For the modeling of this heat exchange, we used the nodal method and the implicit finite difference method. The simulation was done using the FORTRAN computer code. The meteorological data used concern the hourly average ambient air temperatures for 2014 in Ouagadougou. The numerical results show that the temperature of the soil surface varies between 29.6°C and 31.2°C. During hot periods of the day (8 am - 8 pm), when the depth of the soil increases its temperature decreases. Beyond 2 m of depth, the temperature remains almost constant over time whatever the weather conditions outside and it is around 29.1°C. The temperature difference between the soil surface and the 3 m depth is about 2°C. This difference shows that dry sandy soil has good thermal inertia.

1. Introduction

The consumption of large quantities of non-renewable energy has had a negative impact on social and economic development. Therefore, reducing dependence on traditional fossil fuels is critical, and renewables will play an important role in this process (Lingling *et al.*, 2022; Ba *et al.*, 2025). Geothermal energy sources have received significant attention in recent years as a source of renewable energy (Bidarmaghz *et al.*, 2016) and plays an indispensable strategic role in this transition (Zhenggang *et al.*, 2025). It is a clean and sustainable energy, which has been directly explored by over 80 countries (Jia *et al.*, 2021; Zhenggang *et al.*, 2025). Unlike other renewable

sources, geothermal energy offers consistent and weather-independent energy production, making it a valuable component of modern energy systems (Duque *et al.*, 2025; Ouali *et al.*, 2019). Residential buildings account for environ 20% of total energy consumption in developed countries, and for developing countries, more than 35% (Soltani *et al.*, 2019; Lucia *et al.*, 2016; Kim *et al.*, 2023). For the reduction of the energy consumption of these buildings, we use renewable energy sources for cooling (Yoon *et al.*, 2021; Yang *et al.*, 2020; Rached *et al.*, 2024). There are very limited applications in this area (John *et al.*, 2015). Earth is also one of the first basic building materials used by humans, available and low in energy consumption (Togdjim al., 2023). With increasingly growing energy demand, the development of geothermal energy is of interest to our African countries (Céline *et al.*, 2005; Birol, 2022; Randriambolanirina *et al.*, 2025). This form of energy uses the soil as a source. Soil is a porous medium composed by the gas, liquid and solid (Bai *et al.*, 2016). Soil is essential for the propagation of life on Earth and therefore is an integral part of the biosphere. (Stefan *et al.*, 2018). Heat loss from the solar pond to the ground is by unsteady conduction and is affected by the soil's thermal conductivity, density and specific heat. The soil temperature within the sandy backfill material recovers more quickly than sandy clay and clay (Leong *et al.*, 1998).

Therefore, it is necessary to know the thermal behavior of the soil in order to optimize the use of this energy. In this work, it is for us to determine the temperature evolution of a dry sandy soil thermally disturbed on the basis of meteorological data from Ouagadougou.

2. Material and method

2.1 Scheme of the model

The following Fig. 1 shows the scheme of the physical model.

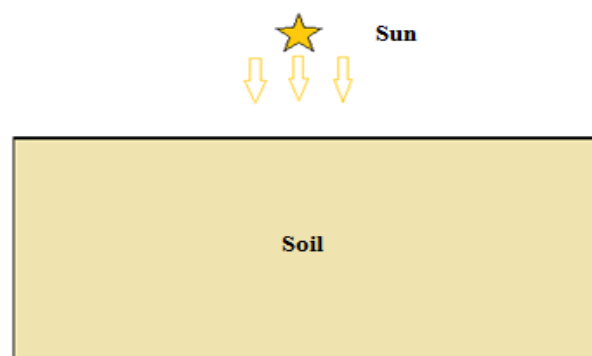


Figure 1. Scheme of the model

We consider a dry sandy soil exposed to solar radiation during the day. There will be a heat exchange between the soil and the external environment. Thus, heat will be diffused inside the soil in the direction from the surface to the depth. The part of the soil that will be experience a change in temperature is called « disturbed soil ». The other part is the « undisturbed soil ».

2.2 Modeling

We use a one-dimensional model for conduction exchanges. For modeling, we use the nodal method. This method consists of a fictions spatial division of the system into «slices» of thicknesses, the sections of which are perpendicular to the direction of the flow. In each slice, the variables are assumed to be homogeneous and the energy balances are written, by successive time intervals until

the duration of the study is exhausted. The passage from one slot to the next is done by retaining the exit conditions of the « upstream » slot as input data of the located « downstream». Traditional algorithms have played a crucial role in early geothermal research due to their good convergence and stability (Ba *et al.*, 2025). For the discretization of the equation, we use the finite difference method (implicit scheme) which gives stable results (Gabbard *et al.*, 2025; Albarak, 2024).

***Scheme of thermal exchanges:**

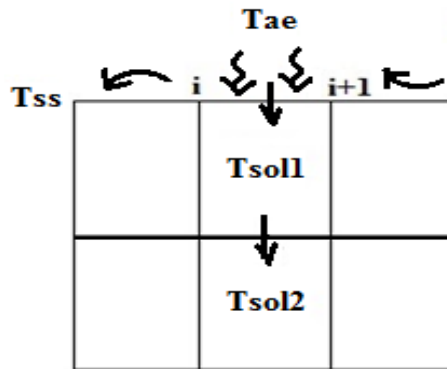


Figure 2. Scheme of thermal exchanges in the soil

Tae: Ambient air temperature (meteorological data)

Tss: Soil surface temperature

Tsoll: Disturbed soil temperature

Tsol2: Undisturbed soil temperature (constant).

***Simplifying assumptions:**

For the model, we assume that:

- The soil has a rectangular geometry;
- The thermo-physical properties of the soil are homogeneous and constant (Ali *et al.*, 2024; Ali *et al.*, 2025);
- There is no heat source in the soil;
- The phenomena of convection and radiation are negligible compared to conduction in the soil.
-

***Heat exchange balance:**

It is necessary to understand the thermal properties of soil to determine the energy balance at the ground surface (Ren *et al.*, 2024). The basic heat exchange equation is therefore (Kaboré *et al.*, 2021):

$$e_i \rho_i c_{pi} \frac{dT_i}{dt} = DFSA_i + Q_{mi} + \sum_j \sum_X h_{xij} (T_j - T_i) \tag{Eqn. 1}$$

$DFSA_i$: Solar density absorbed by (i) ($W m^{-2}$)

Q_{mi} : Exchanged mass flux density (i) ($W m^{-2}$)

h_{xij} : Heat exchange coefficient between (i) et (j) ($W m^{-2} K^{-1}$)

We apply the equation (1) to the various environments of the system:

- At the soil surface :

$$e_s \rho_s c_{ps} \frac{dT_{ss}}{dt} = DFSA_{ss} - h_{cae} (T_{ss} - T_{ae}) - h_{ds} (T_{ss} - T_{sol1}) - h_{rsvvc} (T_{ss} - T_{vc}) \quad \text{Eqn. 2}$$

- In the soil 1 :

$$e_s \rho_s c_{ps} \frac{dT_{sol1}}{dt} = -h_{ds} (T_{sol1} - T_{ss}) - h_{ds} (T_{sol1} - T_{sol2}) \quad \text{Eqn. 3}$$

***Discretization of equations:**

The discretization of equations (2) and (3) give (Gabbard *et al.*, 2025; Albarak, 2024):

$$e_s \rho_s c_{ps} (T_{i,ss}^n - T_{i,ss}^{n-1}) = \Delta t \times DFSA_{ss} - \Delta th_{cae} (T_{i,ss}^n - T_{ae}) - \Delta th_{ds} (T_{i,ss}^n - T_{i,sol1}^n) - \Delta th_{rsvvc} (T_{i,ss}^n - T_{vc}) \quad \text{Eqn. 4}$$

$$e_s \rho_s c_{ps} (T_{i,sol1}^n - T_{i,sol1}^{n-1}) = -\Delta th_{ds} (T_{i,sol1}^n - T_{i,ss}^n) - \Delta th_{ds} (T_{i,sol1}^n - T_{sol2}^n) \quad \text{Eqn. 5}$$

***Matrix of the system:**

The mathematical model of the problem results in the following matrix:

$$\begin{bmatrix} e_s \rho_s c_{ps} + \Delta th_{cae} + \Delta th_{ds} + \Delta th_{rsvvc} & -\Delta th_{ds} \\ -\Delta th_{ds} & e_s \rho_s c_{ps} + 2\Delta th_{ds} \end{bmatrix} \begin{bmatrix} T_{i,ss}^n \\ T_{i,sol1}^n \end{bmatrix} = \begin{bmatrix} e_s \rho_s c_{ps} T_{i,ss}^{n-1} + \Delta th_{cae} T_{ae} + \Delta th_{rsvvc} T_{vc} + \Delta t \times DFSA_{ss} \\ \Delta th_{ds} T_{sol2} \end{bmatrix}$$

***Determination of physical parameters:**

- **Coefficient of natural convection of ambient air with soil surface**

$$h_{cae} = \frac{Nu \times \lambda_{ae}}{L} = \frac{0,6(Gr Pr)^{0,2} \times \lambda_{ae}}{L} = \frac{0,6(0,7Gr)^{0,2} \times \lambda_{ae}}{L} = \frac{0,6 \left(0,7 \times \frac{g \beta L^3 |T_{ss} - T_{ae}|}{\nu^2} \right)^{0,2} \times \lambda_{ae}}{L} \quad \text{Eqn. 6}$$

Nu, the number of Nusselt; λ_a , the thermal conductivity of air; L, the characteristic length of thermal exchange; Gr, the number of Grashof; Pr, the number of Prandtl; g, the intensity of earthly gravity; β , the air coefficient of dilation; $\nu = 15.6 \times 10^{-6} \text{ m}^2\text{s}^{-1}$, the kinematic viscosity of the air.

Other correlation (Kaboré *et al.*, 2017):

$$h_{cae} = 2,8 + 3 \times V_{ae} \quad \text{Eqn. 7}$$

Where: V_{ae} is ambient air velocity.

- **Radiation between the vault of heaven and soil surface**

$$h_{r_{ssvc}} = \frac{\sigma(T_{ss}^2 + T_{vc}^2)(T_{ss} + T_{vc})}{\frac{1 - \varepsilon_{ss}}{\varepsilon_{ss}} + \frac{1}{F_{ssvc}} + \frac{1 - \varepsilon_{vc}}{\varepsilon_{vc}} \times \frac{S_s}{S_{vc}}} \quad \text{Eqn. 8}$$

With:

S_v , the surface of glazing and the surface of the vault of heaven.

$\varepsilon_{vc} = 1$: Emissivity of vault of heaven.

$F_{vevc} = 1$: Form factor between glazing and the vault of heaven.

We obtain equation (9):

$$h_{r_{vevc}} = \varepsilon_{ve} \sigma(T_{VE}^2 + T_{VC}^2)(T_{VE} + T_{VC}) \quad \text{Eqn. 9}$$

$\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$ is Stefan-Boltzmann constant (Brichambaut *et al.*, 1995); T_{VE} is glazing temperature; $\varepsilon_v = 0.88$ is emissivity of glazing.

The temperature of vault of heaven is given by Swinbank expression (Fudholi *et al.*, 2011):

$$T_{vc} = 0.552 \times T_{ae}^{1.5} \quad \text{Eqn. 10}$$

ε_{ss} is emissivity of soil surface.

- **Coefficient de conduction du sol**

$$h_{ds} = \frac{\lambda_s}{e_s} \quad \text{Eqn. 11}$$

λ_v is soil thermal conductivity and e_v is soil thickness.

***Thermo-physical properties:**

The thermo-physical properties of soil and air are given in the following **Table 1**.

Table 1. Thermo-physical properties of soil and air (Chalhoub *et al.*, 2016; Belloufi *et al.*, 2016)

Proprieties	Dry sandy soil	Air
Thermal conductivity λ (W/K/m)	0.4	0.023
Massic thermal capacity Cp (J/kg/K)	853	1000
Density ρ (kg/m ³)	1700	1.250

Dry soils generally do not exhibit thermal conductivity variation with temperature (Leong *et al.*, 1998). Soil thermal properties are among the most important factors of energy and mass exchange between soil and atmosphere (Kaveh *et al.*, 2021). Thermal conductivity (λ), reflecting the ability of soils to transfer heat (Jun *et al.*, 2023). It is an important soil parameter because it is widely used in the numerical modeling of thermal stability (Jun *et al.*, 2020).

*Input parameters:

The input parameters are given in the following **Table 2**.

Table 2. Input parameters for simulation

Parameters	Values
Soil depth	0.5 m - 3 m
Soil temperature at 2 m of depth (Kaboré <i>et al.</i> , 2017)	29 °C
Ambient air temperature	Meteorological data (Ouagadougou)

The numerical resolution of the system of equations is carried out by the Gauss method. The computer program is executed by FORTRAN software (Michel *et al.*, 1993; Magnin *et al.*, 2023). The meteorological data used relate to the hourly average ambient air temperature for 2014 for the city of Ouagadougou.

3. Results and discussion

Figure 3 shows evolution of ambient air temperature during March, April and May. In **Figure 3**, we observe that the ambient air temperature curves have the same profile for all months. Generally, temperatures are between 24°C and 39°C. The maximum temperature values for the months of March, April and May are respectively 37.24°C, 38.41°C and 38.16°C. **Figure 4** shows the evolution of soil surface temperature during the months of March, April and May. The soil surface is the part that directly faces the sun. Weather conditions therefore have a significant influence on the thermal behavior of the soil. In **Figure 4**, we observe that the temperature curves have the same profile as those in Fig. 3. This means that the temperature of the soil surfaces changes with that of the ambient air. During the months of April and May, the temperature values are almost identical, unlike that of March. In general, the temperature of the soil surface varies between 29.6°C and 31.2°C. The relation between soil surface temperature and air temperature depends on the characteristics of the surface and on weather, particularly the amount of solar radiation (Williams *et al.*, 1976). **Figures 5, 6 and 7** respectively show the evolution of the soil temperature during the months of March, April and May for depths of 0.5m, 1m, 2m and 3m.

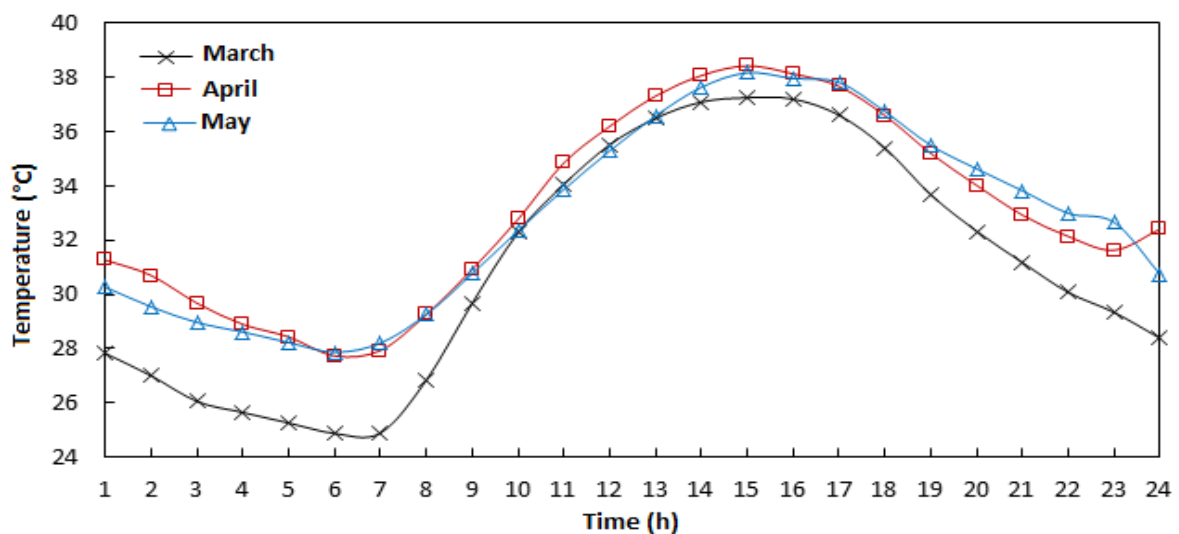


Figure 3. Evolution of ambient air temperature

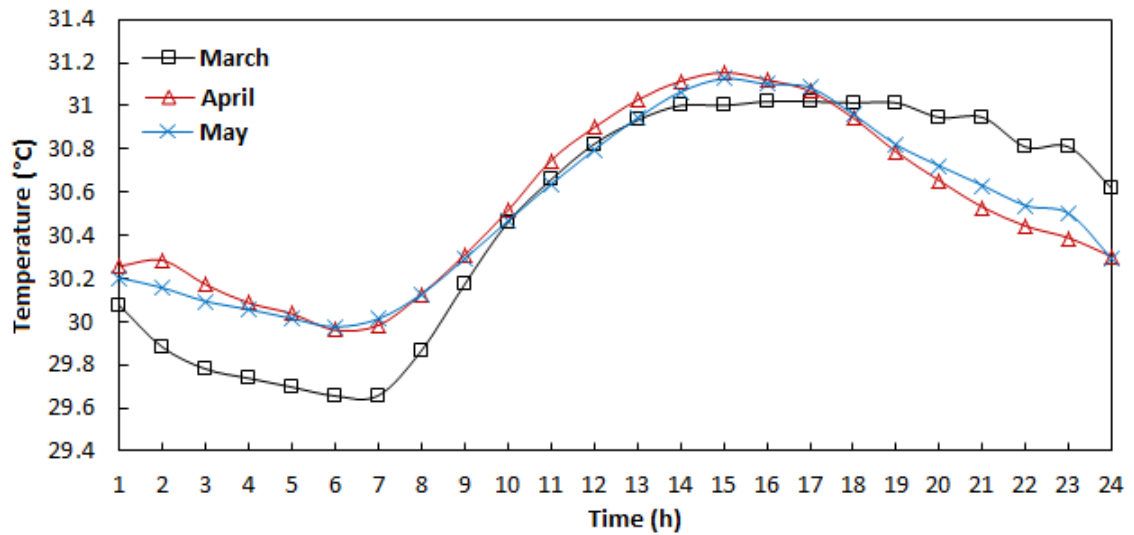


Figure 4. Evolution of soil surface temperature

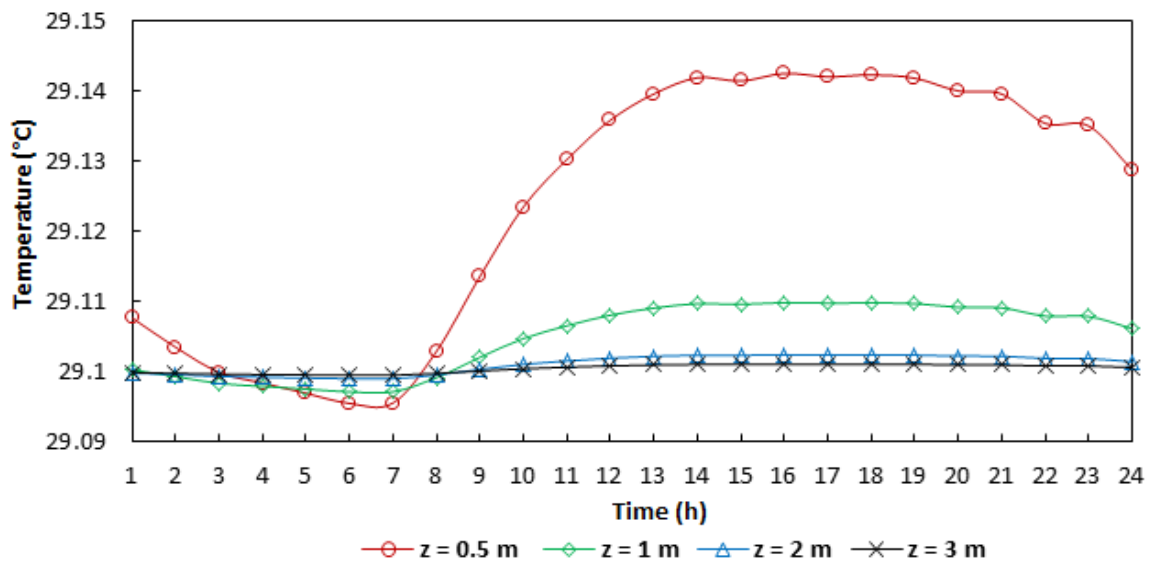


Figure 5. Evolution of soil temperature in March

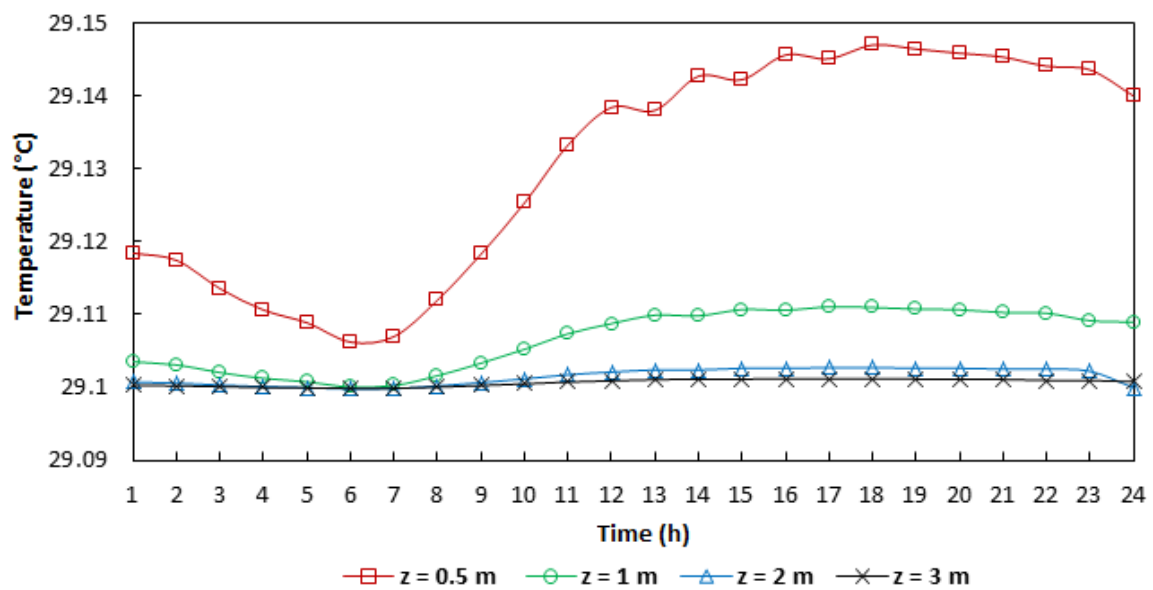


Figure 6. Evolution of soil temperature in April

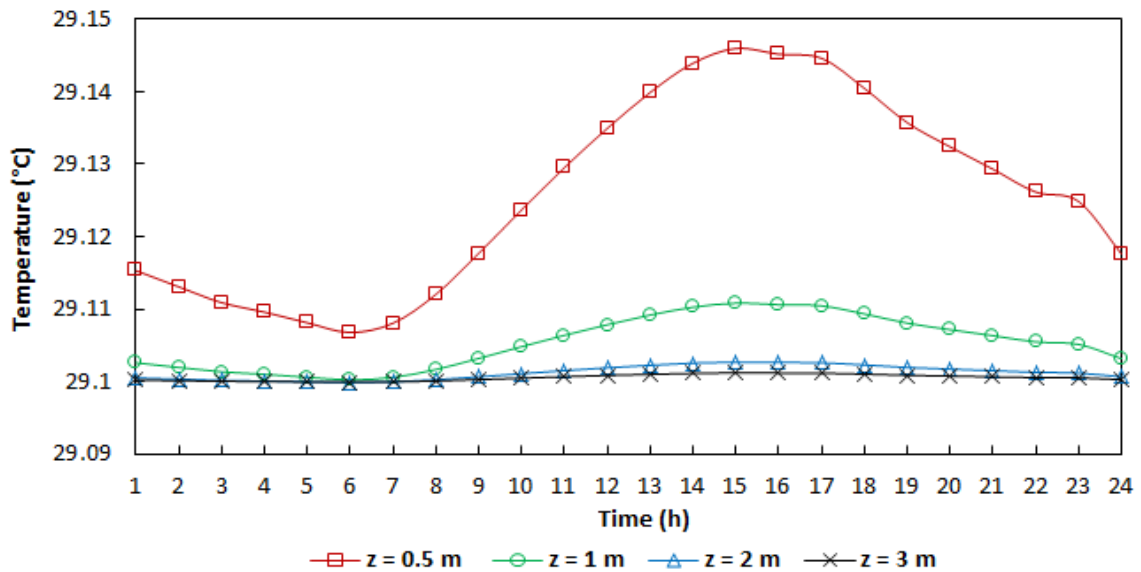


Figure 7. Evolution of soil temperature in May

Figures 5, 6 and 7 show that during hot periods of the day (8h to 20h), as depth increases the soil temperature decreases. In general, the variations are small (between 29.09°C and 29.15°C). Beyond a depth of 2 m, the temperature of the soil remains almost constant over time and is around 29.1°C. This shows that the soil temperature is almost constant regardless of the weather conditions outside. Indeed, this is possible because of the thermal inertia of the soil (Kaboré *et al.*, 2018). According to ASHRAE, below an approximate depth of 3 m the soil temperature remains constant throughout the year and is in close range with mean annual ambient air temperature (ASHRAE, 2019). According to (Tan *et al.*, 2013), because of the relatively high thermal inertia of the ground, temperatures in the soil lag those at the surface, and their fluctuations decrease with depth below grade. It therefore appears that the dry sandy soil is able to maintain its temperature at around 29.1°C at a depth of 2m during the month of March, April and May.

Conclusion

In this work, we conducted a thermal study of dry sandy soil in Ouagadougou. For the modeling, we used the nodal method and implicit finite difference method. The computer program was executed using FORTRAN code.

The numerical results show that:

- The temperature of the soil surface changes with that of the ambient air and takes values between 29.6°C and 31.2°C.
- During hot periods of the day (8am-8pm, when the depth increases the soil temperature decreases.
- Beyond 2m of depth, the temperature of the soil remains almost constant over time and is around 29.1°C.
- The temperature difference between the surface of the soil and the depth of 3m is about 2°C.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

- Albarak R.G. (2024). Study and Comparison of Finite Difference Methods for the Numerical Solution of Partial Differential Equations. *Nanotechnol. Percept*, 208–227. <https://doi.org/10.62441/nano-ntp.vi.3459>
- Ali M.H., Kurjak Z., Beke J. (2024). Estimating the impact of the thermo-physical properties of the multilayer soil on earth-air heat exchanger system performance. *Int. J. Thermofluids*, 23, 100722. <https://doi.org/10.1016/j.ijft.2024.100722>
- Ali P., Asal B., Arman K., Adrian R. (2025). A thermal testing device to determine thermal conductivity and specific heat capacity of saturated and dry soils. *Geotechnique*. <https://doi.org/10.1680/jgeot.24.01232>
- ASHRAE. (2019). handbook: Heating, ventilating, and air-conditioning applications. *ASHRAE, Atlanta, GA*
- Ba Z., Wang Y., Zhao Z., Zhang W. (2025). Assessment on the thermal efficiency of deep borehole heat exchangers under rock and soil heterogeneity. *Comput. Geotech.*, 180, 107075. <https://doi.org/10.1016/j.compgeo.2025.107075>
- Bai L., Che W., Wang S. (2016). Study on the Influence of Groundwater Seepage on the form of the Layout of Soil Source Heat Pump. *Procedia Eng.*, 146, 445–449. <https://doi.org/10.1016/j.proeng.2016.06.427>
- Belloufi Y., Brima A., Atmani R., Moumami N., Aissaoui F. (2016). Etude théorique et expérimentale du rafraîchissement de l'air par un échangeur géothermique air/sol. 121–137 ISSN : 1112-3680. archives.univ-biskra.dz
- Bidarmaghz A., Narsilio G.A., Johnston I.W., Colls S. (2016). The importance of surface air temperature fluctuations on long-term performance of vertical ground heat exchangers. *Geomechanics for Energy and the Environment*. <http://dx.doi.org/10.1016/j.gete.2016.02.003>
- Birol F. (2022). L'Afrique a le plus à gagner de la transition vers des énergies propres. *Work. Pap.*, 1–12.
- Brichambaut C.P., Leroy M. (1995). La mesure de la température de l'air. *La Météorologie*, 14–30. <https://doi.org/10.4267/2042/52002>
- Céline K. (2005). Énergie et pauvreté en Afrique. *OCDE*.
- Chalhoub, M. (2016). Suivi in situ du régime thermique d'un sol sablo-limoneux de la région Centre Val de Loire. BRGM/RP-66187-FR
- Duque J., Moya M., Urresta E., Harnisth K. (2025). Geospatial assessment of soil thermal conductivity for geothermal energy systems in Ecuador. *Geothermics.*, 131, 103373. <https://doi.org/10.1016/j.geothermics.2025.103373>
- Fudholi A., Sopian K., Ruslan M.H., Othman M.Y., Yahya M. (2011). Thermal Efficiency of Double Pass Solar Collector with Longitudinal Fins Absorbers. *Am. J. Appl. Sci.*, 8, 254–260. <https://doi.org/10.3844/ajassp.2011.254.260>
- Gabbard J., Van R. W.M. (2025). A high-order immersed finite-difference discretization for solving linear and nonlinear elasticity problems. *Comput. Methods. Appl. Mech. Eng.*, 446, 118269. <https://doi.org/10.1016/j.cma.2025.118269>
- Jia G.S., Ma Z.D., Xia Z.H., Wang J.W., Zhang Y.P., Jin L.W. (2022). Influence of groundwater flow on the ground heat exchanger performance and ground temperature distributions: A comprehensive review of analytical, numerical and experimental studies. *Geothermics.*, 100, 102342. <https://doi.org/10.1016/j.geothermics.2021.102342>
- John W. L., Tonya L. B. (2015). Direct Utilization of Geothermal Energy 2015 Worldwide Review. *Proceedings World Geothermal Congress, Melbourne, Australia*
- Jun B., Mingyi Z., Yuanming L., Wansheng P., Jianguo L., et al. (2020). A generalized model for calculating the thermal conductivity of freezing soils based on soil components and frost heave. *Int. J. Heat Mass Transf.*, 150, 119166. <https://doi.org/10.1016/j.ijheatmasstransfer.2019.119166>

- Jun B., Zhijian W., Yingmin Z., Haiyan W., Yunxia S., Sheng Y., Tao Z. (2023). An analytical model for the thermal conductivity of soils during a freezing process. *Int. Commun. Heat Mass Transf.*, 140, 106540. <https://doi.org/10.1016/j.icheatmasstransfer.2022.106540>
- Kaboré B., Kam S., Ouedraogo G.W.P., Ousmane M., Bathiébo D.J. (2018). Numerical study of heat diffusion in three soils under the influence of a hot air flow in the Sahelian zone: Case of air-soil heat exchanger. *J. Mater. Environ. Sci.*, Volume 9, Issue 7, Page 1999-2008. <http://www.jmaterenvirosci.com>
- Kaboré B., Kam S., Ouedraogo G.W.P., Zeghmati B., Chesneau X., Bathiébo D.J. (2017). Numerical and experimental study of an air-soil heat exchanger for cooling habitat in Sahelian zone: case of Ouagadougou. *Int. J. Adv. Eng. Res. Sci.*, 4, 24–32. <https://doi.org/10.22161/ijaers.4.10.5>
- Kaboré B., Ouedraogo G.W.P., Ouedraogo A., Kam, S., Bathiebo D.J. (2021). Numerical and Experimental Study of the Thermal Efficiency of an Air-Soil Heat Exchanger in the Sahelian Zone. *Asian J. Phys. Chem. Sci.*, 8–16. <https://doi.org/10.9734/ajopacs/2021/v9i330137>
- Kaveh M., Keyvan M., Fahimeh K. (2021). Response of soil thermal conductivity to various soil properties. *Int. Commun. Heat Mass Transf.*, 127, 105516. <https://doi.org/10.1016/j.icheatmasstransfer.2021.105516>
- Kim Y. S., Dinh H. B., Kang G. O., Hoang D. T. (2023). Performance evaluation of a novel horizontal ground heat exchanger: Coil-column system. *J. Build. Eng.*, 76, 107180. <https://doi.org/10.1016/j.job.2023.107180>
- Leong W.H., Tarnawski V.R., Aittomäki A. (1998). Effect of soil type and moisture content on ground heat pump performance: Effet du type et de l'humidité du sol sur la performance des pompes à chaleur à capteurs enterrés. *Int. J. Refrig.*, 21, 595–606. [https://doi.org/10.1016/S0140-7007\(98\)00041-3](https://doi.org/10.1016/S0140-7007(98)00041-3)
- Lingling B., Xue W., Pengfei J., Junyan C., Yuliang Z., Yusen W. (2023). An analytical heat transfer model for the mid-deep U-shaped borehole heat exchanger considering groundwater seepage. *J. Build. Eng.*, 64, 105612. <https://doi.org/10.1016/j.job.2022.105612>
- Lucia U., Simonetti M., Chiesa G., Grisolia G. (2017). Ground-source pump system for heating and cooling: Review and thermodynamic approach. *Renew. Sustain. Energy Rev.*, 70, 867–874. <https://doi.org/10.1016/j.rser.2016.11.268>
- Magnin V., Alves J., Arnoud A., Markus A. (2023). Esposito Marzino M. Fortran... et puis quoi encore ? 1024 *Bull. Société Inform. Fr.*, 143–161. <https://doi.org/10.48556/SIF.1024.22.143>
- Michel D., Jean V. (1993). Les spécificités du Fortran 90, *Collection informatique ISBN : 2-7108-0652-5 Editions Technip*, Paris.
- Ouali S. (2019). Chauffage et rafraîchissement par la géothermie. *Bull. Energ. Renouvelables.*, N°48, 2–5.
- Rached M., Raoua F., Bouchmel M., Mohamed A. A., Ammar H. (2024). Influence of Double Magnetic Fields on The Heat Transfer and Total Entropy Generation for Nanoliquid. *J. Mater. Environ. Sci.*, Volume 15, Issue 10, Page 1347-1367. <http://www.jmaterenvirosci.com>
- Randriambolanirina G.P., Ratolojanahary F.T. (2025). Optimization of renewable energy to strengthen food security. *Rev. Int. Cherch.* 6.
- Ren X., Niu F., Yu Q., Yin G. (2024). Research progress of soil thermal conductivity and its predictive models. *Cold Reg. Sci. Technol.*, 217, 104027. <https://doi.org/10.1016/j.coldregions.2023.104027>
- Soltani M., M. Kashkooli F., Dehghani-Sanij A.R., Kazemi A.R., Bordbar N., Farshchi M.J., Elmi M., Gharali K., B. Dusseault M. A (2019). Comprehensive study of geothermal heating and cooling systems. *Sustain. Cities Soc.*, 44, 793–818. <https://doi.org/10.1016/j.scs.2018.09.036>
- Stefan D. K., Gурpal S. T. (2018). The Composition of Soils and Sediments. In: *Green Chemistry.*, pp. 339–357. Elsevier
- Tan L., Love J. (2013). A Literature Review on Heating of Ventilation Air with Large Diameter Earth Tubes in Cold Climates. *Energies*, 6, 3734–3743. <https://doi.org/10.3390/en6083734>

- Togdjim J., Malloum S., Abderahman A. O., Abakar A., Alexis M. N., Danala S., Michel Q. (2023). Geotechnical, physicochemical and mineralogical characterizations of soil quarries in Chad with a view to their valorization in eco-construction. *J. Mater. Environ. Sci.*, Volume 14, Issue 02, Page 255-267. <http://www.jmaterenvirosci.com>
- Williams G.P., Gold L.W. (1976). Ground temperatures. *Can. Build. Dig.*, CBD-180. <https://doi.org/10.4224/40000712>
- Yang W., Xu R., Wang F., Chen S. (2020). Experimental and numerical investigations on the thermal performance of a horizontal spiral-coil ground heat exchanger. *Renew. Energy*, 147, 979–995. <https://doi.org/10.1016/j.renene.2019.09.030>
- Yoon S., Kim M. J., Jeon J. S., Jung Y. B. (2021). Significance evaluation of performance factors on horizontal spiral-coil ground heat exchangers. *J. Build. Eng.*, 35, 102044. <https://doi.org/10.1016/j.jobe.2020.102044>
- Zhenggang B., Ye W., Zhuang Z., Weijian Z. (2025). Assessment on the thermal efficiency of deep borehole heat exchangers under rock and soil heterogeneity. *Comput. Geotech.*, 180, 107075. <https://doi.org/10.1016/j.compgeo.2025.107075>
- Zhenggang B., Ye W., Zhuang Z., Weijian Z., Yuanfeng L. (2025). Efficient evaluation of the thermal performance of deep borehole heat exchangers affected by groundwater seepage. *Appl. Therm. Eng.*, 280, 127955. <https://doi.org/10.1016/j.applthermaleng.2025.127955>

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