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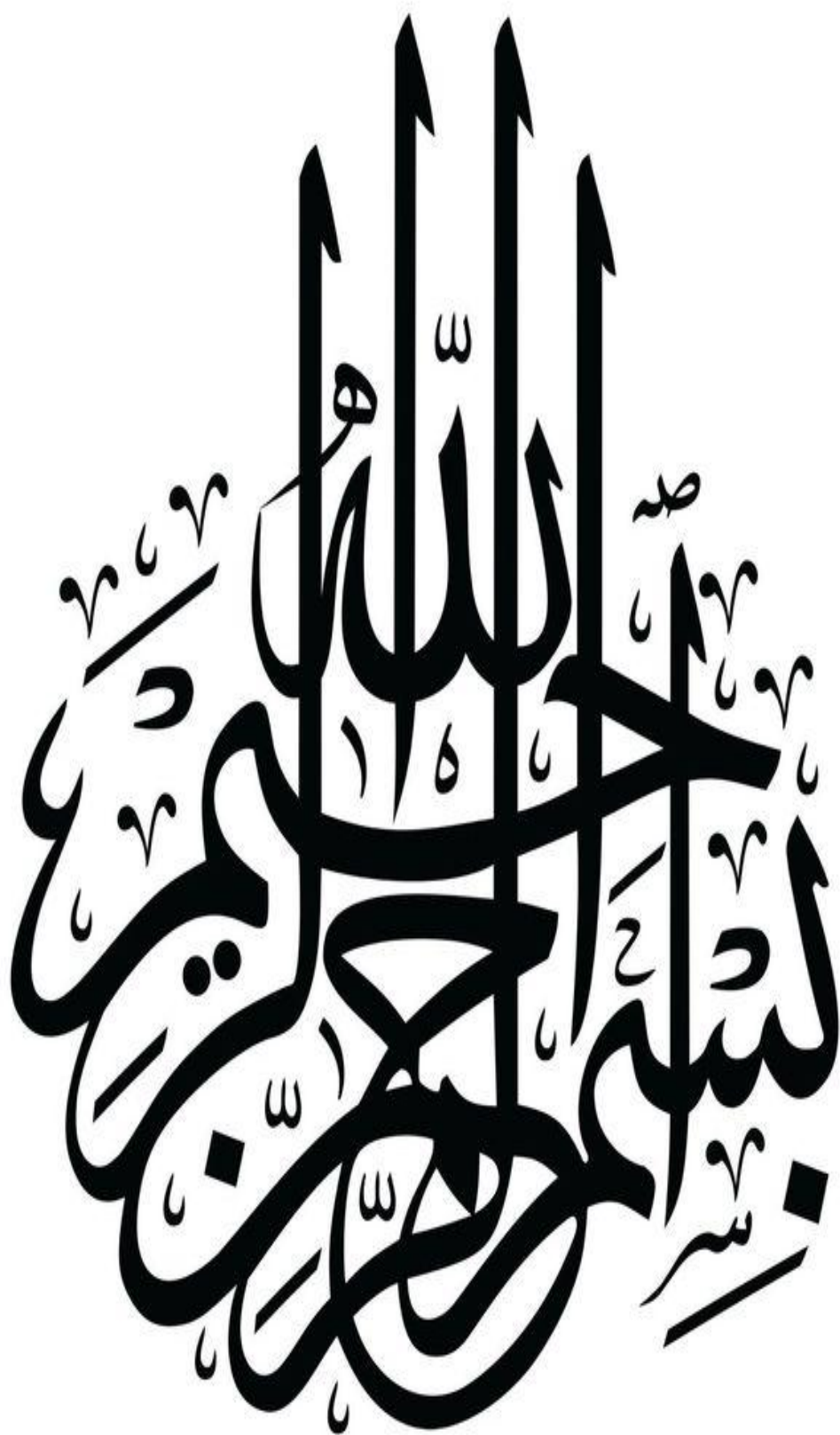
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Abstract

This study analyzes the performance of a 28-meter long Earth-air heat exchanger (EAHE), installed at a depth of 2.3 meters in Ghardaïa, to meet cooling and heating needs in dry climates. The methodology combines on-site experimental monitoring at URAER and laboratory characterization via an equipped box that simulates a continuous heat flow. The high-precision acquisition was carried out using type K thermometers and an Agilent 34972A acquisition.

The results show that the strong thermal diffusivity of limestone contributes to the diffusion of heat towards greater depths and gradually, unlike dry sand, which plays the role of a thermal insulator. In terms of energy, the EAHE system allows a significant reduction in consumption, as it relies on a fan with a capacity of only 21 watts for cooling and preheating.

The economic analysis reveals an initial investment of 102930.00 DA compared to conventional systems, for a low operating cost of 80.29 DA per quarter. This shows that the rocky nature of the soil is the decisive factor in the feasibility of the system, as limestone provides ideal conditions for exploiting underground thermal inertia.

Keywords: performance, diffusivity, thermal, limestone, sand, economic.

ملخص

تحلل هذه الدراسة الأداء المبادل الحراري هوائي-أرضي (EAHE) بطول 28 مترًا، تم تركيبه على عمق 2.3 مترًا في غرداية، لتلبية احتياجات التبريد والتسخين في المناخ الجاف. تجمع المنهجية بين المراقبة التجريبية في الموقع في URAER والتوصيف المختبري عبر صندوق مُجهزة يحاكي تدفق الحرارة المستمر. تم إجراء عملية الاستحواذ عالية الدقة باستخدام أجهزة قياس الحرارة من النوع K ووحدة Agilent 34972A.

وتوضح النتائج، أن الانتشار الحراري المرتفع للحجر الكلسي يساهم في انتشار الحرارة إلى أعماق أكبر وبشكل تدريجي، بخلاف الرمل الجاف، الذي يؤدي دور العازل الحراري. ومن ناحية الطاقة، يتيح نظام EAHE تقليص الاستهلاك بشكل ملحوظ، إذ يعتمد على مروحة بقدرة 21 واط فقط للتبريد والتسخين المسبق.

يكشف التحليل الاقتصادي عن استثمار أولي قدره 102930.00 دج مقارنة بالأنظمة التقليدية، مقابل تكاليف تشغيلية منخفضة تبلغ 80.29 دج لكل فصل من السنة. ويظهر ذلك أن الطبيعة الصخرية للتربة تُعد العامل الحاسم في جدوى النظام، إذ يوفر الحجر الكلسي الظروف المثالية لاستغلال القصور الحراري تحت الأرض.

الكلمات المفتاحية: الأداء، الانتشار، الحراري، الكلسي، الرمل، الاقتصادي.

Résumé

Cette étude analyse la performance d'un échangeur de chaleur air-sol (EAHE) de 28 mètres de long, installé à une profondeur de 2.3 mètres à Ghardaïa, pour répondre aux besoins en refroidissement et chauffage dans les climats secs. La méthodologie combine un suivi expérimental sur site à l'URAER et une caractérisation en laboratoire via une boîte équipée qui simule un flux de chaleur continu. L'acquisition de haute précision a été réalisée à l'aide de thermomètres de type K et d'une acquisition Agilent 34972A.

Les résultats montrent que la forte diffusivité thermique du calcaire contribue à la diffusion de la chaleur vers de plus grandes profondeurs et progressivement, contrairement au sable sec, qui joue le rôle d'un isolant thermique. En termes d'énergie, le système EAHE permet une réduction significative de la consommation, car il repose sur un ventilateur avec une capacité de seulement 21 watts pour le refroidissement et le préchauffage.

L'analyse économique révèle un investissement initial de 102 930.00 DA par rapport aux systèmes conventionnels, pour un faible coût d'exploitation de 80.29 DA par trimestre. Cela montre que la nature rocheuse du sol est le facteur décisif dans la faisabilité du système, car le calcaire offre des conditions idéales pour exploiter l'inertie thermique souterraine.

Mots-clés : performance, diffusion, thermique, calcaire, sable, économique.

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List of abbreviations

EAHE: Earth-Air Heat Exchanger.

URAER: Applied Research Unit in Renewable Energies.

HDPE: High Density Polyethylene.

T_{mean}: Mean annual temperature at the soil surface.

SONELGAZ: National Electricity and Gaz Company.

BTU: British Thermal Unit.

List of symbols

Symbols	Designation	Units
A	Temperature amplitude	°C
C_p	Specific heat capacity	J/kg.K
d	Thermal damping depth	m
m	Mass	kg
P	Power	W
T	Temperature	°C
t	Time	s
v	Volume	m ³
z	Depth	m
α	Thermal diffusivity	m ² /s
λ	Thermal conductivity	W/m.K
ρ	Bulk density	kg/m ³
w	Angular frequency	rad/s

General introduction



General introduction

In recent years, renewable energy has received growing attention due to its important role in addressing severe climate challenges and reducing dependence on conventional energy sources. In this context, the study of subsurface thermal behavior is of strategic importance for the development of applications such as earth-air heat exchangers (EAHE). If the thermo-physical properties of soils directly influence their diffusivity and thermal heat transfer, the specific transfer mechanisms for sand and limestone formations remain insufficiently characterized to optimize their integration into these systems. These two types of soils were selected because they constitute the dominant geological formations in the Ghardaïa region. In addition, a comparative assessment of the economic viability of EAHEs compared to conventional heating and cooling technologies remains necessary. This study aims to evaluate, analyze, and compare the thermal diffusivity of sand and limestone soils, which directly influences temperature variation rates at different soil depths, in order to identify the most efficient conditions for heat exchange in an Earth-to-Air Heat Exchanger (EAHE). The approach is based on an experimental protocol implemented at URAER-Ghardaïa, where a prototype was installed to test the thermal behavior of soils. Soil samples taken from the URAER-Ghardaïa site were also characterized in the laboratory. This device allows the regular acquisition of thermal data, thus providing an accurate characterization of heat flows in the medium. The present work is divided into three parts: the first part presents a general overview and the operating principles of Earth–Air Heat Exchangers (EAHE), the second part describes the materials and experimental methodology, while the third part discusses the experimental results and energy analysis.

Chapter I

General Overview and principles of Earth-Air Heat Exchangers (EAHE)

Introduction

In this chapter we present as trainees at the Applied Research Unit in Renewable Energies (URAER-Ghardaïa) the experimental approach we adopted to analyze the thermal behavior of soil in shallow geothermal applications.

An experimental device designed to simulate heat transfer in the soil was used. It allowed us to record temperature variations at different depths. The three types of soil selected are the most dominant in our Ghardaïa province: limestone and sand and soil collected from the site of URAER-Ghardaïa.

In order to obtain accurate data on the speed and stability of heat flow in these local soils we carried out thermal measurements every second.

1.1 Presentation of the system studied

The system studied in this licence thesis is an EAHE, designed to take advantage of the thermal stability of the earth at shallow depth in order to optimize the energy performance of a building. This device is based on the principle of heat transfer between air circulating in buried pipes and the adjacent geological environment. The installation comprises three main elements: an air intake, a network of buried pipes at a determined depth, and a system for connecting to the building. The soil acts as a natural thermal reservoir, characterized by a relatively constant temperature throughout the year compared to outside air. Thus, in winter, cold air is heated by contact with the earth while in summer hot air is cooled before being introduced into the building. The operation of the heat exchanger is carried out in forced convection mode: heat transfer takes place first by convection between the air and the inner wall of the pipe, then by conduction through the surrounding soil.

EAHE is located within URAER-Ghardaïa, located at geographical coordinates of 32.387° north latitude and 3.779° east longitude, which places it in the heart of the central region of the Algerian Sahara. The altitude of the site is 465 meters above sea level, a topographic datum essential for the analysis and interpretation of climatic and geothermal measurements.



Figure 1-1: The Earth-Air Heat Exchanger (EAHE) installation site in Ghardaïa, Algeria [1].

1.2 General Overview of the EAHE System

The experimental EAHE prototype was installed in May 2023 at URAER. The system consists of a horizontal pipe made of high-density polyethylene (HDPE) with a length of 28 m and an diameter of 160 mm, buried at a depth ranges from 2 to 2.6 meters below earth level. This depth was chosen to ensure favorable thermal conditions for an efficient heat exchange between the air circulating in the pipe and the surrounding soil mass.

The EAHE prototype studied adopts a direct horizontal linear configuration, consisting of a single horizontal pipe buried to a determined depth, connected at its two ends by two vertical pipes ensuring respectively the entry and exit of air. It consists of the following components:

- *Filtration system:* An air filter installed at the intake port ensures a dual function: on the one hand, the retention of particles and impurities suspended in the air, and on the other hand, the protection of the system against the intrusion of undesirable elements such as birds and insects.
- *Vertical air intake:* A suction duct oriented vertically downwards, allowing the outside air to be captured.
- *Horizontal tube:* The buried pipe, arranged horizontally, allows to extend the air path in the earth and thus optimize heat exchanges with the geological environment.

- *Fan*: A low-energy device, rated at 21 watts, ensures the forced circulation of air throughout the circuit.
- *Temperate air outlet*: A discharge pipe connecting the system to the inside of the building requiring thermal regulation (cooling in summer or heating in winter).
- *Thermal insulation*: A layer of insulation is applied to the two vertical sections located above ground in order to limit heat loss to the outside environment.

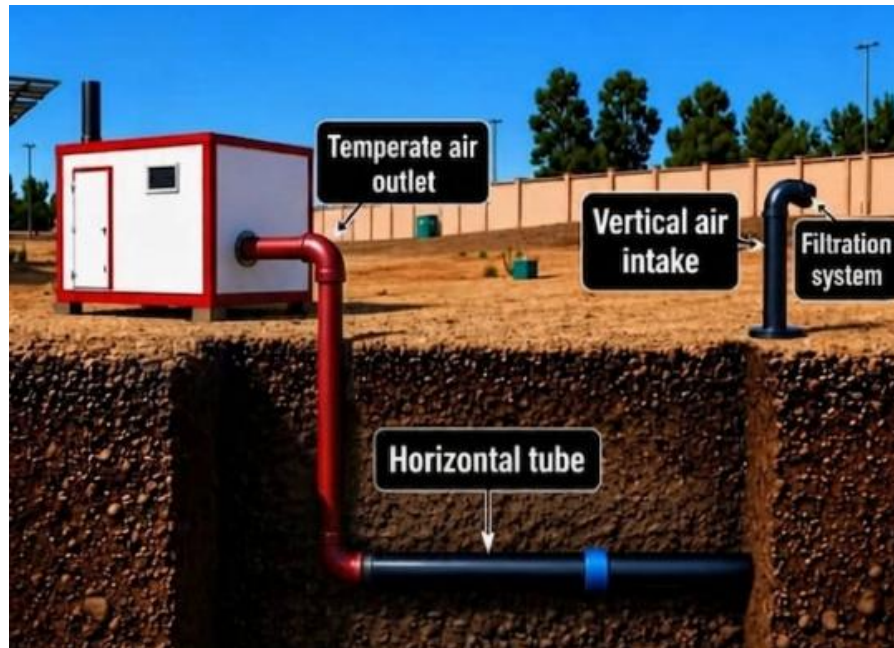


Figure 1-2: View of the prototype on the URAER site.

1.3 Thermal operating principle of the system

The EAHE exploits the temperature difference between the outside air and the shallow earth whose temperature remains relatively constant throughout the year. When the air circulates in the buried conduit, it exchanges heat with the wall of the tube, which is in thermal equilibrium with the adjacent geological medium. This exchange, controlled by forced convection and thermal conduction of the earth makes it possible to mitigate external temperature variations.

- During the summer period, warm outdoor air (up to 45 °C) releases some of its heat into the cooler earth which lowers its temperature to a value not exceeding 29 °C.
- During the winter period cold ambient air captures the residual heat from the sub-surface soil warmer than the outside air and sees its temperature rise beyond 19 °C.

1.4 Field of application in construction

EAHEs are passive systems applicable to various types of buildings—including residential homes, offices, and industrial facilities—where indoor temperature regulation is desired. Their effectiveness is particularly pronounced in regions with a significant thermal contrast between the ambient air and the earth, such as the desert and semi-arid areas exemplified by the province of Ghardaïa.

By preheating the supply air in winter and cooling it in summer, EAHEs reduce reliance on conventional heating and cooling equipment, thereby reducing energy consumption in buildings and contributing to lower carbon monoxide (CO) emissions, making this technology environmentally sustainable.

In addition, EAHEs offer significant health and safety benefits. By reducing or eliminating the use of gas heaters, they reduce fire risks, property damage and the number of victims, while reducing the need for civil protection interventions and protecting occupants from respiratory diseases and poisoning due to combustion appliances.

Finally, the EAHE can be implemented either at the building design stage or during modernization, with adjustable duct length and orientation to adapt to architectural constraints and thermal requirements specific to the project.

1.5 Operation in heating mode and Cooling mode operation

To understand how soil temperature changes with depth and time, we relied on the theoretical equation that relates temperature T , depth z , and time t . This equation takes into account the following:

- T_{mean} : The annual average temperature of the soil surface.
- A : The amount of temperature variation between summer and winter.
- d : The depth at which thermal variations decrease significantly.

$$T(z, t) = T_{\text{mean}} + A * e^{-\frac{z}{d}} * \sin(\omega * (t - t_0) - \frac{z}{d}) \quad (1-1)$$

Table 1-1: Statistical parameters of soil temperature at different depths (minimum, average, maximum and amplitude) recorded during the experimental period.

Temperature	$T(z=\text{surface}, t)$	$T(z=1\text{m}, t)$	$T(z=2\text{m}, t)$	$T(z=3\text{m}, t)$	$T(z=7\text{m}, t)$
Minimum	8.79	13.29	16.31	18.33	21.61
Mean	22.45	22.45	22.44	22.44	22.44
Maximum	36.09	31.59	28.57	26.55	23.27
Amplitude	13.64	9.14	6.13	4.11	0.83

In order to characterize the annual thermal behavior of the subsoil on the URAER site, the temporal evolution of temperature was followed at different depths over a complete cycle of 365 days. The results highlight a progressive damping of the amplitude of thermal variations with depth, a phenomenon directly related to the heat inertia of the medium. On the surface, seasonal fluctuations are marked, while from 3 meters, the gaps reduce considerably to tend towards quasi-stability at around 7 meters. At the same time, a temporal phase shift is observed: the thermal peak propagates with an increasing delay according to depth, as illustrated by the heating and cooling zones identified on the graph. This natural attenuation of thermal stresses at depth is a fundamental parameter for the sizing of geothermal heat exchangers, ensuring a near-constant temperature source. Figure 1-3 summarizes these annual temperature profiles and highlights the transition between the superficial climatic zone of influence and the deep temperature-stabilized zone.

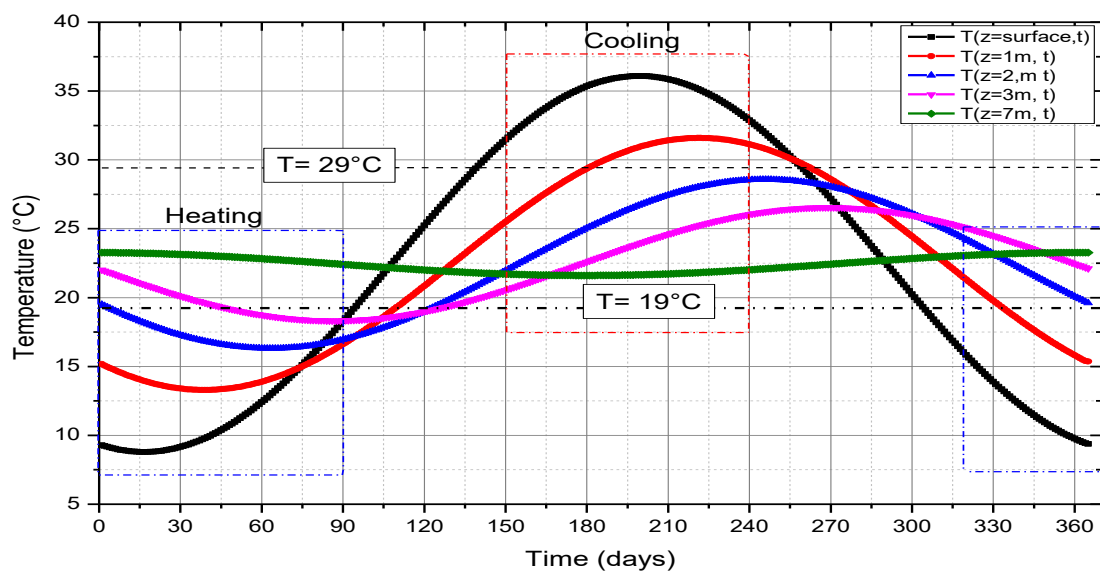


Figure 1-3: Annual variation of temperature at different depths in the soil of the URAER during 2020 [2].

1.5.1 Cooling mode operation

During the summer of 2020, measurements taken at URAER (Ghardaïa) show very high and highly fluctuating outdoor air temperatures, characteristic of intense heat in desert regions. The surface temperature of the earth has a greater amplitude than that of ambient air due to thermal accumulation in the soil. In the subsurface, the thermal signal gradually attenuates with depth and stabilizes at a given depth.

This indicates that deep soil in the Ghardaïa region stays relatively cool and stable during summer. Therefore, it can be effectively used to remove excess heat from buildings. In this case the soil acts as a natural heat sink absorbing heat and helping to maintain indoor thermal comfort while reducing the need for conventional air conditioning systems.

1.5.2 Heating mode operation

In winter, the examination of average temperatures highlights a distinct thermal behavior at the soil-air interface. At the surface, the soil is subject to the combined influence of cold air and daytime solar radiation. The absorption of solar radiation throughout the day allows the ground to accumulate heat, making its average daily temperature higher than that of the air. Thus, during the day, the earth surface is warmer than the ambient air. This relationship reverses during the night, when the air becomes hotter than the earth. Finally, there is an increase in temperature with the penetration into the soil.

This shows that deep soil in the Ghardaïa region retains its heat and is not strongly affected by the cold air above making it a reliable natural source of heat that can be effectively used for winter heating.

1.6 Thermophysical properties of soil

Understanding the thermal behavior of soil particularly in the context of the use of Earth-Air geothermal systems requires a thorough analysis of its physical parameters. Soil composition and structure determine its thermophysical properties which directly influence the efficiency of heat storage and transport.

The present experimental study aimed to evaluate the performance of three types of local soils sampled in the Ghardaïa region namely limestone and sand and soil from the URAER site in the context of a shallow geothermal system. To do this, the following thermophysical properties were determined for each sample: density and thermal diffusivity.

1.6.1 Bulk density (ρ)

Bulk density is the ratio of the soil sample's mass to volume and can be computed as follows:

$$\rho = \frac{m}{V} \quad (1-2)$$

ρ : bulk density (kg/m³).

m : mass (kg).

V : volume (m³).

1.6.2 Thermal diffusivity (α)

The rate at which heat moves through soil is expressed by thermal diffusivity which is computed as follows:

$$\alpha = \frac{\lambda}{\rho * C_p} \quad (1-3)$$

$$\alpha = \frac{\pi}{t} \left(\frac{z_i}{\ln\left(\frac{A_0}{A_i}\right)} \right)^2 \quad (1-4)$$

α : thermal diffusivity (m²/s).

λ : thermal conductivity (W/m·K). Tapez une équation ici.

ρ : density (kg/m³).

C_p : specific heat capacity (J/kg·K).

t : time (s).

z_i : level of depth (m).

A_i : Amplitude of depth (°C)

Table 1-2: Thermophysical Parameters of Selected Soil Types [3].

Soil type	Thermophysical parameter			
	ρ (kg/m ³)	λ (W/m·K)	C_p (J/kg·K)	α (m ² /s)
Limestone	2200 - 1600	2.8 – 1.3	1100 - 900	(1.5 – 0.8)×10 ⁻⁶
Sand	1700 -1400	1.5 – 0.25	1200 - 800	(0.8 – 0.2)×10 ⁻⁶

Conclusion

This chapter provided a general overview of the (EAHE) system and explained its operating principles in both cooling and heating modes. It also highlighted the importance of soil thermophysical properties, particularly bulk density and thermal diffusivity, in determining the system's performance.

Chapter 2

Materials and Experimental Methodology

Introduction

This second chapter is devoted to the presentation of the studied materials as well as to the detailed description of the experimental device implemented within the URAER of Ghardaïa. The main objective of this experimental phase is to characterize the thermophysical properties of three types of local soil: sand, limestone and soil specific to the research unit (URAER).

2.1 Description of the studied materials

In order to assess the thermal performance of the Earth-Air heat exchanger (EAHE) in the specific context of the Ghardaïa region, three types of local geological materials were selected for experimental characterization: sandy, calcareous soil and the specific soil of the URAER research unit. These materials were chosen because they represent the main subsurface compositions of arid environments, which directly influence the thermal diffusivity and the overall efficiency of the geothermal system. The study focuses on understanding how each material's distinct thermophysical properties, such as bulk density and heat retention capacity, affect the stabilization of temperatures inside the horizontal and vertical heat exchanger tubes. By comparing these materials, this study aims to optimize the design of bioclimatic cooling and heating solutions adapted to the local Saharan climate.

2.2 Experimental prototype for determining thermal diffusivity

2.2.1 Design of the instrumented experimental box

The experimental device designed specifically for measuring the thermal of soil samples. Consists of a parallelepiped wooden box with dimensions of 50cm×50cm×50cm, offering sufficient volume to study heat propagation at different depths. The enclosure, thermally insulated by a layer of polystyrene and whose inner wall is coated with an aluminum film to limit losses to the outside, thus ensures heat transfer mainly confined to the soil sample. The enclosure, closed by a side door and lined with an insulating material, must be designed to prevent any loss of heat from the side.

The heat source is a 75 watt incandescent bulb, type E27, fixed above the box (5 cm above the sample). It operated at constant power for the duration of the experiment, producing a regulated heat flow that simulated solar radiation or an external heat source.

2.2.2 Equipment and operating principle

- *Thermocouples:* Six K-type thermocouples were implanted at different depths in the soil sample to assess the thermal distribution. The measuring points were positioned at depths of 1 cm, 2 cm, 3 cm, as well as on the surface, one sensor was used to measure the air temperature inside the experimental box a sixth thermocouple was dedicated to the measurement of the ambient temperature inside the box, positioned between the bulb and the soil sample.
- *Operating principle:* The soil sample, is placed in a parallelepiped wooden mould 2 cm thick, whose internal dimensions are 17 cm long, 8 cm wide and 5,5 cm high. Only the upper side of this mould is open, which allows heat transfer from the surface through the different depths of the sample.
- *After closing the box:* we wait for the thermal stabilization of the system (ambient temperature of the enclosure and the soil sample). The soil surface is heated continuously by an incandescent bulb. Thermocouples record temperature every second at every depth, ensuring high-resolution acquisition. The same procedure is repeated under identical conditions for the other type of soil.
- *Measuring device:* The experimental box is equipped with six K-type thermocouples positioned at different depths and connected to an Agilent 34972A data acquisition unit, ensuring accurate and reliable measurements.

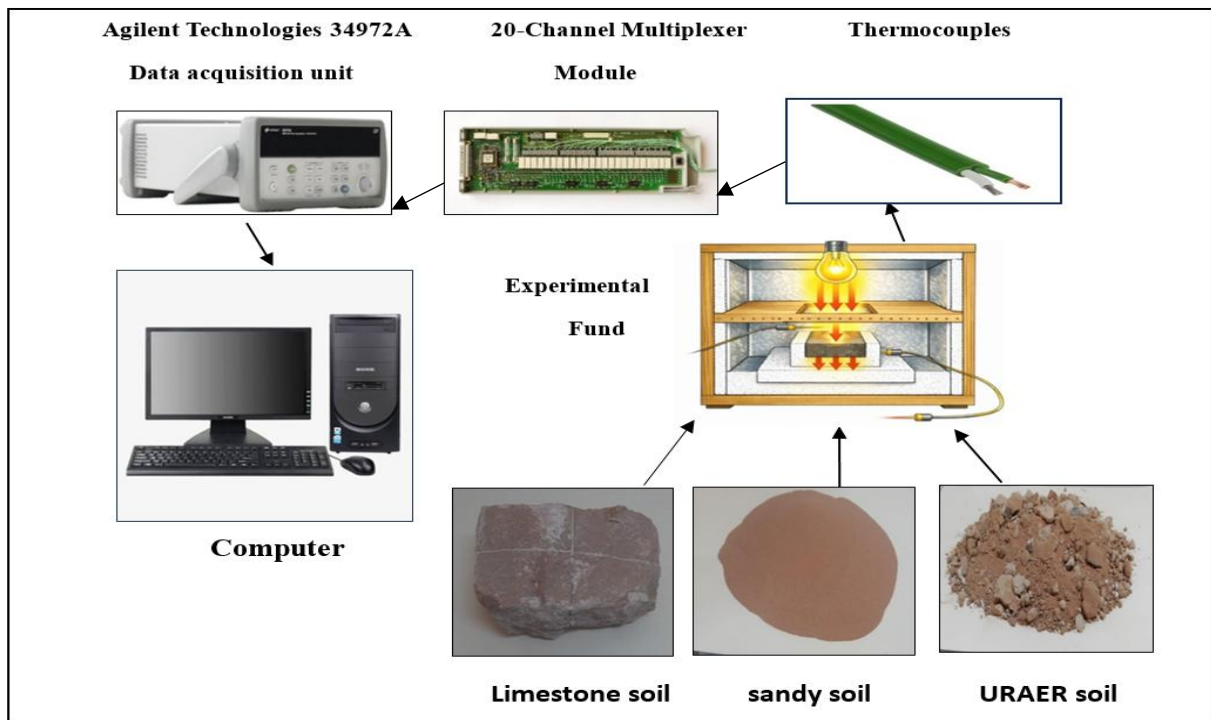


Figure 2-1: General diagram of the experimental system used to measure the temperature in sand and limestone soil at different depths.

2.2.3 Calibration of Thermocouples

Before each experimental series, the six Type-K thermocouples were calibrated to ensure accurate and reliable temperature measurements. The calibration was carried out using two fixed reference points: 0 °C, obtained from a melting ice bath, and 100 °C, corresponding to boiling water under normal atmospheric pressure. This procedure allowed verification of both the accuracy and linearity of the sensors across the studied temperature range.

After calibration, the thermocouples were placed at the predefined positions (surface, 1 cm, 2 cm, 3 cm, ambient air, and the heat source). The system was then closed and left until thermal equilibrium was reached, indicated by stable and uniform readings across all sensors. A 75 W E27 incandescent bulb, positioned 5 cm above the soil surface, was then activated to provide a constant heat flux. Throughout the experiment, temperature variations were continuously recorded by the Agilent 34972A data acquisition system at a sampling rate of one measurement per second.

2.2.4 Description of the Measuring Device

The measurement system used in this study was designed to accurately monitor soil temperature variations during the heating process. It consists of six Type-K thermocouples connected to an Agilent 34972A data acquisition unit, ensuring precise and continuous temperature recording. Four thermocouples were placed at different depths within the soil sample (surface, 1, 2, and 3 cm) to track the temperature distribution inside the material. One sensor was used to measure the air temperature inside the experimental box, while another was positioned at the heat source to monitor its temperature. Type-K thermocouples were selected due to their high sensitivity, reliability, and wide operating temperature range. Great care was taken during installation to ensure good thermal contact between the sensors and the soil, minimizing errors caused by air gaps or poor placement. The data acquisition system automatically records all measurements every second, allowing detailed and accurate analysis of the system's thermal behavior over time.

2.3 Experimental protocol and Data Processing

The experimental procedure followed a rigorous protocol conducted at the URAER-Ghardaïa research unit to ensure the accuracy of thermal measurements. The raw data, consisting of temperature readings recorded at specific intervals, was first organized and pre-processed using Microsoft Excel. Subsequently, advanced thermal depth and temperature-time curves were

generated using the OriginPro software to visualize subsurface behavior. The analysis of these profiles was fundamental to determine the thermal diffusivity (α) of the three specific materials: limestone, sand and URAER soil. This systematic approach has allowed a precise characterization of the thermal propagation kinetics within each sample, providing the necessary data to assess their suitability for earth-air heat exchanger (EAHE) applications in arid environments.

Conclusion

This chapter allowed to expose the rigorous experimental approach adopted to characterize the thermal behavior of materials from the Ghardaïa region. The implementation of a systematic calibration protocol for thermocouples and the use of an isolated instrumented box ensured the reliability of temperature measurements collected at different depths.

The organization of data via Microsoft Excel and its graphical processing under OriginPro is the key step to move from raw observation to scientific analysis. The temperature-time curves and depth profiles thus obtained provide essential parameters, in particular thermal diffusivity, to compare the suitability of sand and limestone for use as storage or heat transfer media. These experimental results, which will be detailed in the next chapter, are fundamental to validate the design models of bioclimatic cooling solutions adapted to the Saharan climate.

Chapter 3

Experimental results and energy analysis

Introduction

This chapter presents the experimental results obtained from the study of the thermal behavior of sand and limestone soils. The objective is to analyze how temperature evolves with time and depth within these two types of soil. Measurements were carried out with a high time resolution (one measurement per second) allowing a detailed observation of transient thermal changes.

This work is part of a broader effort to understand the performance of shallow geothermal systems particularly the EAHE which relies on the thermal stability of the earth to improve indoor heating and cooling conditions. Therefore, studying the thermal properties of soil is essential for evaluating the efficiency of such systems.

The results are presented in the form of tables and graphs showing temperature variation over time for each soil type. A natural soil sample from the Applied Research Unit in Renewable Energies (URAER-Ghardaïa) is also included for comparison purposes.

Finally, this chapter aims to link the experimental findings to their energy implications especially in terms of heating and cooling energy demand.

3.1 Presentation of experimental results

This section presents the experimental results obtained from the study of the thermal behavior of sandy soil and limestone soil with the addition of a from URAER soil of Ghardaïa for comparison purposes only. Temperature measurements were taken at regular vertical intervals, from the soil surface to 3 cm below it, while the soil was exposed to a continuous heat source in order to assess the thermal response of each soil layer.

The results are displayed in the form of tables and graphs showing the variation of temperature with time for each soil type. This part is mainly descriptive and aims to clearly present the thermal behavior .

The next section will be devoted to the comparative analysis and discussion of the thermal behaviors of the soils studied, as well as an evaluation of their respective thermal diffusivity.

3.1.1 Sandy soil

Sand soil is one of the most important types of soils studied in heat transfer applications due to its physical properties, which strongly influence heat conduction and diffusion within the porous medium. In this section, sand soil variation curves are used to analyze its thermal

behavior under different conditions. This analysis provides a better understanding of the soil response and allows evaluating its suitability for EAHE applications and improving building energy performance.

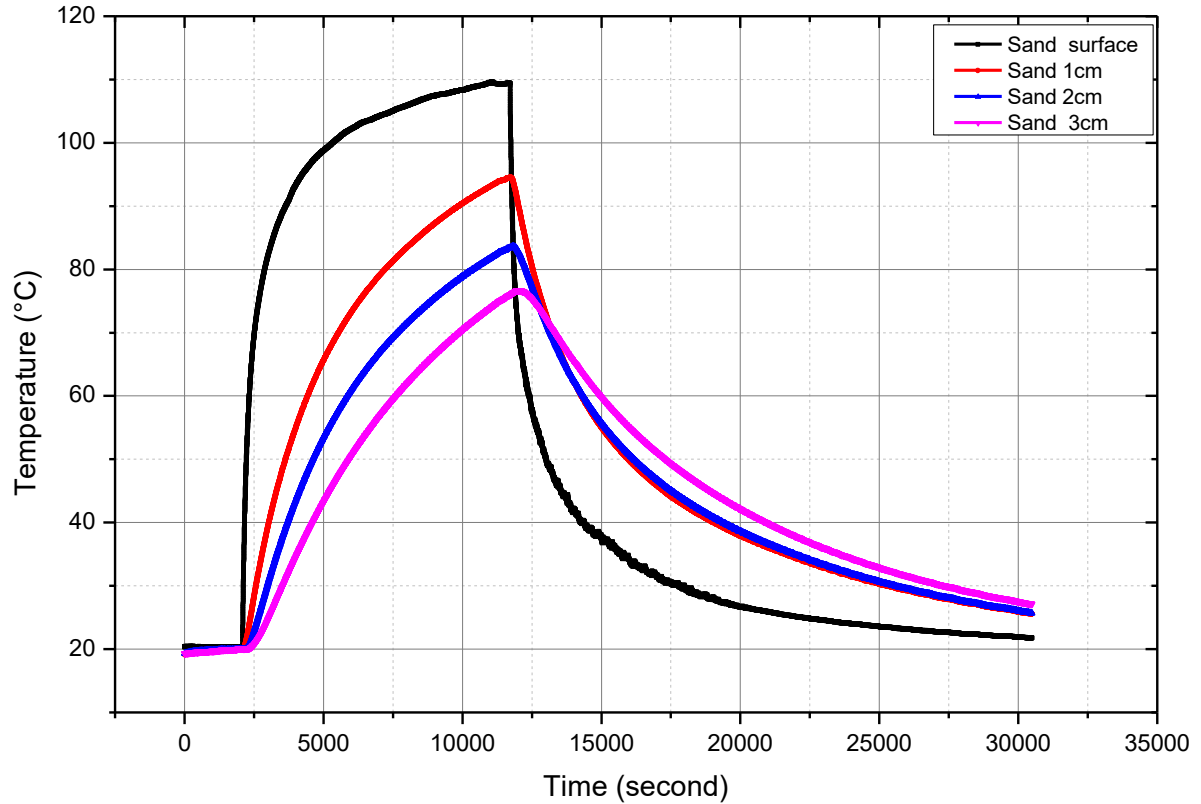


Figure 3-1: Temperature variation in sandy soil at depths of surface, 1, 2, and 3 cm (measurements taken every second).

This graph illustrates the temperature evolution in sandy soil at different depths (surface, 1, 2, and 3 cm). Measurements were recorded every second, which allows a clear step-by-step observation of the thermal changes over time. It can be seen that the surface layer surface responds immediately to temperature variations, while the 1 cm layer reacts quickly but with a slight delay. In contrast, the deeper layers at 2 and 3 cm show slower and more gradual changes, highlighting the progressive heat transfer from the surface toward the deeper soil layers.

3.1.2 Limestone soil

Limestone soil has thermal properties that influence how heat is transferred within it. In this section, variation curves are used to analyze its thermal behavior as a function of time and depth, helping to understand heat propagation and assess its suitability for applications such as the EAHE.

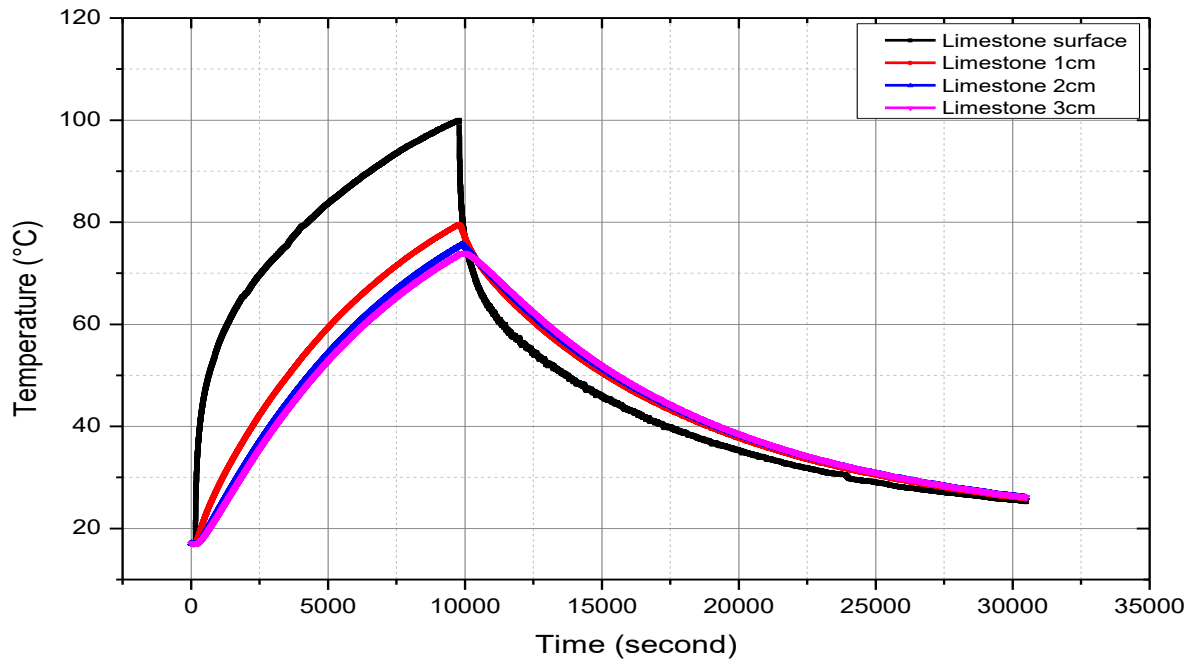


Figure 3-2: Temperature variation in limestone soil at depths of surface, 1, 2, and 3 cm (measurements recorded every second).

This figure shows how the temperature changes in the limestone soil at depths of 1, 2, and 3 cm. The measurements were taken every second which allows us to clearly observe the small variations over time. The temperature is higher at 1 cm since it is closer to the heat source while it decreases gradually with depth. The deeper layers respond more slowly showing how heat progressively moves through the limestone soil.

3.1.3 URAER soil

The soil from URAER is an important reference for experimental studies, as it represents real local soil conditions. In this section, variation curves are presented to analyze its thermal behavior as a function of time and depth. These curves help to understand how heat propagates through the soil and allow the evaluation of its performance in applications such as the EAHE, contributing to improved energy efficiency.

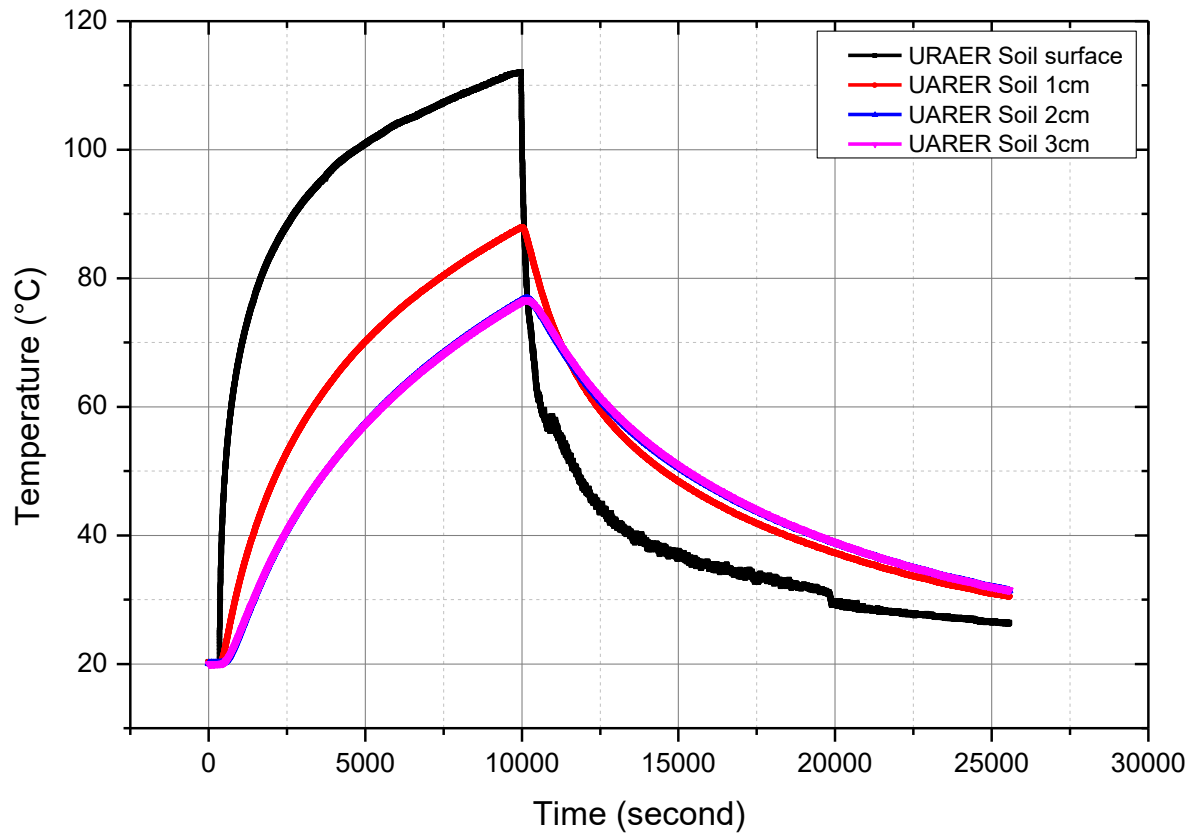


Figure 3-3: Temperature variation in soil URAER at depths of surface, 1, 2, and 3 cm (measurements recorded every second).

3.2 Calculating properties of soils (sandy, limestone and URAER soil)

3.2.1 Calculating the density

The apparent mass density of the three studied materials (sand, limestone and URAER soil) was determined using a plate balance, allowing direct acquisition of the mass and determination of the volume of each sample.



Figure 3-4: Photographs of the sand, limestone and URAER soil samples during their weighing before analysis.

The density value was then calculated according to equation (1-2). The results obtained are recorded in the following table.

Table 3-1: Physical characteristics of soil samples.

Type de sol	m (kg)	V (cm ³)	ρ (Kg/m ³)
Sand	2.152	1400	1537
Limestone	1.574	748	2104
URAER Soil	2.302	1400	1644

3.2.2 Estimation of the thermal diffusion coefficient

The thermal diffusivity was determined by graphical analysis of the transient heating and cooling regimes. As illustrated in Figure 3-5, the thermal propagation delay was quantified by measuring the time lag between the activation (or extinction) of the source and the onset of temperature change at a given depth. This difference, measured between the surface stress and the depth response, was then introduced in equation (1-4) to calculate the diffusivity of the material.

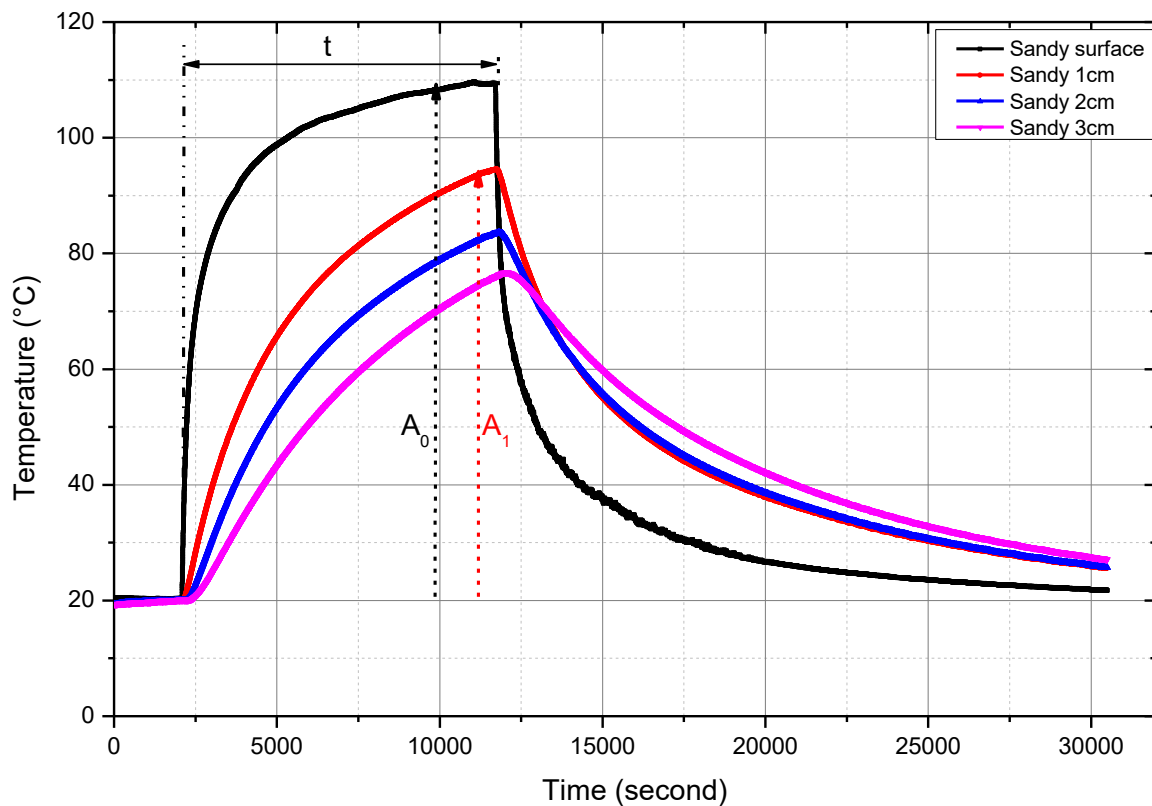


Figure 3-5: Transient thermal profiles of sandy soil (surface–3 cm) illustrating the determination of thermal diffusivity by propagation delay analysis

As an example of a numerical application, the calculation of the thermal diffusivity was carried out for the sand by applying equation (1-4), The time parameters (t) as well as the thermal amplitudes (A_0 and A_1) are determined by graphical analysis of the experimental measurements.

Table 3-2: Thermal parameters measured of the soils studied between (Surface-1 cm).

Soil type	ρ (kg/m ³)	α (m ² /s) Befor
Sand	1537	7.81×10^{-7}
Limestone	2104	1.47×10^{-6}
URAER	1644	6.41×10^{-7}

3.3 Comparative thermal analysis

In this section the thermal profiles of both sand and limestone soils are presented and analyzed in order to compare their behavior under the same experimental conditions. This comparison helps to highlight the ability of each soil type to conduct and store heat by observing the variation of temperature with depth and/or time. Such analysis is essential for understanding the influence of soil nature on thermal performance particularly in applications related to thermal engineering and renewable energy systems.

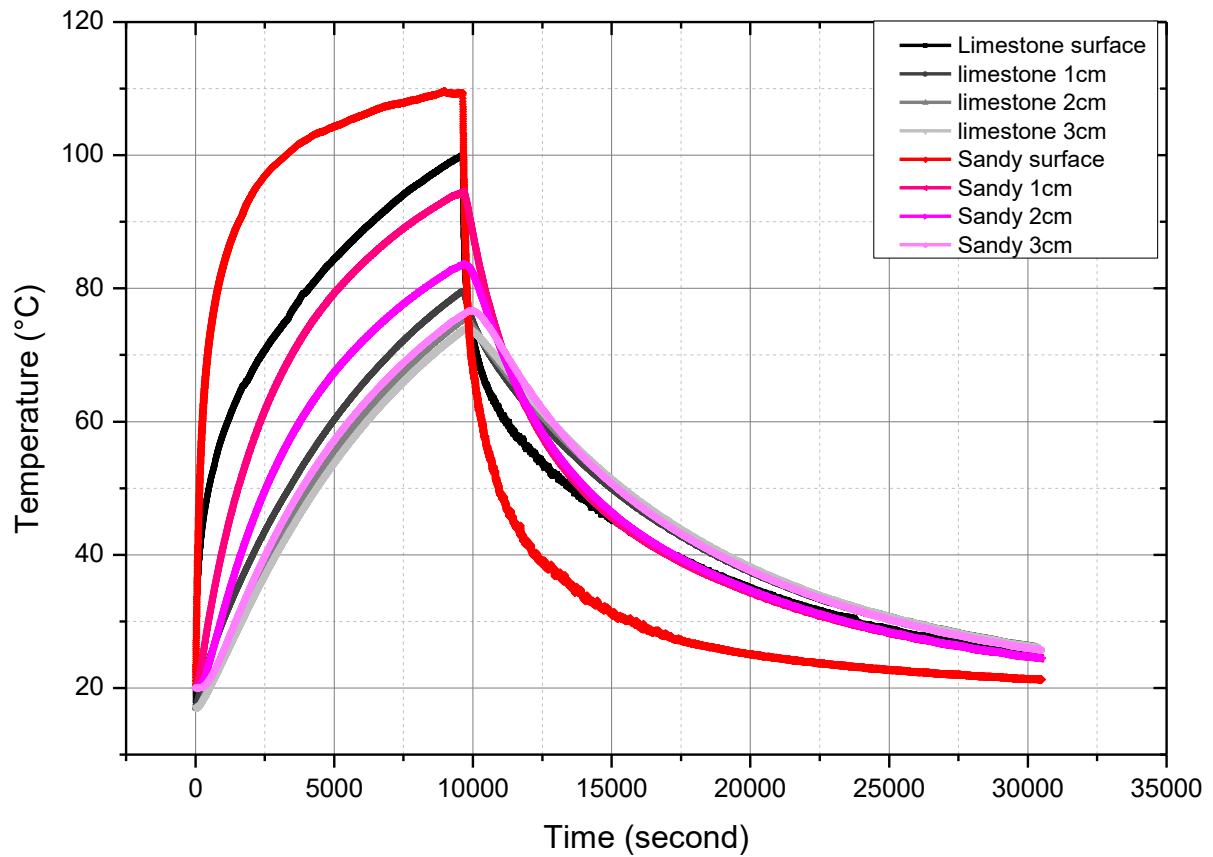


Figure 3-6: Comparison of temperature variation between sandy soil and limestone soil at different depths (surface, 1, 2, and 3 cm).

The curves reveal a marked divergence between the two materials during the heating phase. Sandy soil shows a much faster temperature rise and reaches higher peak values at each depth exceeding 109 °C on the surface against ~100 °C for limestone. This more pronounced gradient between the surface and deep layers indicates a more localized thermal propagation and less vertical heat diffusion.

As soon as the source is cut off (~10.000 s), the behavior of the two materials reverses: the sand cools abruptly, with a marked exponential decay, while limestone shows a more gradual temperature drop and maintains higher thermal levels over time. The limestone curves, more grouped and spread over time, reflect better conduction to the depths and a graduated energy restitution.

These thermal transients directly reflect the intrinsic properties of the materials. The volatile response of sand (rapid heating, accelerated dissipation) is characterized by a low volume thermal capacity and reduced conductivity, favoring heat accumulation on the surface but limiting storage in depth. Conversely, limestone, which is denser and better conductive, diffuses heat more uniformly, attenuates temperature peaks and releases energy over a long period. This

higher inertia and smoothing of fluctuations gives limestone a clear thermodynamic advantage for geothermal applications requiring a temperature-stabilized source.

In addition, the natural soil from the URAER of Ghardaïa shows an intermediate behavior between sand and limestone soils this supports the reliability of the results and provides a more realistic representation of actual earth conditions.

3.4 Calculation of damping depth

The thermal damping depth refers to the characteristic depth at which the amplitude of periodic surface temperature changes is attenuated by a factor of $1/e$ ($\approx 37\%$). This parameter is fundamental for the sizing of EAHE, as it defines the area of the subsoil where seasonal climate fluctuations become negligible, thus ensuring an almost constant thermal source. Its evaluation is based on the thermal diffusivity of the medium (α) and the angular pulsation associated with the cycle in question (ω), according to the following relationships:

$$d = \sqrt{\frac{2 \cdot \alpha}{w}} \quad (3-1)$$

With : $w = \frac{2\pi}{T}$ and T represents the period of the annual cycle, fixed at 365 days.

Table 3-3: Thermal parameters characteristic of the soils studied: thermal diffusivity (α), damping depth (d), inverse of the depth ($1/d$) and exponential attenuation coefficient ($\exp(-1/d)$).

Type soil	α (m ² /s) After	d (m)	1/d	$\exp(-1/d)$
Sand	5.95×10^{-7}	2.43	0.41	0.66
limestone	1.19×10^{-6}	3.45	0.29	0.74
URAER soil	6.92×10^{-7}	2.63	0.38	0.68

After means the diffusivity calculated at the end of the curve, i.e., when the temperature starts to decrease after the lamp is turned off (cooling phase).

According to equation (1-1), the temperature variation in the subsurface at shallow depth is expressed as follows:

Table 3-4: Analytical equations of temperature attenuation with depth in different soil types.

Soil type	Equation
Sand	$T(z, t) = T_{mean} + A * e^{-\frac{z}{2.43}} * \sin(\omega * (t - t_0) - \frac{z}{2.43})$
Limestone	$T(z, t) = T_{mean} + A * e^{-\frac{z}{3.45}} * \sin(\omega * (t - t_0) - \frac{z}{3.45})$
URAER soil	$T(z, t) = T_{mean} + A * e^{-\frac{z}{2.63}} * \sin(\omega * (t - t_0) - \frac{z}{2.63})$

These formulations make it possible to estimate the thermal attenuation with depth and constitute the basis for the sizing of air-earth exchange.

At a depth of 1 cm, the amplitude of the thermal signal has a damping coefficient of 0.66 for sand, 0.74 for limestone and 0.68 for URAER soil. These values, obtained by the ratio between the thermal amplitude at 1 cm and that measured on the surface; indicate that limestone attenuates less the superficial thermal variations, followed by URAER soil, then sand.

3.5 Influence of Soil Thermal Properties on Heating and Cooling Needs

The thermophysical properties of the studied soils have a significant influence on the performance of air-soil exchange systems and, consequently, on the heating and cooling needs of buildings. The experimental results showed that limestone, characterized by a high thermal diffusivity ($\alpha = 1.19 \times 10^{-6} \text{ m}^2/\text{s}$) and a large damping depth ($d = 3.45 \text{ m}$), offers better thermal stability at depth compared to sandy soil ($\alpha = 5.95 \times 10^{-7} \text{ m}^2/\text{s}$; $d = 2.43 \text{ m}$) and the URAER floor ($\alpha = 6.92 \times 10^{-7} \text{ m}^2/\text{s}$; $d = 2.63$). This superior capacity of limestone to conduct and store heat results in a higher attenuation coefficient ($\exp(-1/d) = 0.74$), ensuring more stable temperatures throughout the annual cycle. In winter, this thermal inertia allows to maintain temperatures deeper than those of the ambient air, thus reducing heating requirements thanks to an efficient preheating of the insufflated air. Conversely, in summer, limestone provides greater damping for surface temperature peaks, maintaining a fresh and stable exchange zone that optimizes passive cooling. Conversely, sandy soil, with its volatile thermal response (rapid heating, accelerated cooling) and lower damping (0.66), requires deeper sizing of the exchangers to achieve comparable stability, thus increasing installation costs. These results confirm that the selection of a predominantly limestone site, or failing that, a soil with intermediate thermal properties such as the URAER soil, is an essential feasibility criterion to maximize the energy

efficiency of shallow geothermal systems and minimize heating and cooling consumption over the entire annual cycle.

3.6 Estimation of Energy Savings and Economic Impact

Data on natural gas and electricity consumption were extracted from SONALGAZ invoices for an individual dwelling located in the URAER city, occupied by a two-person household. The analysis campaign, conducted in the 2025 fiscal year, covers the entire annual cycle divided into four seasonal quarters (Q1 to Q4), making it possible to characterize the evolution of residential energy demand according to climate variations and domestic uses.

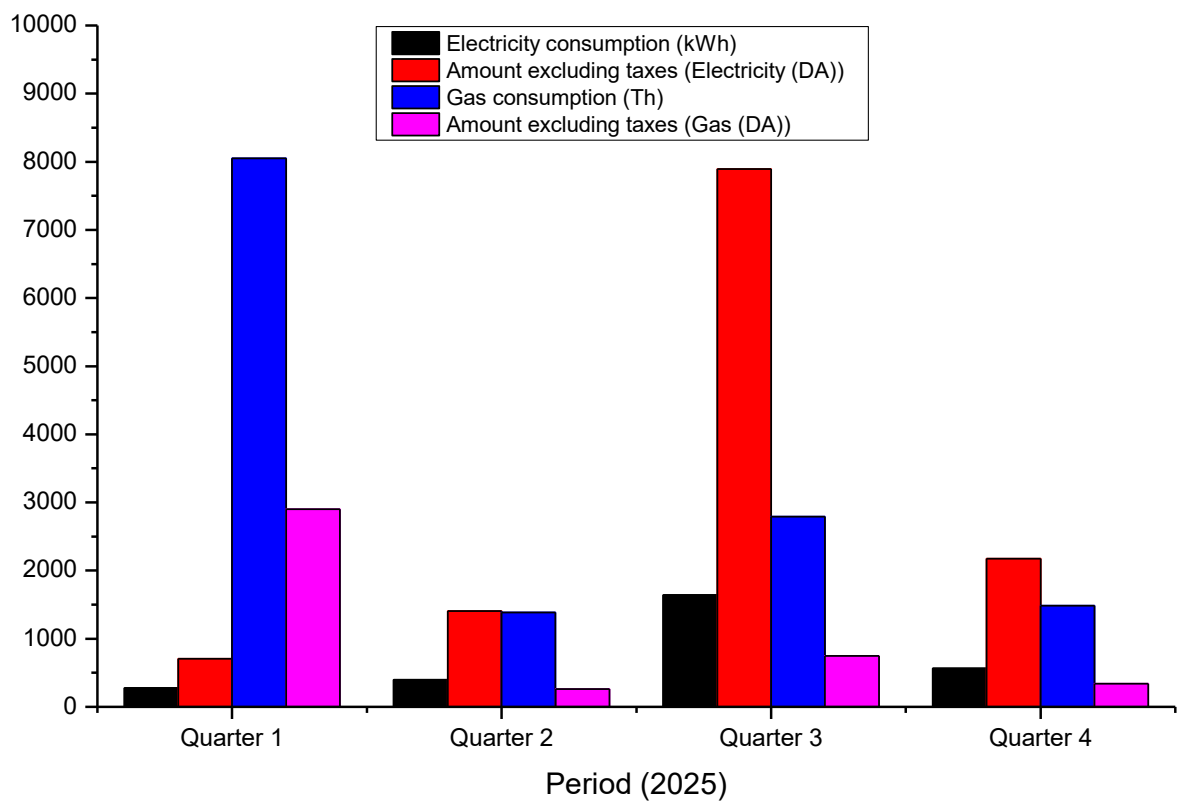


Figure 3-7: Changes in energy consumption and associated costs during the year 2025[4].

The graphical analysis of consumption reveals a peak in electricity demand in the third quarter (summer), directly correlated with the intensive use of the air conditioner (1 740 W, or 18 000 BTU/h). To optimize this energy balance, a partial replacement by an air-earth exchanger of the Canadian well type is envisaged. Exploiting the thermal inertia of the subsoil, this geothermal device ensures not only summer cooling, but also preheating new air during the heating period (winter). Its operation, which requires only a 21 Watt fan, allows to cover a significant part of

the seasonal thermal needs while drastically reducing the overall electrical load compared to the conventional system.

The costs of installing the system EAHE are detailed in table 3-5 and the energy consumption of the fan used in the EAHE system is based on the indicators provided in table 3-6.

Table 3-5: Breakdown of costs for installing the EAHE system

Component	Cost (DA)
Excavation (hollowing)	52 500.00
Backfilling (refilling)	7 000.00
Pipes	42 480.00
Fan (ventilator)	950.00
Total cost	102 930.00

Table 3-5 presents a breakdown of the total installation cost of the EAHE system, including excavation and backfilling works, pipe procurement, and the fan (ventilator). The total cost amounts to approximately 102930.00DA. This initial investment is comparable to conventional air-conditioning systems; however, the EAHE system has the advantage of requiring only a single low-energy fan for operation, which significantly reduces long-term operating costs.

Table 3-6: Energy consumption of the fan (EAHE system)

Parameter	Symbol	Value	Unit
Power	P	0.021	kW
Quarterly consumption	E _{Quarter}	45.36	kWh
Electricity cost		1.77	DA/kWh
Total cost		80.29	DA

The results clearly show that the energy consumption of the conventional air conditioning system is significantly higher than that of the fan used in the EAHE system. This difference highlights the potential of earth-based systems to reduce energy consumption and improve overall energy efficiency, especially in hot climates.

Conclusion

This chapter was devoted to the exhaustive exposition and critical analysis of the experimental results obtained. The study focused on the characterization of the thermal behavior of local soils, particularly sand and limestone formations, as well as on the evaluation of in situ performance at the site of the Applied Research Unit in Renewable Energies (URAER) of Ghardaïa.

This experimental study made it possible to characterize the thermophysical properties of the Ghardaïa soils, revealing a thermal diffusivity of limestone higher than that of dry sand. The temperature profiles show that limestone promotes a deep and gradual diffusion of heat, while the sand generates an insulating surface accumulation. These results confirm that a limestone environment optimizes the efficiency of the air-earth exchanger at a depth of 2.3 m. Conversely, a sand substrate limits the performance of the EAHE by slowing heat transfer. In short, the lithological nature of the implantation site appears as a determining parameter for the energy sizing of the system.

General Conclusion



General Conclusion

This study, conducted at the URAER research Unit in Ghardaïa, highlights the strategic importance of soil characterization in improving the performance of EAHE, particularly in arid and semi-arid climates where reducing energy consumption for cooling and heating is a major concern.

The comparative experimental analysis of the two dominant geological formations in the region, sandy soil and limestone, reveals significant differences in their thermophysical behavior. The results show that limestone exhibits superior thermal properties compared to dry sand, especially in terms of thermal diffusivity. This allows heat to propagate more deeply and more uniformly through the ground, ensuring a more stable thermal response over time.

In contrast, sandy soil, due to its lower thermal and diffusivity, tends to act as a thermal barrier. It promotes heat accumulation near the surface and limits its transfer to deeper layers, which ultimately reduces the efficiency of the EAHE system.

The study also confirms that a limestone medium at a depth of approximately 2.3 meters provides the most favorable conditions for efficient and heat transfer, significantly improving the overall performance of the system. In contrast, sandy soil reduces the effectiveness of heat transfer, leading to lower overall energy efficiency.

In this context, the use of EAHE systems represents an effective solution for reducing electricity consumption for heating and cooling in Ghardaïa, by taking advantage of the natural thermal stability of the ground instead of relying heavily on conventional energy-intensive systems.

In conclusion, the lithological nature of the site is not a secondary factor but a key design parameter in underground heat exchange systems. Proper soil selection and characterization directly influence energy efficiency, system performance, and long-term economic viability, making this approach a promising pathway toward more sustainable and energy-efficient climate control solutions.

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انا الاستاذ(ة):
بصفتي المشرف المسؤول عن تصحيح مذكرة تخرج (ليسانس/ ماستر/ دكتورا) المعنونة ب:

Shallow geothermal energy as a strategy to reduce
electricity consumption for cooling and heating in Ghardaïa
من انجاز الطالب (الطالبة):

Oubal MIR Kacubher

Oubal Hadj-gencef chaïma

التي نوقشت بتاريخ: 2026/06/13

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امضاء المسؤول عن التصحيح