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Practical Design of Earth-Air Heat Exchanger

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" وَقُل رَّبِّ زدني عِلْمًا "

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Dedication

In the name of Allah, the most gracious, the most merciful

With deep gratitude and endless love, I dedicate this achievement to my beloved father, HEBIA Mounir, whose strength, sacrifices, and unwavering support have always been my guiding light

To my dear mother, BILLITA Naziha, whose prayers tenderness, and unconditional love have been the source of my courage

To my wonderful family, My Brothers Abdo, Mossab and Moussa. My sisters Intissar and Hanin. And officially to my brother's wife Salma and all my family members, thank you for your constant encouragement and believe in me throughout every step of this journey.

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I would also like to express my sincere appreciate to my friend CHOUIREB Hanane who share with me every step in our project, Big thanks to all my friends . k<3

To my kind neighbors whose positivity and support have always meant to me.

HEBIA yasmine

Dedication

I would like to dedicate this modest work:

To my dear parents BOUTASSOUNA Naouia & CHOUIREB Horma their support, understanding and great tenderness.

To My sisters Nassima, Nour Djihane, Fatima.

Those who supported me throughout my life and years of study

To My companion ZIANE Abbas, I dedicate this thank you for your continuous support and encouragement, which was my greatest motivation

To the one who shared the hardships of the journey with me HEBIA Yasmine, thank you for your constant support and presence

And thanks to all My friends who supported me

Moreover to all detainees of opinion all around the world

CHOUIREB Hanane

Abstract:

Earth-air heat exchangers (EAHE) are a passive geothermal technology that utilizes the relatively stable subsurface soil temperature to precondition ventilation air for buildings, thereby reducing conventional heating and cooling loads. This study develops a mathematical model for a horizontal EAHE system that explicitly accounts for heat transfer in both insulated and non-insulated descending pipe sections, providing a more realistic representation of practical installation conditions. The model predicts soil temperature distribution, outlet air temperature, and overall thermal efficiency as functions of key design and operating parameters. Experimental validation was conducted using field data from the URAER research facility in Ghardaïa, Algeria. The numerical results show excellent agreement with measurements, with relative errors ranging from 0.48% to 4.28% along the pipe length, all below the 5% threshold. Soil temperature analysis reveals a marked attenuation with depth: surface fluctuations of approximately 13.75 °C are reduced to less than 2 °C at 4 m depth, with a phase lag of up to 2–3 months. Parametric analysis indicates that increasing pipe length from 10 m to 50 m improves thermal efficiency from 35% to over 80%, while higher air velocities (from 1 m/s to 5 m/s) reduce outlet temperature differences by up to 60%. The vertical–horizontal EAHE configuration achieves outlet air temperatures 2–3 °C lower than the horizontal configuration under identical conditions. These findings confirm that EAHE systems can significantly reduce building energy consumption while enhancing indoor thermal comfort in arid climate regions.

Keywords: Earth-air heat exchanger, geothermal energy, heat transfer modeling, thermal performance, passive cooling and heating, experimental validation

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الملخص:

تُعد المبادلات الحرارية الأرضية–الهوائية (EAHE) من التقنيات الجيوحرارية السلبية التي تستغل الاستقرار النسبي لدرجة حرارة التربة تحت السطح لتهيئة هواء التهوية قبل دخوله إلى المباني، مما يساهم في تقليل أحمال التدفئة والتبريد التقليدية. تهدف هذه الدراسة إلى تطوير نموذج رياضي لمبادل حراري ارضي–هوائي أفقي يأخذ بعين الاعتبار انتقال الحرارة في الأجزاء الهابطة المعزولة وغير المعزولة من الأنابيب، مما يوفر تمثيلاً أكثر واقعية لظروف التركيب الفعلية. ويُمكّن هذا النموذج من التنبؤ بتوزيع درجة حرارة التربة، ودرجة حرارة الهواء عند المخرج، والكفاءة الحرارية الكلية للنظام تبعاً لمختلف المعلمات التصميمية وظروف التشغيل.

تم التحقق من صحة النموذج باستخدام بيانات تجريبية تم الحصول عليها من منشأة البحث التابعة لوحدة البحث في الطاقات المتجددة بالوسط الصحراوي (URAER) مدينة غرداية، الجزائر. وأظهرت النتائج العددية توافقاً ممتازاً مع القياسات التجريبية، حيث تراوحت الأخطاء النسبية بين 0.48٪ و4.28٪ على طول الأنبوب، وهي قيم أقل من الحد المقبول البالغ 5٪.

كما أظهرت دراسة درجة حرارة التربة انخفاضاً ملحوظاً في سعة التذبذب الحراري مع زيادة العمق، حيث انخفضت من حوالي 13.75 درجة مئوية عند السطح إلى أقل من درجتين مئويتين على عمق 4 أمتار، مع تأخر زمني في الاستجابة الحرارية يصل إلى شهرين أو ثلاثة أشهر. وبينت الدراسة البارامترية أن زيادة طول الأنبوب من 10 أمتار إلى 50 متراً تؤدي إلى رفع الكفاءة الحرارية من 35٪ إلى أكثر من 80٪، في حين أن زيادة سرعة الهواء من 1 م/ثا إلى 5 م/ثا تقلل من فرق درجة حرارة الهواء عند المخرج بنسبة تصل إلى 60٪.

كما حقق التكوين العمودي–الأفقي للمبادل الحراري درجات حرارة خروج أقل بمقدار 2 إلى 3 درجات مئوية مقارنة بالتكوين الأفقي التقليدي تحت نفس ظروف التشغيل. وتؤكد هذه النتائج أن المبادلات الحرارية الأرضية–الهوائية قادرة على المساهمة بفعالية في خفض استهلاك الطاقة بالمباني وتحسين الراحة الحرارية الداخلية، خاصة في المناطق ذات المناخ الجاف.

الكلمات المفتاحية: المبادل الحراري الأرضي–الهوائي، الطاقة الجيوحرارية، نمذجة انتقال الحرارة، الأداء الحراري، التبريد والتدفئة السلبية، التحقق التجريبي.

# *Résumé :*

Les échangeurs de chaleur sol-air (EAHE) sont une technologie géothermique passive qui utilise la température relativement stable du sous-sol pour reconditionner l'air de ventilation des bâtiments, réduisant ainsi les charges conventionnelles de chauffage et de refroidissement. Cette étude développe un modèle mathématique pour un système EAHE horizontal qui prend explicitement en compte le transfert de chaleur dans les sections descendantes de tuyaux isolées et non isolées, fournissant une représentation plus réaliste des conditions pratiques d'installation. Le modèle prédit la distribution de la température du sol, la température de l'air à la sortie et l'efficacité thermique globale en fonction des principaux paramètres de conception et de fonctionnement. La validation expérimentale a été réalisée à l'aide de données de terrain provenant du centre de recherche URAER à Ghardaïa, en Algérie. Les résultats numériques montrent un excellent accord avec les mesures, avec des erreurs relatives allant de 0,48 % à 4,28 % sur la longueur du tuyau, toutes inférieures au seuil de 5 %. L'analyse de la température du sol révèle une atténuation marquée avec la profondeur : les fluctuations de surface d'environ 13,75 °C sont réduites à moins de 2 °C à 4 m de profondeur, avec un retard de phase allant jusqu'à 2–3 mois. L'analyse paramétrique indique que l'augmentation de la longueur du tuyau de 10 m à 50 m améliore le rendement thermique de 35 % à plus de 80 %, tandis que des vitesses d'air plus élevées (de 1 m/s à 5 m/s) réduisent les différences de température de sortie jusqu'à 60 %. La configuration verticale horizontale EAHE permet d'obtenir des températures d'air de sortie inférieures de 2–3 °C à celles de la configuration horizontale dans des conditions identiques. Ces résultats confirment que les systèmes EAHE peuvent réduire considérablement la consommation d'énergie des bâtiments tout en améliorant le confort thermique intérieur dans les régions au climat aride.

Mots-clés : échangeur de chaleur terre-air, énergie géothermique, modélisation du transfert de chaleur, performance thermique, refroidissement et chauffage passifs, validation expérimentale.

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Abbreviation

Symbol	Meaning	Unit
A	Temperature amplitude	$°C$
c_a	Air heat capacity	$J.kg^{-1}.K^{-1}$
c_s	Soil heat capacity	$J.kg^{-1}.K^{-1}$
CDER	Centre de Développement des Énergies Renouvelables	-
EAHE	Earth Air Heat Exchanger	-
f	Friction factor	-
H	Heat exchange factor	m^{-1}
h_a	Air convective heat transfer coefficient	$W.m^{-2}.K^{-1}$
k_a	Air thermal conductivity	$W.m^{-1}.K^{-1}$
k_p	Pipe thermal conductivity	$W.m^{-1}.K^{-1}$
k_s	Soil thermal conductivity	$W.m^{-1}.K^{-1}$
L	Pipe length	*m*
$\dot{m}$	Air mass flow rate	*kg*
Nu	Nusselt Number	-
P	Period	*s*
Pr	Prandtl Number	-
Q	Heat transfer rate	*W*
R_{air}	Air thermal resistance	$K.w^{-1}$
R_{pipe}	Pipe thermal resistance	$K.w^{-1}$
R_{soil}	Soil thermal resistance	$K.w^{-1}$
Re	Reynolds number	-
r_{es}	Effective soil radius	*m*
r_i	Inner pipe radius	*m*
r_o	Outer pipe radius	*m*
T	Time	*s*

T_a	Air temperature	$°C$
T_{ai}	Inlet air temperature	$°C$
T_{ao}	Outlet air temperature	$°C$
T_m	Annual average temperature Soil or air	$°C$
T_S	Soil temperature	°C
T_{max}	Maximum soil surface temperature	°C
T_{min}	Minimum soil surface temperature	°C
U	Global heat transfer coefficient	$W.m^{-2}.K^{-1}$
URAER	Unité de Recherche Appliquée en Énergies Renouvelables	-
$\overline{V}$	Mean air velocity	$m.s^{-1}$
Z	Soil depth	m
μ_a	Air dynamic Viscosity	Pa.s
E	Thermal efficiency	%
$\boldsymbol{\delta}$	Thermal penetration depth	m
$\boldsymbol{\omega}$	Angular frequency	s^{-1}
ρ_a	Air density	$kg.m^{-3}$
ρ_s	Soil density	$kg.m^{-3}$
HVAC	Heating ventilation and air conditioning	-
α_s	Soil diffusivity	$m^2.s^{-1}$

General introduction

Renewable energy systems are mainly designed to supply facilities with clean energy, which may include equipments like wind turbines, biomass, thermal and electrical solar systems, thereby reducing reliance on non renewable energy resources and enhancing sustainability [1, 2]. Geothermal energy is defined as heat generated within the Earth's crust that can be harnessed for electricity generation or direct heating applications. It is a reliable and consistent renewable energy source, though its availability is limited to specific locations with suitable geological conditions [3,4]. Earth source heat pumps are defined as a system that utilizes the ground as a heat source or sink to provide space heating, cooling, and domestic hot water, offering higher energy efficiency compared to conventional air conditioning systems due to less temperature fluctuation in the underground environment [4-6]. An earth-air heat exchanger EAHE, also known as a ground heat exchanger GHE, is a key component of ground source heat pump GSHP systems, enabling heat exchange between the ground and the circulating fluid or air. Its performance plays a major role in determining the system's energy efficiency and environmental sustainability [5, 6]. The effectiveness of an EAHE/GHE is strongly influenced by the ground's thermal characteristics, particularly thermal conductivity, density, heat capacity, and the initial soil temperature [7, 8]. Earth-air heat exchangers, also known as ground tube heat exchangers, offer a promising technique to reduce energy consumption in buildings by cooling down or heating up the ventilated air, using the temperature difference of the ambiance and the soil at certain shallow depth soil. There exist several papers that treat this kind of specific heat exchangers [9-11].Numerous numerical and experimental investigations have been carried out to explore methods for enhancing the thermal performance of these sustainable heating and cooling systems [11-14].

However, most of the investigations that deal with earth-air heat exchanger ignore the thermal contribution of the vertical descending pipe section, a characteristic that could lead to incorrect results, especially when using experimental comparison.

The present dissertation will be devoted to the mathematical modeling of a of horizontal earth-air heat exchanger where the heat transfer between the air and soil in the descending pipe section is taken into consideration. The dissertation is organized into three chapters.

Chapter 1 is centered on general concepts and definitions related to the earth–air heat exchanger. It begins with an overview of geothermal energy, followed by a description of earth–air heat exchanger systems, their components, and their working principles. Then, the different types and classifications of these systems are presented.

Chapter 2 constitutes the core of the dissertation. In this chapter, we establish a mathematical model for a horizontal earth–air heat exchanger for two cases : one with insulated descending and ascending pipe sections, and another with a non-insulated descending pipe section, which represents a more realistic and practical situation. The mathematical model aims to evaluate the thermal performance parameters, such as the overall heat transfer coefficient, the outlet air Temperature and the thermal efficiency.

Chapter 3 is devoted to the results and discussion. We begin with a detailed description of the experimental site at URAER in Ghardaïa, where the practical experiments were conducted. Then, comparative results are presented to validate the mathematical model. Finally, different results concerning the thermal performance are provided, which help improve the thermal sizing of earth–air heat exchanger systems.

Chapter 1

Earth-air heat exchangers concepts and definitions

Introduction

The present chapter focuses on the concepts and definitions related to the earth-air heat exchanger EAHE. It begins with an overview of the ground as a thermal resource, highlighting its thermal storage capacity and its role in regulating air temperature through underground heat exchange. The chapter one presents the working principle of the EAHE system, explaining the mechanisms of heat transfer between the soil and the circulating air. Afterward, the different classifications of EAHE systems are discussed according to their configuration, operating mode, and installation characteristics. Finally, the chapter examines the main parameters affecting the thermal efficiency of EAHE systems, including soil properties, pipe material and geometry, burial depth, air flow rate, and climatic conditions.

1-1 Ground as a thermal resource for earth air heat exchanger:

Geothermal energy is a renewable resource that is readily accessible for providing low-grade thermal energy with minimal environmental impact. It is abundant and particularly suitable for space heating and cooling applications [1]. The earth temperature generally increases with depth due to the geothermal gradient, which represents the rate of temperature rise within the Earth's interior, see **figure 1-1**.

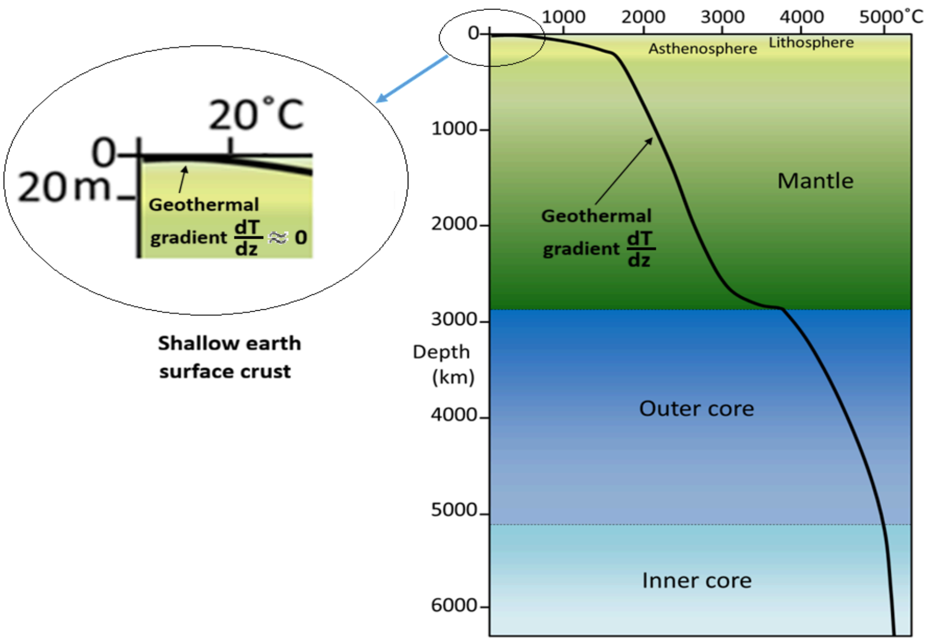

Figure 1-1: Variation of temperature in shallow surface and inner earth with respect to depth [20].

One key property of the Earth is that, beyond a certain depth below the crust surface when the geothermal gradient is extremely small, the ground temperature mains nearly constant throughout the year. This underground temperature is typically lower than the surface temperature during summer and higher during winter.

In this shallow earth surface crust, different types of earth-air heat exchangers systems can find industrial and residential applications by exchanging heat with the surrounding soil via convection and conduction heat processes. As a result, the air is either cooled or warmed before entering the building, depending on the season.

1-2 Earth-air heat exchanger, working principle and components:

An earth-air heat exchange EAHE system, also known as an earth tube or ground-coupled air system operates on the basic principle of heat transfer between ambient air and the relatively stable temperature of the subsurface soil [17]. It has three main components: Pipe, fan and air filter, as is it shown in the **figure 1-2**.

Figure 1-2: Main components of earth-air heat exchanger.

At a certain depth (typically 2–4 meters), the ground maintains a nearly constant temperature throughout the year, close to the annual average surface temperature of that region [8-11].In an EAHE system, a network of buried pipes (usually made of PVC, HDPE, or similar materials) [8, 9, 11, 13] is installed underground, and outside air is drawn through these pipes using a fan. As the air travels through the tubes, it exchanges heat with the surrounding soil via conduction through the pipe walls and convection within the air flow. During hot summer conditions, the incoming warm air loses heat to the cooler soil, resulting in a reduction in air temperature before it enters the building, thereby providing passive cooling. Conversely, in winter, cold outside air gains heat from the relatively warmer ground, thus preheating the air and reducing heating demand, see **figure 1-3**.

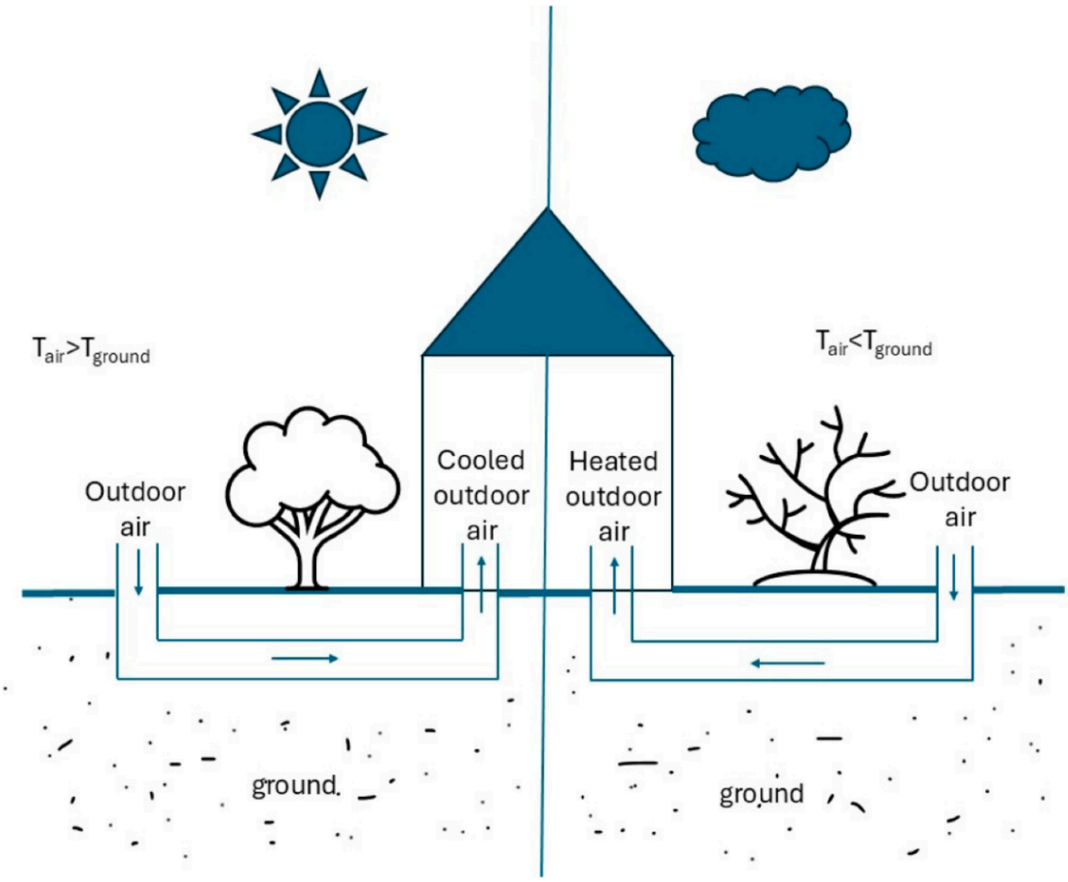

Figure 1-3: Horizontal earth-air heat exchanger for pre-heating and pre-cooling the outdoor [11].

The efficiency of this system depends on several factors, including soil thermal conductivity, pipe length and diameter, airflow velocity, burial depth, and moisture content of the soil that will be discussed later in the end of the chapter. EAHE systems are considered energy-efficient and environmentally friendly because they reduce reliance on conventional HVAC systems and utilize renewable geothermal energy for passive heating and cooling.

1-3 Earth-air heat exchanger types and classification:

Earth-air heat exchangers can be constructed in several geometric configurations depending on land availability, installation depth, and desired thermal performance. In a horizontal EAHE, pipes are buried parallel to the ground surface at shallow depths, typically between 1 and 4 meters, making this arrangement simple and economical where sufficient land area is available. A vertical EAHE uses deep boreholes with pipes installed vertically into the ground, allowing access to more stable subsurface temperatures and making it suitable for urban or space-limited sites, although drilling costs are higher. The slinky EAHE is a modified horizontal configuration in which the pipe is coiled in overlapping loops, resembling a slinky spring, to increase pipe length and heat-transfer area within a smaller trench footprint. In a trenched EAHE, straight or coiled pipes are laid inside long excavated trenches filled with soil or backfill material, offering easier construction and maintenance while maintaining effective thermal contact with the ground, **see figure 1-4.**

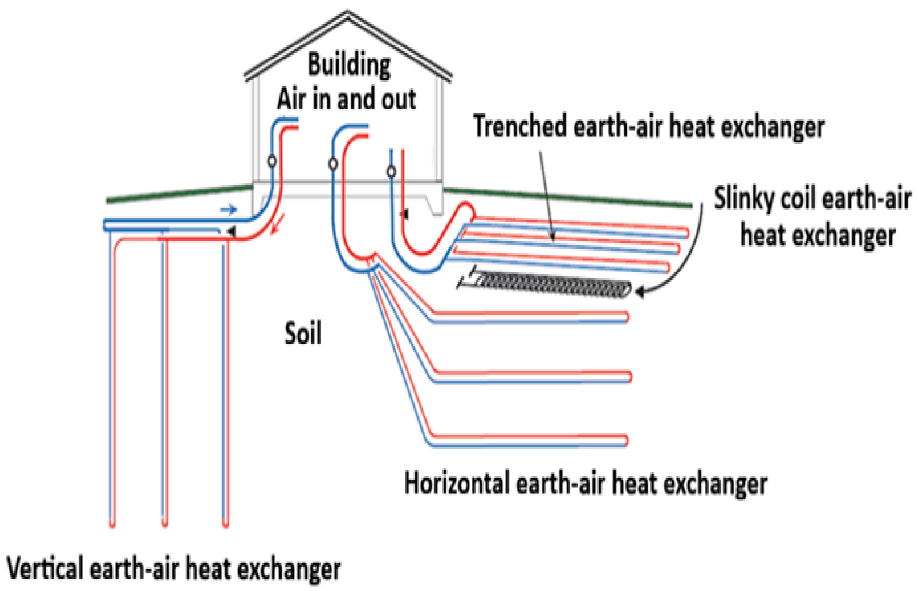

Figure 1-4: Closed loop vertical, horizontal, trenched and slinky earth-air heat exchangers [3].

A spiral EAHE arranges pipes in a spiral or helical geometry, either horizontally or vertically, to maximize heat exchange surface area and improve thermal efficiency in compact spaces. These configurations are selected based on climatic conditions, soil properties, installation cost, and available land area, see **figure 1-5**.

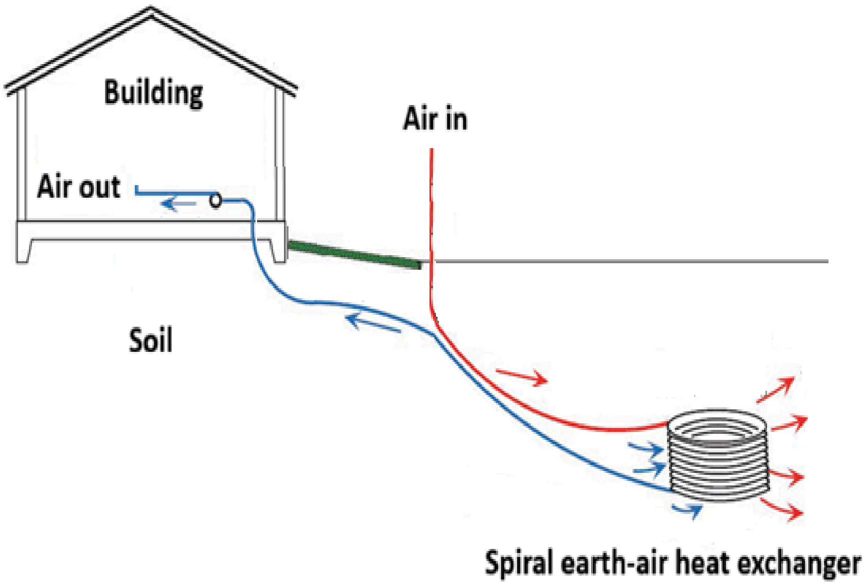

Figure 1-5: Open loop spiral earth-air heat exchanger [3].

There are several other different types of air-to-ground heat exchangers that can be found in industrial and residential settings. The types of air-to-ground heat exchangers will vary based on several parameters, including the volume of air in the cooled or heated space, the geometric and dimensional restrictions applied by the location, the soil type, and the climate zone **The figure 1-6** provides a good recompilations of these systems.

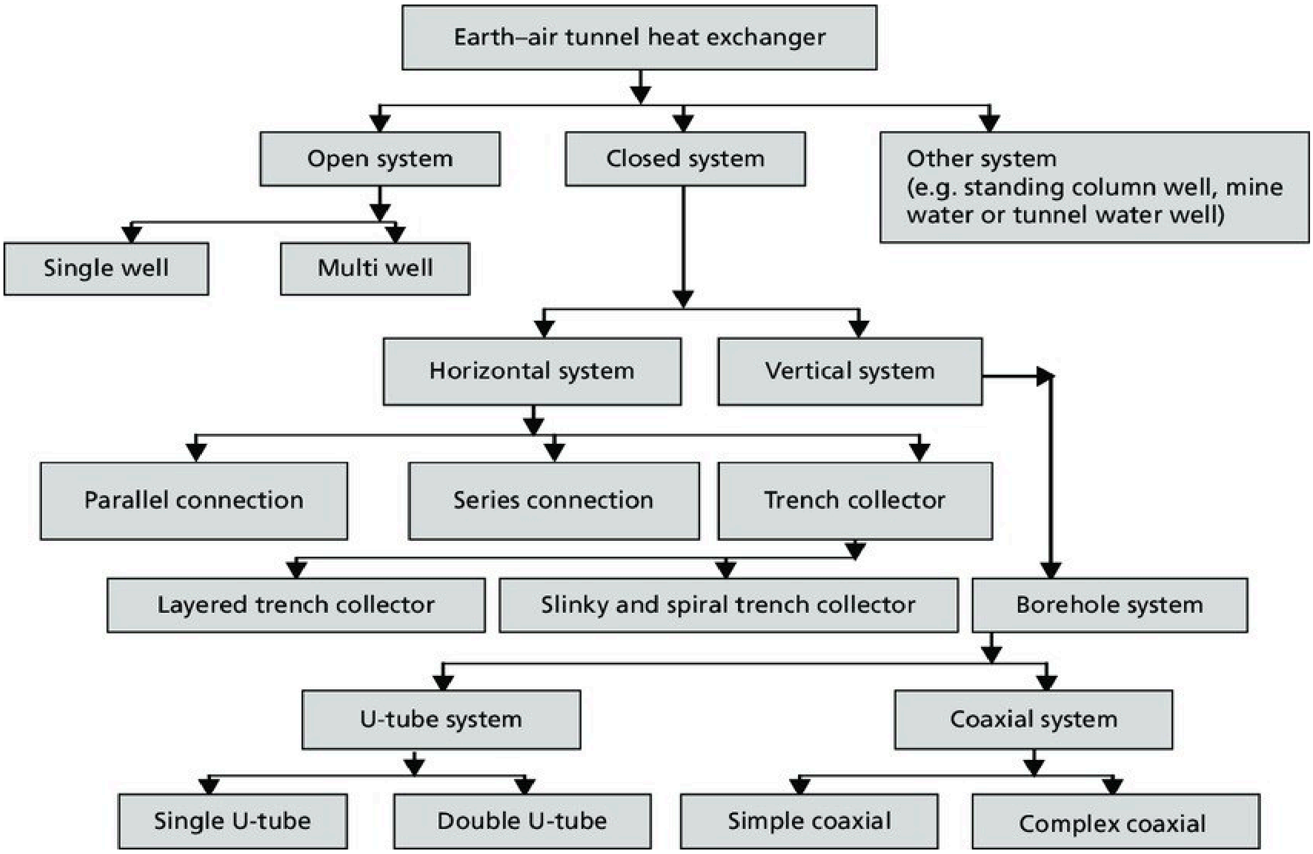

Figure 1-6: Recompilation of different type of earth-air heat exchanger systems [15].

1-4 Parameters affecting the thermal sizing of earth-air heat exchangers:

The thermal efficiency of an earth-Air heat exchanger is controlled by a combination of various design parameters design parameters, mainly, the soil properties, climatic conditions, and operating conditions [17].

1-4-1 Soil properties:

The surrounding soil acts as the thermal storage medium and plays a major role in the performance of the heat exchanger. Its thermal properties, including thermal conductivity, heat capacity, density, moisture content, directly affect heat transfer between the air and the soil. Higher thermal conductivity improves heat exchange efficiency, with wet clay soils generally providing better performance than dry sandy soils. Similarly, moist soil transfers heat more effectively than dry soil due to its enhanced thermal capacity and conductivity [9, 10]. Thermal diffusivity determines how quickly the soil temperature responds to atmospheric variations, while stable and moderate undisturbed ground temperatures contribute to more efficient and reliable exchanger operation.

1-4-2 Burial depth:

The soil temperatures near the surface vary significantly with outdoor air conditions, which reduce system efficiency. As burial depth increases, the surrounding soil temperature becomes more stable. At considerable soil depths, typically around 2-4 m, the soil temperature will be maintained nearly constant, improving cooling performance in summer and heating efficiency in winter. However, installing pipes deeper also leads to higher construction costs [14].

1-4-3 Pipe length:

The increase of pipe length extends the contact time between air and the surrounding soil that enhances the heat exchange process. A longer duct generally improves thermal performance and results in more stable outlet air temperatures. However, beyond the optimal length, the performance gains gradually diminish, while whereas the fan's energy consumption continues to increase due to higher pressure losses.

1-4-4 Pipe diameter:

Diameter influences both the airflow characteristics and the available contact surface area. A smaller diameter results in higher air velocity but shorter residence time, where as a larger diameter produces lower velocity, a greater heat exchange surface, and weaker turbulence.

Therefore, an optimal diameter range exists depending on the airflow rate and the intended application.

1-4-5 Pipe material:

The thermal conductivity of the pipe material plays an important role in heat transfer performance. Commonly used materials include PVC, HDPE, concrete, and metal.

1-4-6 Airflow rate:

Airflow rate and air velocity strongly influence the thermal performance of the system. Low airflow rates provide longer residence time inside the pipe, leading to better temperature conditioning but lower ventilation capacity. In contrast, high airflow rates reduce the contact time between the air and the pipe surface, resulting in smaller outlet temperature changes while increasing the ventilation rate. Therefore, a balance must be achieved between heat exchange effectiveness and the amount of delivered airflow.

1-4-7 Pipe configuration:

Pipe configuration significantly affects both the heat transfer performance and the pressure losses within the system. Common layouts include straight pipes, serpentine arrangements, helical designs, and multiple parallel pipes. Each configuration influences the contact area between the air and the surrounding soil as well as the airflow resistance. In particular, parallel pipe configurations are often preferred because they improve airflow distribution, reduce pressure drop, and increase the effective heat transfer area.

The schematic representation below provides a clearer illustration of all the potential parameters that may influence the thermal performance of the earth-air heat exchanger EAHE system. These parameters include geometrical characteristics, airflow conditions, pipe material properties, soil thermal properties, and installation configuration, all of which play a significant role in determining the overall heat exchange efficiency and system performance.

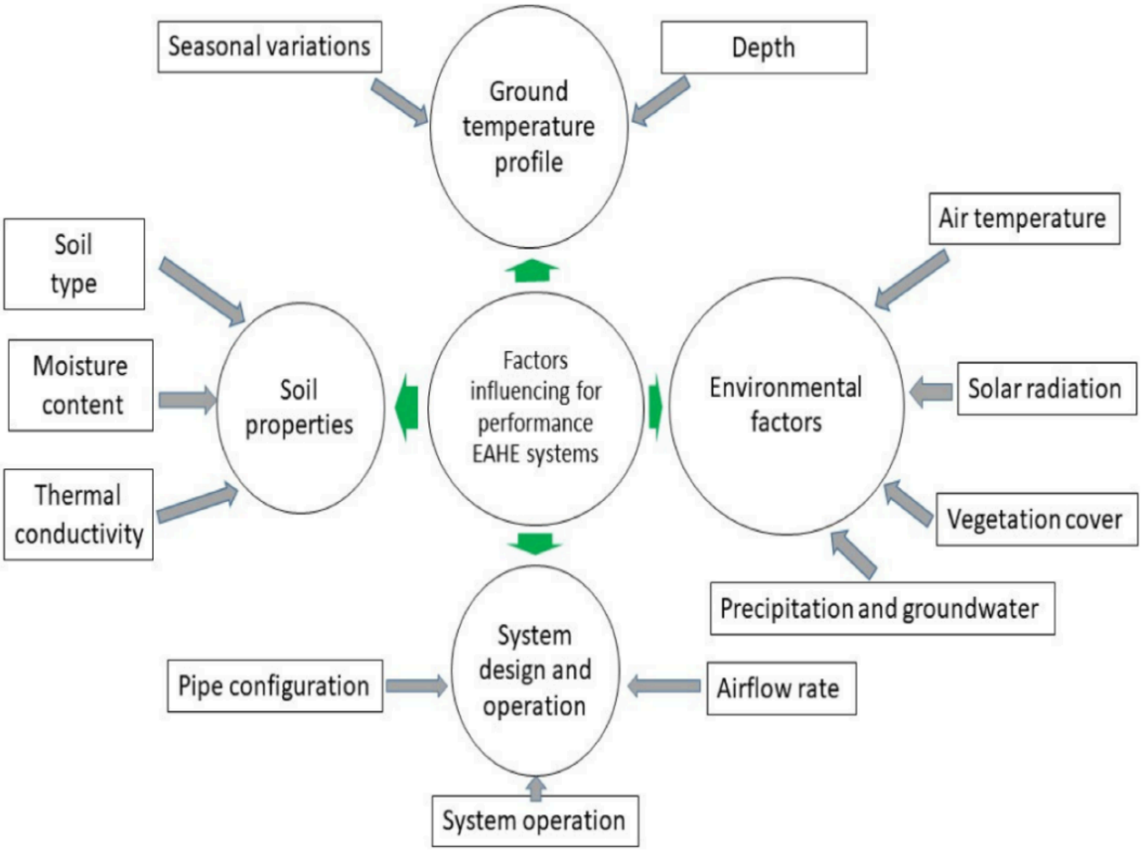

Figure 1-7: Illustrative representation of potential parameters that may influence the thermal performance of the earth-air heat exchanger [12].

Conclusion

This chapter introduced the main concepts related to Earth-to-Air Heat Exchangers (EAHEs) First a brief overview of geothermal energy was provided Next the operating principles and essential components were described The different configurations and classifications were subsequently reviewed followed by a discussion of the principal parameters affecting thermal sizing and system performance.

Chapter 2

Earth-air heat exchanger: mathematical formulation

Introduction

The present mathematical formulation of the earth-air heat exchanger EAHE involves first determining the soil temperature distribution, followed by the air temperature distribution within the horizontal pipe. This analysis considers two cases: one with insulated descending and ascending sections, and another without insulation on the descending section, which is more realistic. The thermal efficiency formula will also be evaluated, along with the thermal characteristic equations of the EAHE, which are essential for proper numerical and experimental validation of the model. The complete set of equations governing the EAHE is derived based on a number of assumptions [10].

- Soil is considered to be a homogenous medium with constant thermal properties.
- Soil conduction heat transfer is considered to be one-dimensional and transient.
- Pipe is considered to be a homogenous medium with constant geometrical and thermal properties.
- Air thermal properties are considered to be temperature-dependent.
- Pressure drop in the pipe is ignored.

2-1 Soil temperature distribution:

The determination of the soil temperature distribution can obtain by treating the classical conduction problem of semi-infinite wall, governed by the following second order differential equation:

$$\frac{\partial^2 T_s}{\partial z^2} = \frac{1}{\alpha_s}\frac{\partial T_s}{\partial t} \qquad (2\text{-}1)$$

$T_s[°C]$ is the soil temperature, $z[m]$ is the soil depth, $t[s]$ is the time and $\alpha_s\left[m^2.s^{-1}\right]$ is the soil diffusivity, expressed in terms of soil thermal conductivity$k_s\left[W.K^{-1}.m^{-1}\right]$, density $\rho_s\left[Kg.m^{-3}\right]$, density$\rho_s$ and heat capacity $c_s\left[J.kg^{-1}.K^{-1}\right]$ as[11-14]:

$$\alpha_s = \frac{k_s}{\rho_s c_s} \qquad (2\text{-}2)$$

The problem is subjected to:

The initial condition:

$$T_s(z, t = 0) = T_m \qquad (2\text{-}3)$$

And the boundary conditions:

$$T_s(z = 0, t) = T_m + A \cos cos \left(\omega(t - t_0)\right) \qquad (2\text{-}4)$$

And:

$$T_s(z \longrightarrow \infty, t) = T_m \qquad (2\text{-}5)$$

T_m[°C] Is annual average temperature and$A$[°C] is the amplitude temperature, computed respectively by:

$$T_m = \frac{T_{max} + T_{min}}{2} \qquad (2\text{-}6)$$

And:

$$A = \frac{T_{max} - T_{min}}{2} \qquad (2\text{-}7)$$

T_{max}[°C] and T_{min}[°C] are the maximum and the minimum recorded surface soil temperatures respectively [7-10].

Solutions for such a conduction problem are usually formulated by assuming that soil temperature can be separated as:

$$T_s(z, t) - T_m = \left(\theta(z)e^{i\omega(t - t_0)}\right) \qquad (2\text{-}8)$$

This kind of separation of variables approach allows the obtaining of a quasi-steady solutions, also known as long time periodic solution, expressed [13-16] as :

$$T_s(z, t) = T_m + Ae^{-\frac{z}{\delta}} \cos cos \left(\omega(t - t_0) - \frac{z}{\delta}\right) \qquad (2\text{-}9)$$

$\omega\left[s^{-1}\right]$ is the angular frequency, expressed in terms of period$P[s]$ as :

$$\omega = \frac{2\pi}{P} \qquad (2\text{-}10)$$

We define the temperature amplitude attenuation (temperature decay) as:

$$A(z) = Ae^{-\frac{z}{\delta}} \qquad (2\text{-}11)$$

And the term $\frac{z}{\delta}$ represents the phase shift due the soil thermal inertia, while $\delta[m]$ stands for the thermal penetration depth, expressed as:

$$\delta = \sqrt{\frac{2\alpha_s}{\omega}} \qquad (2\text{-}12)$$

It should be mentioned that the thermal penetration depth represents the distance of heat propagated into a soil material during a specific time or oscillation cycle, defining how deep temperature changes significantly affect a material.

2-2 Air temperature distribution in the EAHE with insulated descending and ascending sections:

The determination of air temperature distribution $T_a[°C]$ in the horizontal pipe is obtained basing the elementary energy balance equation, given by [2-4]:

$$\dot{m}C_a dT_a = U2\pi r_i(T_s - T_a)dx \qquad (2\text{-}13)$$

Where $T_a[°C]$ is the air temperature, $C_a\left[J.Kg^{-1}.K^{-1}\right]$ is the air heat capacity, $\dot{m}\left[Kg.s^{-1}\right]$ is the air mass flow and $U\left[W.m^{-2}.K^{-1}\right]$ is the global heat transfer coefficient.

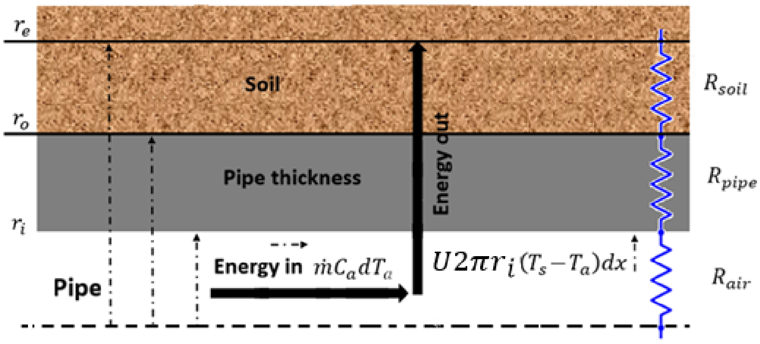

Figure 2-1: Schematic representation of elementary heat exchange between air and soil.

Equation (2-13) is reformulated into a more suitable form for integration, as follows:

$$\frac{dT_a}{(T_a - T_s)} = -Hdx \qquad (2\text{-}14)$$

The factor $H\left[m^{-1}\right]$ appears as the ratio of the heat transfer rate between the air and the soil to the heat transfer rate of the air flow. It is defined as:

$$H = \frac{U2\pi r_i}{\dot{m}C_a} \qquad (2\text{-}15)$$

The global heat transfer coefficient $U[W.m^{-2}.K^{-1}]$ is expressed in terms of thermal resistances as [7-10]:

$$\frac{1}{U} = R_{air} + R_{pipe} + R_{soil} \qquad (2\text{-}16)$$

$R_{air}[K/W]$, $R_{pipe}[K/W]$ and are $R_{soil}[K/W]$ are the thermal resistances of air, pipe and soil respectively.

$$R_{air} = \frac{1}{2\pi r_i h_a L} \qquad (2\text{-}17)$$

And:

$$R_{pipe} = \frac{\ln ln \frac{r_o}{r_i}}{2\pi k_p L} \qquad (2\text{-}18)$$

And :

$$R_{soil} = \frac{\ln ln \frac{r_e}{r_o}}{2\pi k_s L} \qquad (2\text{-}19)$$

The use equations (2-17), (2-18) and (2-19) enables to express the global heat transfer coefficient U as [13-17]:

$$\frac{1}{U2\pi L r_i} = \frac{1}{h_a 2\pi L r_i} + \frac{1}{2\pi L k_p} \ln ln \frac{r_o}{r_i} + \frac{1}{2\pi L k_s} \ln ln \frac{r_{es}}{r_o} \qquad (2\text{-}20)$$

Where $L[m]$ is the total pipe length, $r_i[m]$ and $r_o[m]$ are the inner and outer pipe radii. $r_{es}[m]$ is the effective soil radius that represent the distance where soil temperature is undisturbed, we approximate it in this dissertation by:

$$r_{es} = 10\, r_o \qquad (2\text{-}21)$$

This approximation of r_{es} has been supported by different numerical simulations.

$k_s[W.K^{-1}.m^{-1}]$Is the soil thermal conductivity, $k_p[W.K^{-1}.m^{-1}]$ is the pipe thermal conductivity and $h_a[W.K^{-1}.m^{-2}]$ is the air convection coefficient, determined according to Gnielinski correlation as:

$$N_u = \frac{\left(\frac{f}{8}\right)\left(R_e - 1000\right)P_r}{1+12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(P_r^{\frac{2}{3}} - 1\right)} \quad (2\text{-}22)$$

f is the friction coefficient, for a smooth pipe it is given as :

$$f = \left(0.79 \ln ln\,(R_e) \;-\; 1.64\right)^{-2} \quad (2\text{-}23)$$

R_e , P_r and N_u are numbers of Reynolds, Prandtl and Nusselt, respectively expressed as:

$$R_e = \frac{2r_i\rho_a\overline{V}}{\mu_a} \quad (2\text{-}24)$$

And:

$$P_r = \frac{\mu_a C_a}{k_a} \quad (2\text{-}25)$$

And:

$$N_u = \frac{2r_i h_a}{k_a} \quad (2\text{-}26)$$

$\rho_a[Kg.m^{-3}]$ is the air density, $k_a[W.K^{-1}.m^{-1}]$ is the air thermal conductivity, $\mu_a[Pas]$ is the air dynamic viscosity and $\overline{V}[m.s^{-1}]$ is the air mean velocity, computed using the mass flow $\dot{m}$ as :

$$\overline{V} = \frac{\dot{m}}{\rho_a\pi r_i^2} \quad (2\text{-}27)$$

The outlet air temperature can be calculated by integrating equation (2-14) using the boundary conditions, $x = 0,\ T_a = T_{ai}$and $x = L,\ T_a = T_{ao}$as [10-13]:

$$T_{ao} = T_s + (T_{ai} - T_s)e^{-HL} \quad (2\text{-}28)$$

Using equation (2-9), the outlet air temperature T_{ao} can be terms of soil depth z and time t as:

$$T_{ao} = T_m + \left(T_{ai} - T_m\right)e^{-HL} + Ae^{-\frac{z}{\delta}} \cos cos\,(\omega(t - t_0) - \tfrac{z}{\delta})\,(1 - e^{-HL}) \qquad (2\text{-}29)$$

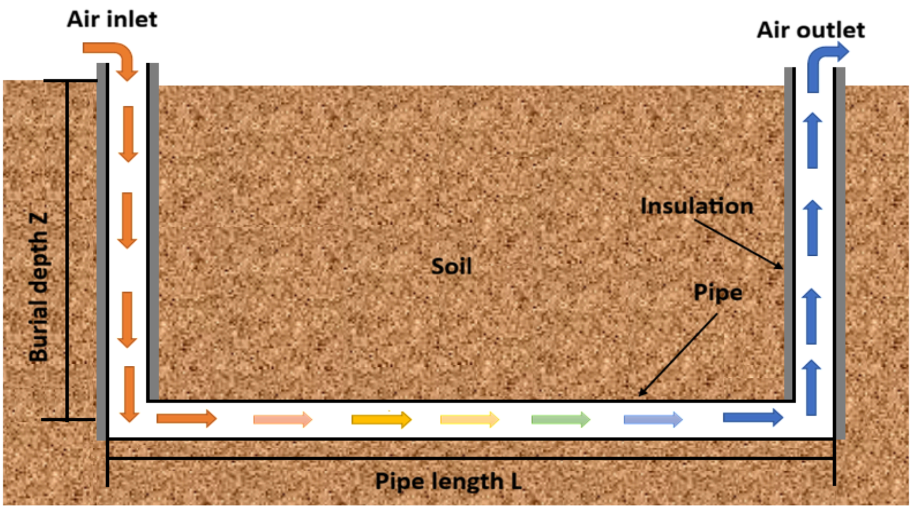

Figure 2-2: Schematic representation of horizontal EAHE with insulated descending and ascending sections.

2-3 Air temperature distribution in the vertical pipe with non-insulated descending section:

For the practical situation when of vertical descending pipe section is not insulated, it is absolutely necessary to take into account the variation of the soil temperature with respect to depth $z \equiv x$. Therefore, equation (2-13) is transformed into more suitable form for analytical integration as:

$$T_a' + HT_a = HT_s \qquad (2\text{-}30)$$

Introducing the integrating factor Fas:

$$F = e^{\int Hdz} \qquad (2\text{-}31)$$

The multiplication of both sides of equation (2-31) by integrating factor F leads to:

$$e^{Hz}T_a = \int He^{Hx}T_s dz \qquad (2\text{-}32)$$

The substitution of equation (2-9) into equation (2-32) gives:

$$e^{Hz}T_a = \int He^{Hz}\left[T_m + Ae^{-\frac{z}{\delta}} \cos cos\,(\omega(t - t_0) - \frac{z}{\delta})\right]dz \qquad (2\text{-}33)$$

The rearrangement of equation (2-33) leads:

$$e^{Hz}T_a = T_m \int He^{Hz}dx + AH\int e^{(H-\frac{1}{\delta})z} \cos cos\,(\omega(t - t_0) - \frac{z}{\delta})\,dz \qquad (2\text{-}34)$$

The first integral in equation (2-34) evaluated as:

$$\int He^{Hz}dx = e^{Hz} \qquad (2\text{-}35)$$

While the second integral in equation (2-34) is evaluated using on the following integral propriety:

$$\int e^{az} \cos cos\,(bz + c)\,dz = \frac{e^{az}}{a^2+b^2}[a \cos cos\,(bz + c) + b \sin sin\,(bz + c)] + C$$

(2-36)

This results into:

$$\int e^{(H-\frac{1}{\delta})z} \cos cos\,(\omega(t - t_0) - \frac{z}{\delta})\,dz = \frac{e^{(H-\frac{1}{\delta})z}}{(H-\frac{1}{\delta})^2+\frac{1}{\delta^2}}\left[\left(H - \frac{1}{\delta}\right) \cos cos\,(\omega(t - t_0) - \frac{z}{\delta}) - \frac{1}{\delta}\sin sin\,(\omega$$

(2-37)

The vertical air temperature profile is determined as:

$$T_a = T_m + \frac{AH}{(H-\frac{1}{\delta})^2+\frac{1}{\delta^2}}\left[\left(H - \frac{1}{\delta}\right) \cos cos\left(\omega(t - t_0) - \frac{z}{\delta}\right) - \frac{1}{\delta}\sin sin\left(\omega(t - t_0) - \frac{z}{\delta}\right)\right]e^{-\frac{z}{\delta}} + Ce^{-Hz}$$

(2-38)

The air temperature T_{az} distribution in the vertical descending pipe section can be calculated using the boundary condition, $z = 0,\ T_a = T_{ai}$

$$T_{az} = T_m + \left[T_{ai} - T_m\right]e^{-Hz} + \frac{AH}{\left(H-\frac{1}{\delta}\right)^2+\frac{1}{\delta^2}}\left[\left(H - \frac{1}{\delta}\right) \cos cos\left(\omega(t - t_0) - \frac{z}{\delta}\right) - \frac{1}{\delta}\sin sin\left(\omega(t - t_0)\right.\right.$$

(2-39)

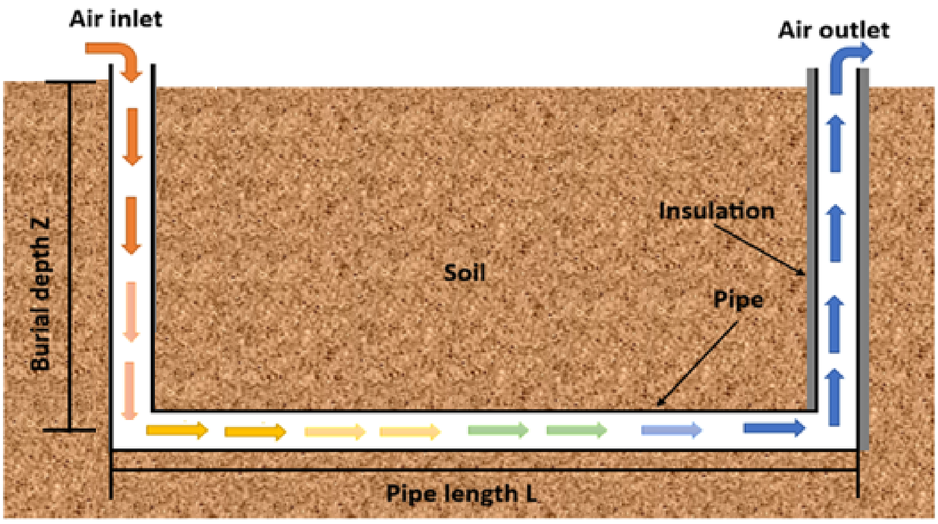

Figure 2-3: Schematic representation of horizontal EAHE with non-insulated descending Section.

Basing on equation (2-29), we can express the outlet air temperature for this case $T_{ai} = T_{az}$ as

$$T_{ao} = T_m + \left(T_{az} - T_m\right)e^{-HL} + Ae^{-\frac{z}{\delta}} \cos cos\,(\omega(t - t_0) - \tfrac{z}{\delta})\,(1 - e^{-HL}) \qquad (2\text{-}40)$$

Remark

It is important to emphasize that the ascending section of the EAHE must always be properly insulated. Without adequate insulation, the air traveling through this upward segment can absorb unwanted heat from the surrounding soil, especially as it approaches the outlet where it is more exposed to heat gradient. This unintended heat gain can significantly reduce the overall cooling efficiency of the system and compromise its intended performance. Therefore, ensuring consistent and effective insulation along the entire ascending section is essential to maintain the desired air temperature and to optimize the energy efficiency and reliability of the EAHE system.

2-4 Thermal efficiency of EAHE:

The thermal efficiency of a heat exchanger is the ratio of the real heat transfer rate to the maximum possible heat transfer rate where the length is supposed to be infinitely long. It is expressed as a decimal or percentage. It measures how effectively a system transfers energy between fluid, located inside the pipe and the soil. The EAHE thermal efficiency is given by :

$$\varepsilon = \frac{Q_L^{real}}{Q_{L\to\infty}^{maximum}} = \frac{\dot{m}C_a\left(T_{ao}-T_{ai}\right)}{\dot{m}C_a\left(T_s-T_{ai}\right)} = \frac{T_{ao}-T_{ai}}{T_s-T_{ai}} \qquad (2\text{-}41)$$

For the horizontal (EAHE), the thermal efficiency is obtained by combining the equation (2-4) with equation (28) that represents the outlet air temperature evolutions:

$$\varepsilon = \frac{T_s+(T_{ai}-T_s)e^{-HL}-T_{ai}}{T_s-T_{ai}} = 1 - e^{-HL} \qquad (2\text{-}42)$$

Note that the temperature difference $(T_{ai} - T_s)$ will cancel out in both numerator and denominator and the thermal efficiency of the horizontal (EAHE) will only are a function of the factor H and the pipe length L.

2-5 Characteristic equations for Horizontal and Vertical EAHE:

Now, rearranging and applying the natural logarithmic function on both sides of the equation (2-42) as:

$$\ln ln \frac{1}{1-\varepsilon} = HL \qquad (2\text{-}43)$$

Replacing H by $\frac{U2\pi r_i}{\dot{m}C_a}$, we obtain:

$$\ln ln \underbrace{\frac{Tai-T_{ao}}{T_s-T_{ai}}}^{Y} = \underbrace{\frac{U2\pi r_i}{C_a}}^{A}\underbrace{\frac{1}{\dot{m}}}^{X} \qquad (2\text{-}44)$$

The present linear equation$Y = AX$, which relates the natural logarithm of the temperature difference ratio $\ln ln \frac{T_s-T_{ao}}{T_s-T_{ai}}$ to the inverse of the mass flow rate $\frac{1}{\dot{m}}$, has signify cant practical importance, particularly for the experimental validation of EAHE mathematical models and for predicting the global heat transfer coefficient U from the slope of the equation.

Conclusion

The present chapter has been devoted to the modeling and derivation of the main quantities that characterize the earth-air heat exchanger EAHE system. The analysis began with the determination of soil temperature, which represents a key parameter influencing the overall performance of the system, particularly its thermal efficiency. Accurate estimation of soil temperature is essential, as it directly affects heat exchange between the buried pipes and the surrounding ground. Subsequently, two different configurations of horizontal piping systems were examined. The first configuration consists of a horizontal pipe with insulated descending and ascending sections, designed to minimize heat losses during air circulation. The second configuration involves a horizontal pipe with a non-insulated descending section, which is considered more representative of real-world installation conditions. By comparing these configurations, the study highlights the impact of insulation and design choices on the thermal behavior and efficiency of the EAHE system.

Chapter 3

Results and discussions

Introduction

This chapter begins with a detailed description of the experimental site in Ghardaïa, Algeria, where field measurements on a horizontal earth-air heat exchanger (EAHE) were conducted, along with an overview of the instrumentation used for temperature and climatic monitoring. Recent experimental monitoring in the region (2020–2023) demonstrates that soil thermal diffusivity decreases with depth, while subsurface temperatures stabilize at approximately 24 °C beyond 4 m, exhibiting pronounced thermal damping and phase lag [18]. Supported by a highly accurate predictive model ($R^2 = 0.995$), these findings confirm the shallow subsoil's reliable thermal buffering capacity for geothermal applications in arid climates, providing a robust experimental foundation for the present study. Building on this geothermal characterization, the chapter proceeds to validate the proposed numerical model through direct comparison with field data. Finally, a comprehensive analysis of the EAHE's thermal performance is presented, evaluating the influence of key design and operational parameters on system efficiency.

3-1 Geographic location:

The province of Ghardaïa is situated in the central-northern Sahara, approximately 600 km south of Algiers (Fig. 3-1). It shares administrative boundaries with the following neighboring provinces: Laghouat and Djelfa to the north, Ouargla to the east, El Menia to the south, and El Bayadh to the west.

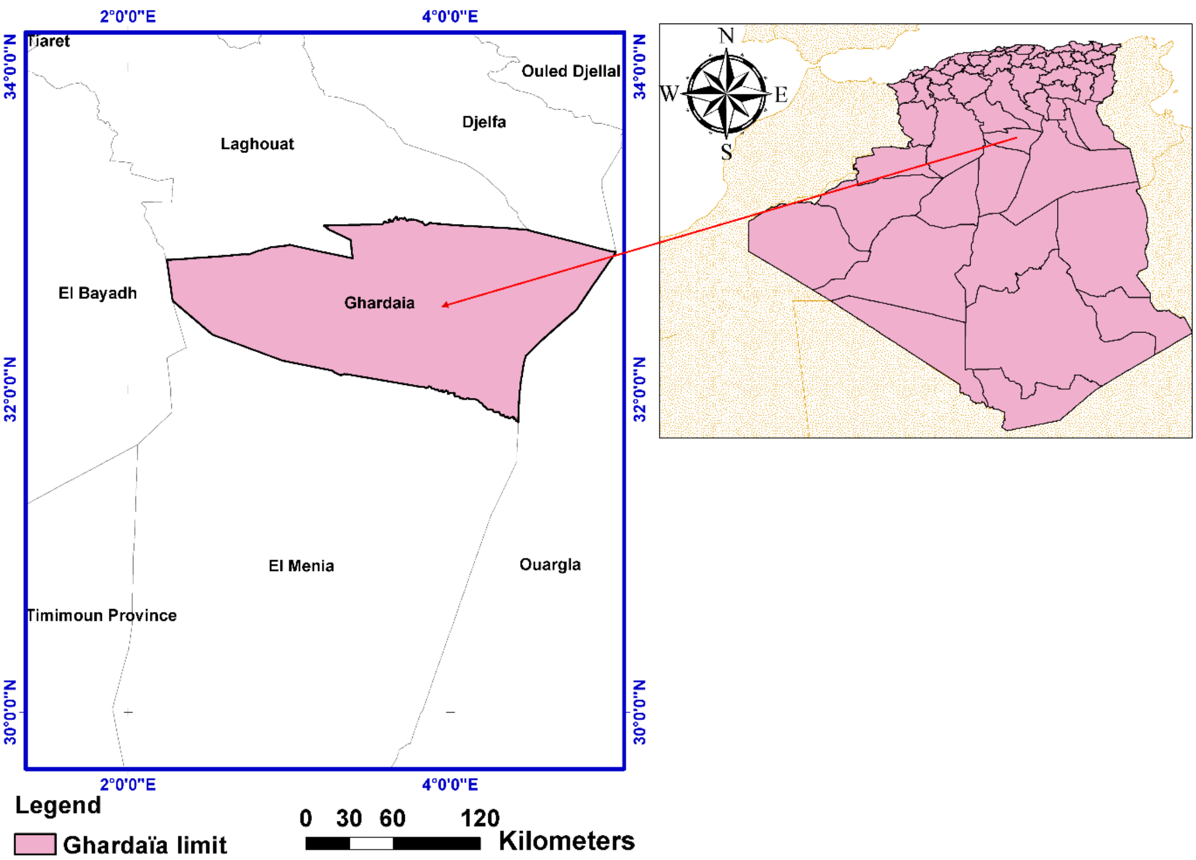

Figure 3-1: Geographical location of the study area.

3-2 Experimental Earth-Air Heat Exchanger prototype:

The experimental site selected for this study is located within the Applied Renewable Energy Research Unit (UARER), a structure offering particularly favorable conditions for conducting the scientific investigations. This choice is based primarily on the availability of infrastructure and equipment adapted to energy research and shallow geothermal energy. The site is notably equipped with a functional prototype air-to-earth heat exchanger, a radiometric station monitoring the components of solar radiation (global, direct, and diffuse), and a complete system for acquiring and recording experimental data.

Geologically and topographically, the study area is characterized by outcropping limestone bedrock, devoid of vegetation cover, with a flat, horizontal morphology. This configuration guarantees homogeneous and continuous solar exposure throughout the day, an essential factor for analyzing heat transfer within the Saharan soil. Exploiting shallow geothermal potential requires a detailed understanding of the soil's thermal behavior. With this in mind, a thorough study of temperature variations was undertaken at different depths throughout the year. The methodological approach adopted relies on experimental measurements carried out directly on-site, providing representative and reliable data on the climatic and thermal conditions specific to the Saharan region of Ghardaïa. The study site is located at the geographic coordinate's 32.387° North latitude and 3.779° East longitude (Fig. 3-2), at an altitude of 465 m above mean sea level. This geographic location is an important parameter in the interpretation of the climatic phenomena and heat exchanges observed during the study.

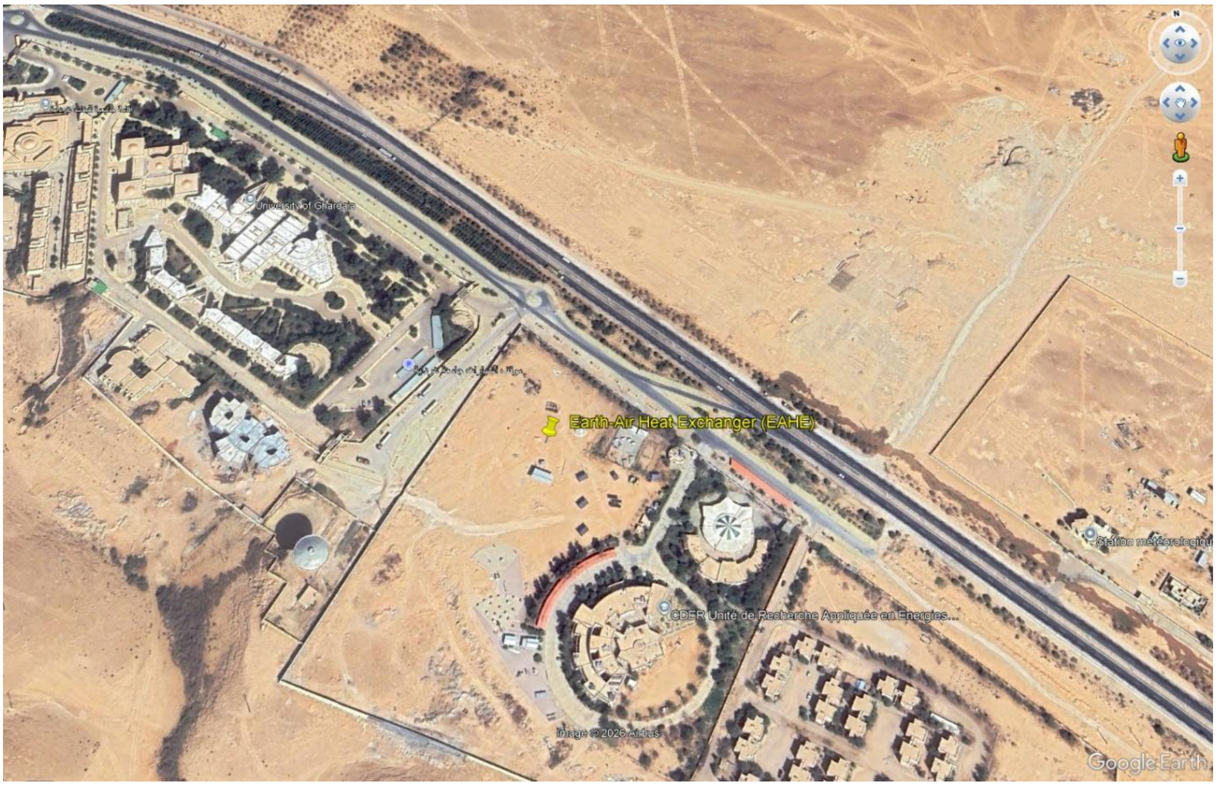

Figure 3-2: Location of the experimental site and location of the air-to-ground heat exchanger [21].

3-3 Meteorological instrumentation and data acquisition system:

The meteorological sensors included in this station are used to measure the following parameters: air temperature, atmospheric humidity, wind speed and direction, atmospheric pressure, dew point temperature and rainfall. These instruments are connected to a data acquisition system of the type Campbell Scientific, RS232 model for the storage and collection of radiometric data **(Fig. 3-3).** These measurements are programmed at a one-minute and ten-minute time step.

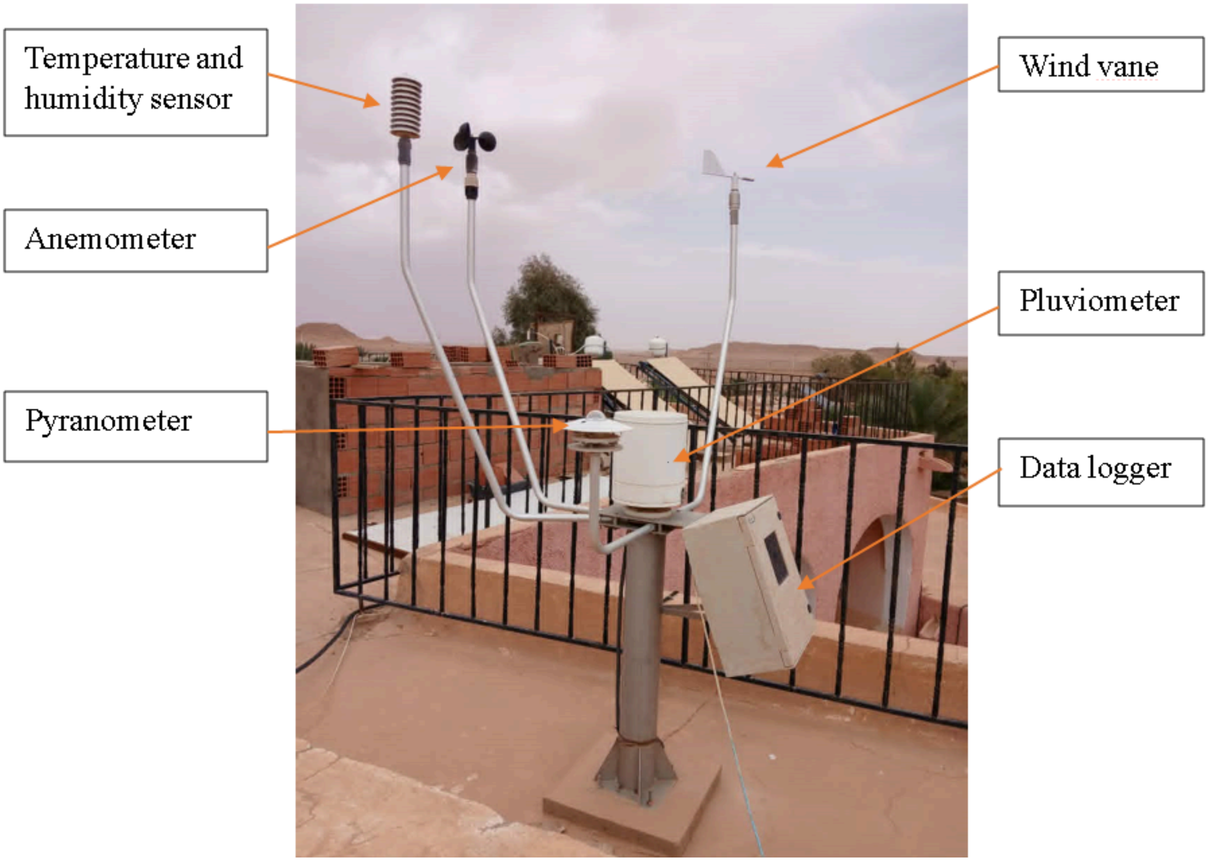

Figure 3-3: The meteorological station installed on the roof of URAER (Ghardaïa).

3-3-1 Solar Irradiation:

3-3-1-1Direct solar radiation:

Corresponds to the luminous flux that reaches the Earth's surface in a straight line from the Sun. It consists of photons that have not undergone any significant interaction with atmospheric constituents, thus maintaining a parallel trajectory and their initial energy.

3-3-1-2 diffuses radiation:

Diffuse radiation results from the scattering of photons by molecules and particles present in the atmosphere, which diverts them from their initial trajectory. This interaction transforms the initial parallel beam into a multidirectional radiation, emanating from the entire sky. For a given surface, the diffuse component is the most complex to model due to its variable angular distribution and dependence on atmospheric conditions.

3-3-1-3 Global solar radiation:

Global solar radiation is the sum of the direct and diffuse components received on a flat surface. In the analysis of solar resources, we distinguish two formats of sunshine data:

• Instantaneous radiation: solar power received at a specific moment, expressed according to the time of day (W/m^2).

• Cumulative radiation: total energy accumulated over a given period (usually daily), obtained by temporal integration of instantaneous radiation (kWh/m^2 or MJ/m^2).

3-3-2 Air Temperature:

The annual temperature profile exhibits pronounced seasonal amplitude, with monthly averages ranging from 11°C in January to 33°C during July and August. This marked thermal variability is characteristic of arid continental climates, which feature relatively mild winters and intensely hot summers. Such a climate regime directly influences the thermal operating conditions and seasonal performance of solar energy systems.

3-3-3 Relative Humidity:

Relative humidity shows a strong inverse correlation with ambient temperature, peaking at about 58% in December and decreasing to an annual minimum of about 24% in July. This pronounced seasonal aridity, especially during the summer, intensifies atmospheric dryness and directly modulates building cooling loads. The low moisture content reduces latent cooling demand but increases sensible heat gain, shaping the overall space conditioning requirements across the region.

3-3-4 Wind Speed:

Mean monthly wind speed exhibits a pronounced seasonal cycle, peaking in spring at approximately 4.7 m/s in April and declining to an annual minimum of ~3.1 m/s in October. This variability directly modulates convective heat transfer coefficients at exposed surfaces, thereby influencing both the efficacy of natural ventilation strategies and the thermal performance of convection-dependent systems. Accurate characterization of this wind regime is essential for optimizing passive airflow design and minimizing convective heat losses in solar thermal and building energy applications.

Table 3-1: Monthly variations in meteorological parameters and horizontal solar radiation at Ghardaïa [19].

Months	Air temperature	Soil surface temperature	Relative humidity	Rainfall	Wind speed	Horizontal Daily Solar Radiation
	ºC	ºC	%	mm	m/s	KWh/m²/j
January	10,9	8,9	54,8	11,47	3,9	3,83
February	13,4	11,8	47,1	3,36	4	4,78
March	15,6	16,4	41,7	11,47	4,3	5,92
April	19,5	21,8	35,6	5,7	4,7	6,97
May	24,5	27,7	30,9	4,96	4,6	7,67
June	30	33,3	27,3	2,7	4,1	7,89
July	32,7	36,2	24,2	0,93	3,7	7,89
August	32,5	35,3	25,3	2,48	3,5	7,44
September	28	29,6	35,6	9,6	3,6	6,17
October	21,6	22,7	45,2	11,47	3,1	5,11
November	15,4	15,4	54,3	9,3	3,3	3,94
December	11,6	10,2	58,8	9,61	3,8	3,5

This graph illustrates the seasonal evolution of key meteorological parameters (temperature, relative humidity, wind speed and solar radiation) over an annual cycle. The curves reveal marked cyclical variations, characteristic of the continental desert climate of the Ghardaïa region.

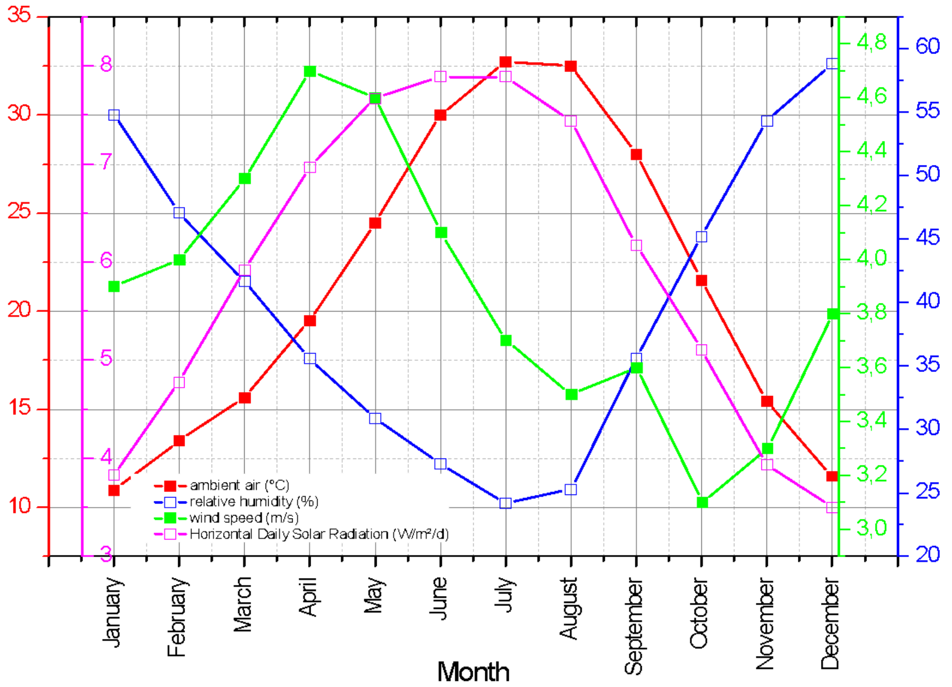

Figure 3-4: Monthly variation of climatic parameters in the Ghardaïa region.

3-4 Description of the experimental Site (URAER):

The Applied Research Unit in Renewable Energies, commonly known by its French acronym (**URAER)** (*Unité de Recherche Appliquée en Énergies Renouvelables*), is one of Algeria's leading scientific institutions dedicated to renewable energy research and technological innovation. It operates under the Centre for the Development of Renewable Energies (**CDER**), which itself is supervised by Algeria's Ministry of Higher Education and Scientific Research through the Directorate-General for Scientific Research and Technological Development (**DGRSDT**), see **figure 3-5**.

Figure 3-5: The Applied Research Unit in Renewable Energies, **URAER** (Ghardaïa).

The principal mission of (**URAER**) is to conduct applied scientific research and technological development in renewable energies, particularly technologies adapted to Algeria's climatic and socio-economic conditions. The institution focuses on transforming scientific knowledge into practical systems and prototypes that can support sustainable development, energy security, and environmental protection.

Its objectives include:

- Developing renewable-energy technologies suitable for arid and semi-arid regions.
- Supporting Algeria’s energy transition away from dependence on fossil fuels.
- Designing pilot projects and experimental installations.
- Training researchers, engineers, and graduate students.
- Promoting innovation and technology transfer between academia and industry.
- Assisting national authorities with scientific expertise and energy planning.

The Earth-to-Air Heat Exchanger (EAHE) experiment was carried out using different devices for measurement and data acquisition, see **figure 3-6**.

Figure 3-6: Experimental earth-air heat exchanger**, URAER** (Ghardaïa).

The used measurement instruments in an earth-air heat exchanger experimental setup are illustrated in **figure 3-7**.

-**Testo 176T4**: is a robust, high-precision, professional temperature data logger capable of simultaneously monitoring up to four measurement points via external thermocouple probes (types T, K, J). Ideal for industrial, pharmaceutical, and food environments, it offers ample memory and a display screen.

-**Anemometer**: is an instrument for measuring airflow speed. There are many types of anemometers; the most commonly used in weather stations is the suction cup anemometer, which consists of three parabolic conical cups fixed at 120° intervals to a support (formerly the induction element). The concave surfaces of the cups are all oriented in one direction. The entire induction element is mounted on a vertical rotating shaft. Under the action of the wind, the wind cups rotate around the shaft at a speed proportional to the wind speed.

-**Agilent 34970a** :The Agilent 34970A is a data acquisition unit used to measure, monitor and record various electrical and physical quantities such as voltage, current, resistance and temperature.

-**K type thermocouples :**are temperature sensors made of two different metals, Chrome and Alumel .They operate according to the thermoelectric effect and are widely used due to their wide measurement range and good accuracy.

Figure 3-7: Different measuring instruments, A: Testo 176T4, B: K-type thermocouples, and C: Anemometer, D: Agilent 34970a.

3-5 Experimental validation of numerical model:

The experimental validation of the Earth-to-Air Heat Exchanger (EAHE) model was carried out based on the following soil properties, pipe characteristics, and ambient air conditions

Table 3-2: Used parameters for experimental validation.

Parameters	Soil	Pipe	Ambiant air
Length [m]	-	28	-
Inner radius [m]	-	0.14	-
Outer radius [m]	-	0.16	-
Depth [m]	2.3	-	-
Thermal conductivity [$W.m^{-2}.K^{-1}$]	1.3	0.53	0.025
Heat capacity [$J.Kg^{-1}.K^{-1}$]	600	-	1007
Density [$Kg.m^{-3}$]	2160	-	1.24
Dynamic viscosity [Pa.s]	-	-	0.000018
Average temperature [°C]	-	-	22.44
Amplitude temperature [°C]	-	-	13.75
Inlet Air temperature [°C]	-	-	28.1
Air velocity [$m.s^{-1}$]	-	-	1.71

Table 3-3: Comparative results.

Date : 14-05-2026			
Pipe [m]	Measured temperature [°C]	Computed temperature [°C]	Error [%]
14	23.418	23.532	0.484
20	23.265	23.500	1.000
26	24.131	23.500	2.685
28	24.505	23.500	4.276

For a constant air speed, measurements were taken at four sections of the buried pipe located at using Agilent 34970a data logger. The results comparison depicted **in table 3-3** clearly shows the high agreement between our numerical solutions and the experimental measurements. This is confirmed by the computed percentage error, which doesn't exceed 5 % for the four measurements which is very satisfactory. There is a decrease in the calculated temperature values, which corresponds to the expected behavior in the earth-air heat exchangers thermal design. The slight rise in the measured temperature, located at which should not have occurred, was probably engendered by improper placement of the temperature sensor inside the pipe.

3-6 EAHE thermal performances results:

The following numerical simulation of an earth-air heat exchanger is conducted using the soil properties, pipe characteristics, and ambient air conditions listed above. These parameters are kept constant unless intentionally varied to investigate their effects. The variation of soil temperature as a function of time exhibits a clear attenuation pattern of with increasing soil depth, Figure 3-8. Near the soil surface, temperature fluctuations were more pronounced, showing rapid and high-amplitude changes in response to diurnal atmospheric conditions and solar radiation. In contrast, deeper soil layers displayed progressively smaller temperature amplitudes and a noticeable time lag in reaching maximum and minimum temperatures. This damping effect indicates that the soil acts as a thermal buffer, reducing the influence of short-term atmospheric variations with depth. Furthermore, while shallow depths responded almost instantaneously to daytime heating and night time cooling, deeper layers maintained relatively stable temperatures over time, reflecting the reduced thermal diffusivity and delayed heat transfer within the soil profile.

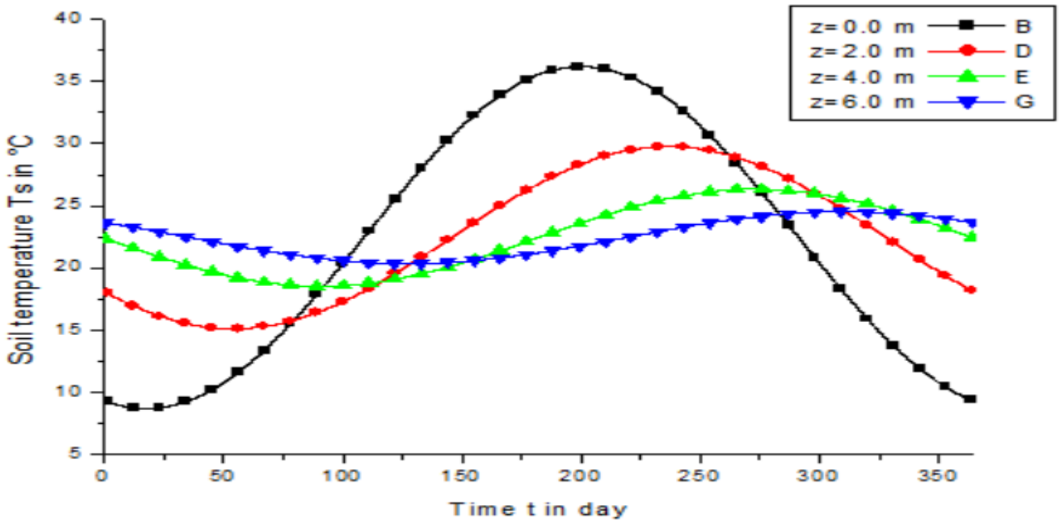

Figure 3-8: Variation of soil temperature as a function of time for different values of soil depths.

The variation of soil temperature as a function of soil depth across the four seasons shows a strong dependence on both surface forcing and thermal damping within the soil profile, **figure 3-9**. In all seasons, temperature generally decreases in amplitude with increasing depth reflecting the insulating properties of the soil and the attenuation of atmospheric influences .During summer, the highest temperatures are observed near the surface, with a pronounced thermal gradient extending downward, whereas in winter, the surface layers exhibit the lowest temperatures and the cold signal penetrates to greater depths, though with reduced in density Spring and autumn act as transitional periods, characterized by intermediate temperature levels and smoother vertical gradients compared to the more extreme seasonal conditions. At greater depths, seasonal variations become increasingly subdued, and soil temperature tends to stabilize, approaching the mean annual air temperature with a noticeable phase lag. This behavior highlights the soil's role as a thermal reservoir, integrating seasonal energy flux while progressively damping temperature fluctuations with depth.

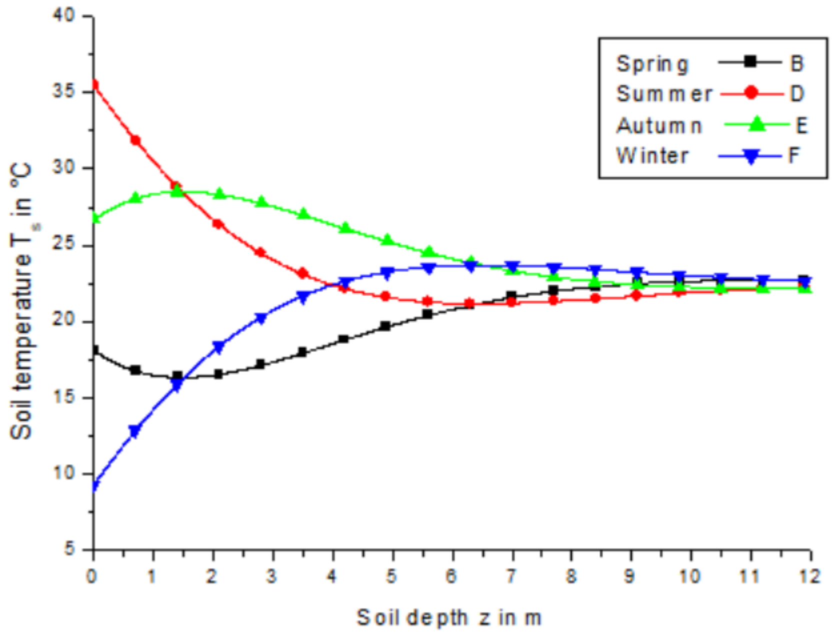

Figure 3-9: Variation of soil temperature as a function of depth for four seasons.

During the summertime, t=200 day and ambient temperature 40°C, the variation of outlet air temperature as a function of pipe length for different air velocities indicates a strong coupling between convective heat transfer and flow residence time, **figure 3-10**. In general, the outlet air temperature evolves more significantly with increasing pipe length due to the extended contact time between the flowing air and the pipe wall, which enhances thermal exchange. At lower air velocities, the longer residence time allows the air to approach thermal equilibrium more effectively, resulting in a greater change in outlet temperature along the pipe length. In contrast, at higher air velocities, the reduced residence time limits heat transfer, leading to weaker temperature variations and a less sensitive response to changes in pipe length. Consequently, the temperature curves tend to diverge at low velocities and become more flattened as velocity increases, highlighting the dominant role of flow rate in controlling the efficiency of thermal conditioning within the pipe.

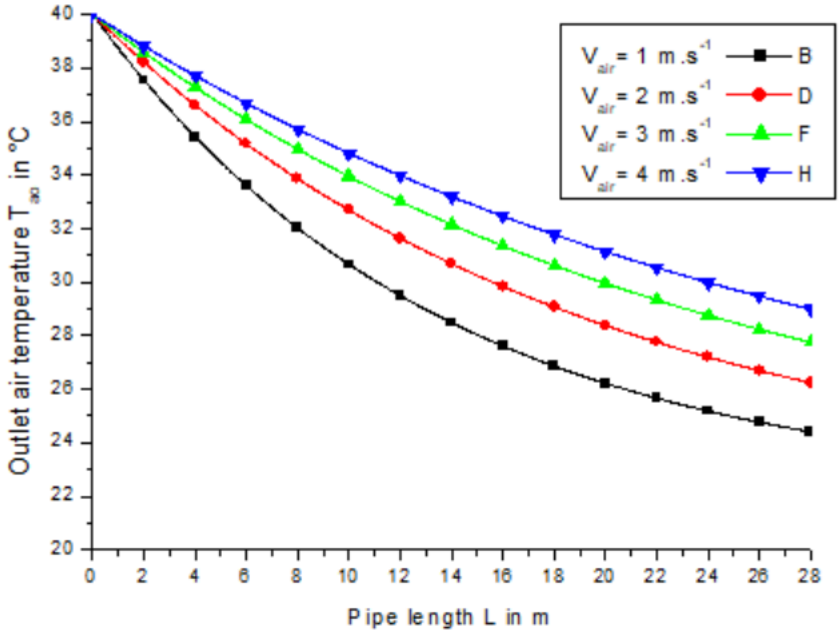

Figure 3-10: Variation of outlet air temperature as a function of pipe length for different values of air velocities.

During the summertime, t=200 day and ambient temperature 40°C, the variation of thermal efficiency as a function of pipe length for different air velocities demonstrates the combined influence of heat transfer area and fluid residence time on system performance, **figure 3-11**.

In general, thermal efficiency increases with pipe length due to the greater available surface for heat exchange and the enhanced opportunity for thermal interaction between the air and the surrounding medium. However, the rate of improvement tends to diminish at larger lengths, indicating an asymptotic approach toward a limiting efficiency. At lower air velocities, the efficiency is higher for a given pipe length because the longer residence time promotes more complete thermal exchange. Conversely, at higher air velocities, reduced contact time weakens the heat transfer process, resulting in lower overall efficiency and also were increase with pipe length. This behavior highlights a trade-off between flow rate and thermal performance, where increasing pipe length enhances efficiency while increasing velocity tends to limit it due to reduced heat transfer effectiveness.

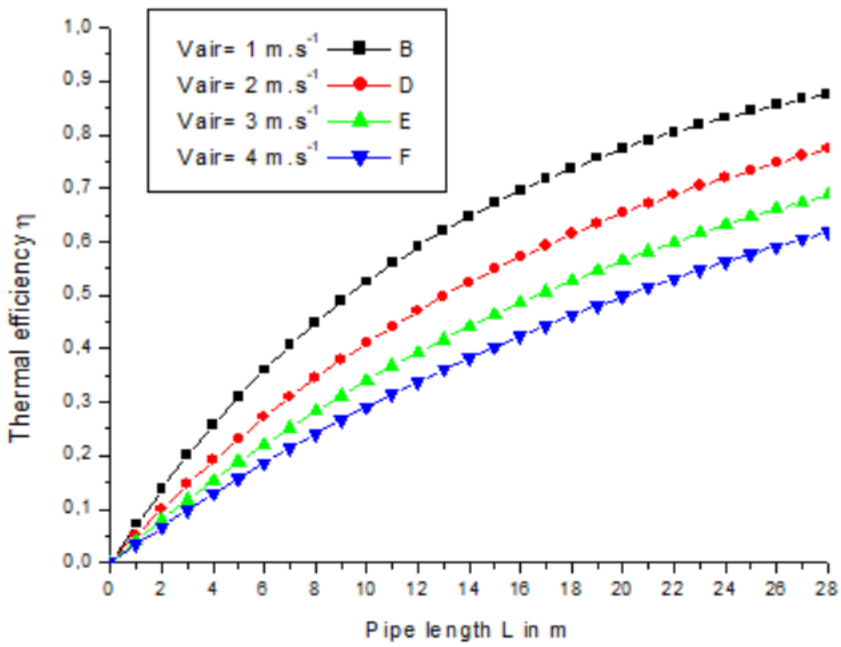

Figure 3-11: Variation of thermal efficiency as a function of pipe length for different values of air velocities.

During the summertime, t=200 day and ambient temperature 40°C, the variation of thermal efficiency as a function of pipe length for different air velocities demonstrates the combined influence of heat transfer area and fluid residence time on system performance, **figure 3-12**. In general, thermal efficiency increases with pipe length due to the greater available surface for heat exchange and the enhanced opportunity for thermal interaction between the air and the surrounding medium. However, the rate of improvement tends to diminish at larger lengths, indicating an asymptotic approach toward a limiting efficiency. At lower air velocities, the efficiency is higher for a given pipe length because the longer residence time promotes more complete thermal exchange. Conversely, at higher air velocities, reduced contact time weakens the heat transfer process, resulting in lower overall efficiency and as lower increase with pipe length. This behavior highlights a trade-off between flow rate and thermal performance, where increasing pipe length enhances efficiency while increasing velocity tends to limit it due to reduced heat transfer effectiveness.

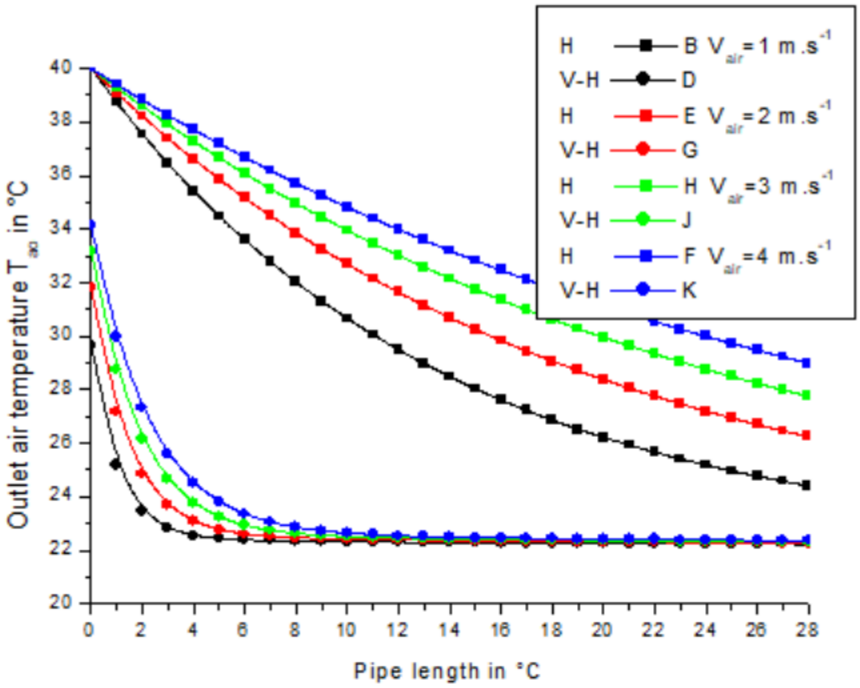

Figure 3-12:Variation of outlet air temperature as a function of pipe length for different air velocities in horizontal and vertical–horizontal EAHE configurations.

Conclusion

The present chapter is devoted to results and discussion. First, the numerical model was validated using experimental data provided by URAER Ghardaïa, demonstrating good agreement between simulated and measured results. Subsequently, a series of numerical investigations was carried out to analyze the soil temperature distribution, the outlet air temperature, and the thermal efficiency of the horizontal EAHE. In addition, a comparative study was conducted to evaluate the outlet air temperature for two different configurations ,namely the horizontal EAHE and the vertical–horizontal EAHE. The results highlight the influence of key parameters on system performance and emphasize the advantages of the vertical–horizontal configuration in terms of thermal effectiveness and heat exchange efficiency.

Conclusion general

In conclusion, this dissertation presented a comprehensive study on the mathematic a modeling and thermal analysis of a horizontal earth–air heat exchanger EAHE, with particular attention given to the heat transfer occurring in the descending pipe section. The work contributes to a better understanding of the thermal behavior of EAHE systems and their potential for improving energy efficiency in building applications, especially in region characterized by harsh climatic conditions like Ghardaïa.

The first chapter provided the theoretical foundation of the study through an overview of geothermal energy and earth-air heat exchanger technology, including their operating principles, configurations, and classifications. This background highlighted the importance of EAHE systems as sustainable and environmentally friendly solutions for passive heating and cooling.

The second chapter focused on the development of the mathematical model for two different configurations: insulated and non-insulated descending pipe sections. The inclusion of heat transfer in the descending section allowed the model to represent real operating conditions more accurately. The proposed model enabled the prediction of key thermal performance parameters, including the overall heat transfer coefficient, the outlet air temperature, and the thermal efficiency of the system.

In the third chapter, the numerical results were validated using experimental data obtained from the CDER experimental site in Ghardaïa. The comparison between theoretical and experimental results showed good agreement, confirming the reliability and accuracy of the developed model. Furthermore, a detailed parametric analysis was carried out to investigate the influence of several operating and geometric parameters on the thermal performance of the EAHE. The results demonstrated that pipe length, burial depth, soil temperature distribution, and air velocity play significant roles in determining the effectiveness of the system.

The study confirms that vertical-horizontal earth-air heat exchangers can provide a more significant reduction in outlet air temperature than horizontal configurations and can achieve better thermal conditioning of ventilation air while reducing conventional energy consumption.

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Thesis Title: Practical Design of Earth-Air Heat Exchanger

Hereby authorize the above-mentioned student(s) to print and submit their final manuscript to the department.

Ghardaia : 29/06/2026

President of the jury

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في العلوم والتكنولوجيا
شوية فيصل