UNIVERSITY OF KASDI MERBAH OUARGLA

Faculty of Hydrocarbons, Renewable Energies and Sciences of Earth and Universe

Department of Renewable Energies

THESIS

Presented to obtain the diploma of

MASTERS

Field: Mechanical Engineering

Specialty: Renewable Energies in Mechanics

Presented by:

Maissa AFFOUN

Sabrina LIMAME

Theme:

Study of a hybrid cooling system combining a direct evaporative cooler and an earth-air heat exchanger

Discussed publicly on 13/06/2023

In front of the jury composed of:

Dr. Hichem NECIB	**University Kasdi Merbah Ouargla**	**President**
Dr. Chouaib AMMARI	**University Kasdi Merbah Ouargla**	**Examiner**
Dr. Amar ROUAG	**University Kasdi Merbah Ouargla**	**Director**

Academic Year: 2022/2023

Dedication

I would like to dedicate this work to my beloved Mom & Dad who prayed for me and helped me pass every difficult moment, to my dear brothers NEDJMO & SABER and sisters MINA & FOUFA, to my dearest cousin AMANI, to my lovely MAMA MALIKA, to the pure soul of BABA LAKHDER, to my whole family, all of my friends and my colleagues throughout the 4 years in Renewable Energies class, to all those who are dear, and finally to whoever taught us a letter in this world, and to all those who use science for the success and wealthiness of mankind.

Above all, we thank ALLAH the Almighty.

Maissae.

الإهداء

إلى أمي الحبيبة "سعاد خمقاني"

إلى والدي الذي غمرني بكرمه لحسن،

واخوتي أعزائي بغداد، بدر، شريفة، إبتسام، رشيدة، عبد الكريم وحمزة

حفظكم الله

أهديكم جميعا هذا العمل المتواضع

الإمام صبرينة

Acknowledgment

First, we thank ALLAH the Almighty for giving us the breath of life, health, will, courage, and patience during all these years of studies

And it is thanks to ALLAH that this thesis was realized.

We would like to express our great appreciation and gratitude to the director of this thesis Mr. Amar ROUAG who beard us with assistance, advice, and a lot of patience, for his total blind trust in us, and for keeping up late hours to accomplish the work.

Without forgetting to thank the jury members for reviewing this work.

We thank Mr. Abdessamie HADJADJ and Mr. Djamel BELATRECHE for providing us with measuring tools and instruments, Mr. Djamel MEZZAR and Mr. Abd El Hamid MALKI for giving us all the authorization to freely use the laboratory, Mrs. Ismahan DJEDIAI for her support and encouragement, and always for giving us hope.

Also, all the regards and appreciation to our friends, Redhwane, Soheib, Ilham, Amine, Abd El Ghani, and Omar El Farouk for helping us since the beginning of the preparation of this thesis, for their support and reassurance.

We also would like to express our gratitude to the laboratory and the maintenance staff at the Renewable Energies department.

Finally, we widen our sincere thanks to everyone who had the hands to carry out and fulfill this work.

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Nomenclature

Abbreviations List

Abbreviations	Definition
DEC	Direct evaporative cooler
DSF	Double skin facade
EAHE	Earth-air heat exchanger
EATHE	Earth-air-tunnel heat exchanger
IEC	Indirect evaporative cooler
IRR	Internal rate of return

Symbols List

Symbols	Definition	Unit
$\mathbf{B}$	Pad module width	m
$\mathbf{C_p}$	Specific heat of the air	J/kg.K
$\mathbf{D_h}$	Hydraulic diameter	m
$\mathbf{f_a}$	Air humidity ratio	/
$\mathbf{f_s}$	Saturated air humidity ratio	kg_w/kg_a
$\mathbf{G_a} / \dot{\mathbf{m}}_\mathbf{a}$	Air mass flow rate	kg/s
$\mathbf{H}$	Pad module height	m
$\mathbf{h_c}$	Convective heat transfer coefficient	$W/m^2.K$
$\mathbf{h_m}$	Convective mass transfer coefficient	$W/m^2.K$
$\mathbf{J_0}$	Bessel function of the first kind of order zero	/
$\mathbf{J_1}$	Bessel function of the first kind of order one	/
$\mathbf{L}$	Pipe lenght	m
Nu	Nusselt number	/
Pr	Prandtl number	/
$\mathbf{q'}$	heat flux by length	W/m
$\mathbf{r}$	Latent heat of water vaporization	kJ/kg

Re	Reynolds number	/
R_p	Pipe thermal resistance	K.m/W
R_s	Soil thermal resistance	K.m/W
R_{tot}	Sum of thermal resistances	K.m/W
S	surface	m^2
T	Temperature	°C
t	time	s

Greek Symbols List

Symbols	Definition	Unit
δ	Thickness	m
λ	Thermal conductivity	W/m.K
ρ	Density	kg/m^3
ξ	Pore surface coefficient	m^2/m^3
η	Efficiency	%
μ	Dynamic viscosity	Kg/m.s
ν	kinematic viscosity	m^2/s
α	Thermal diffusivity	m^2/s

Subscripts List

Subscripts	Definition
0	initial
a	air
amb	ambient
cv	convective
h	hydraulic
i	index of time

in	inlet
j	index of layer
k	index of radius
n	index
out	outlet
p	pipe
s	soil
tot	total
w	water

GENERAL INTRODUCTION

General Introduction

The majority of countries around the world rely heavily on oil, natural gas, and coal for their energy needs. These fuels draw on numerous resources that will eventually fade, which makes them too expensive or environmentally damaging to recover. Therefore, based on the benefits of renewable energy resources, utilizing renewable energies instead of fossil fuels will be a good solution for the control of the environmental, social problems of our communities (1).

Arid regions around the world occupy large surfaces. In Africa, dry areas are vast such as in South-west Algeria. In this region, inside thermal comfort is hard to achieve without the employment of air conditioning and refrigeration systems. In 2006, more than 240 million air-conditioning units were installed worldwide, leading to a global electricity consumption of 15%. This enormous amount of energy can be optimized and saved using passive cooling and renewable energies (2).

The achievement of indoor thermal comfort while minimizing energy consumption in buildings is a target in most countries. In general, most people feel comfortable indoors when the temperature is between 22 °C and 27 °C and relative humidity is within the range of 40–60% (3). Hence, there is a rising interest in cooling systems based on renewable energy sources to achieve thermal comfort. Among the proposed solutions is exploiting geothermal energy. Which is an abundant, reliable, sustainable, and safe energy source for the environment (1). The basis of using geothermal energy is the temperature difference between the depth of the ground and the outside air is used to pre-heat or pre-cool the incoming air into the building using an earth-air heat exchanger system (3). Also, operating evaporative cooling that is a heat and mass transfer process that uses only water evaporation for air cooling instead of chemical refrigerants (4), in which a large amount of heat is transferred from air to water and consequently causes air temperature to decrease. They are separated into indirect evaporators where there is a separation between the working fluids (air and water), and direct evaporators where the working fluids are in direct contact (4).

This thesis aims to study the applicability and feasibility of a hybrid natural ventilation-cooling system distinguished as the merge of an earth air heat exchanger with a direct evaporative cooler (EAHE-DEC). The proposed system was studied experimentally and modeled and validated numerically using the parameters of a residential building in the Ouargla, Algeria region. For that, this thesis is visualized as four chapters where:

In the first chapter, general studies on the natural ventilation and cooling systems that use renewable energy resources were presented. Also, different reliable systems and their technical characteristics were presented.

In the second chapter, a detailed literature review of some previous realizations from recent years world widely were done, studying different functioning modes of earth air heat exchangers and evaporative cooling systems.

In the third chapter, the experimental procedures of the direct evaporative cooling system in addition to the numerical study we did on both EAHE and DEC systems were presented. The purpose of this chapter is to present the parameters used to measure the changes in different temperatures such as soil temperature, and air temperature inside the EAHE and at the outlet of the DEC system. Thus, the developed numerical model is displayed in the form of a flowchart.

The last chapter is devoted to identifying the obtained results and discussing the effect of different parameters on the evolution of temperature at the outlet of the proposed hybrid system EAHE-DEC.

CHAPTER I:

Generalities on natural ventilation and passive cooling systems

Introduction

The energy crisis, global warming, climate change, and ozone layer depletion increased global energy consumption, mainly for cooling and ventilation. Therefore, it is vital and urgent to find alternative passive cooling technologies (clean energy sources) to reduce the consumption of conventional fuels and reduce energy consumption that harms the environment. Therefore, this chapter will discuss some general aspects of natural ventilation and passive cooling systems.

1. Natural ventilation

Natural ventilation is one of the most efficient methods to enhance thermal comfort in buildings, particularly when it concerns passive and hybrid cooling (5). It is also a valuable tool for sustainable development as it relies only on natural air movement. It can save a significant amount of energy by reducing the need for mechanical ventilation and air conditioning. Reducing electrical power used for cooling contributes to limiting greenhouse gas emissions from fossil fuel-based energy generation. From the earliest times, building designers have exploited naturally induced air movement to meet two main objectives in buildings: eliminating foul air and wetness, and ensuring personal thermal comfort (6). Natural ventilation systems have received considerable attention over the last two decades the main reason embraces their direct application in buildings for energy saving, mainly in areas with hot and humid climates like the Mediterranean (7). Natural ventilation depends on three climatic elements: wind velocity, wind direction, and temperature changes. The speed and direction of the wind over a structure generate a pressure field around the building as shown in **Fig I. 1 (8).**

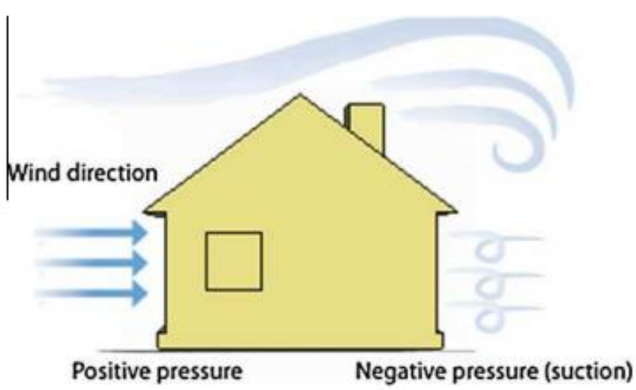


Fig I. 1: Pressure field generated around a building by wind speed and direction (8).

1.1. Natural Ventilation Systems

There are a wide variety of natural ventilation systems found in the literature. Solar wind towers, double skin facades (DSF), and solar chimneys are examples among others. Solar wind towers are appropriated for areas where low buildings are constructed and the wind velocity is strong enough to produce ventilation. Natural ventilation and even the luminous intensity to the interior of a building may be controlled by double facades. Solar chimneys are passive devices that may fit the construction, but they must be installed properly so that solar radiation should impinge the absorber plate without any shade in order to produce enough natural ventilation (6).

1.1.1. Wind Towers

The wind tower provides natural ventilation by taking advantage of the pressure differences surrounding the building. Therefore, the device must be placed to maximize the pressure differential between the inlet and outlet. The primary driving force for the wind tower is the external driving wind. Positive pressure on the windward side drives the fresh air into the room, and the negative pressure on the leeward side extracts the stale and warm air. A slight change in air pressure can create sufficient airflow to improve the thermal comfort of the inhabitants. The wind changes direction over an evident range on an hourly, daily, and seasonal basis. Thus, the pressure field surrounding a building will also change accordingly. A wind tower inlet opening can change from positive to negative pressure from one day to the next. In this case, the gap will function as an exhaust vent. The function of a ventilation device varies continuously throughout the day. During the daytime, the operation of a wind tower is dependent upon the wind movement due to the pressure difference across the inlet and outlet as shown in **Fig I. 2**. The wind tower catches the prevailing wind and leads the air downwards at higher velocity. During the nighttime, the lower external air temperature cools the building mass, which provides additional cooling the next day (8).

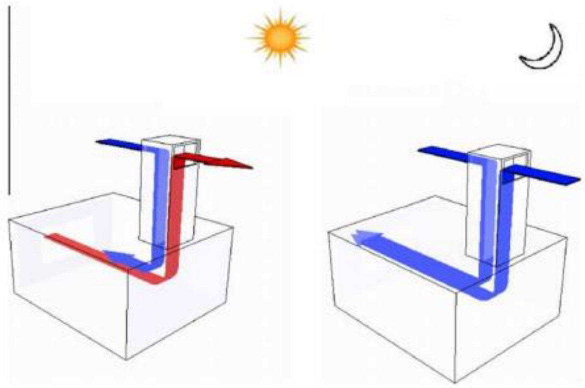


Fig I. 2: Function of a wind tower during daytime and nighttime (8).

1.1.2. Double skin facade

Double-skin is an uncommon type of wrapped wall, where a second skin, usually a transparent glazing, is placed in front of a building. The air space in between, called the channel, can be rather important (up to 0.8–1.0 m). Generally, the channel is aerated naturally, mechanically, or using a hybrid system to diminish overheating problems in summer and contribute to energy savings in winter (9). Double skin facade systems are employed increasingly in high-profile buildings, designed by famous Architects, using acclaimed engineering consultants, and approved as an ideal ‘green’ building strategy. It is a new technology that’s often found in high-end European and Pacific Rim Architecture and far less often in North American buildings. For the majority of mainstream architects, double-skin technology remains elusive. From standpoint of both knowledge and budget, double skin systems are often beyond the scope of most commercially driven North American projects. The Double Skin Facade is based on an idea of exterior walls that respond dynamically to varying ambient circumstances and can incorporate a range of integrated sun-shading, natural ventilation, and thermal insulation devices or strategies. Only recently has double skin technology become analogous with explorations in transparent and glass Architecture and acclaimed as an environmentally “responsible” design (10).

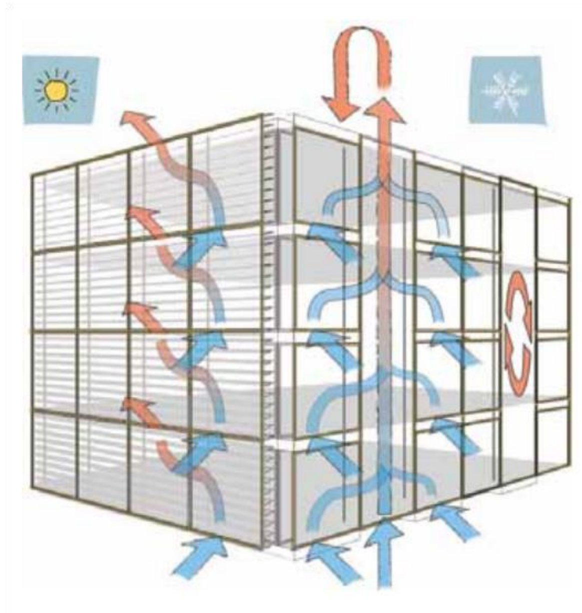


Fig I. 3: Double skin facade system functioning during summer and winter (11).

1.1.3. Ground coupled heat exchanger (earth-air heat exchanger)

Earth-to-air heat exchangers are pipes located underground through which draw out ventilated air. At a sufficient depth, the ground temperature is sufficiently low to cool down the ventilation air in contact with the tube in the ground (12). The use of such a system predicts to reduce the consumption of electrical energy (13).

a. Function principle of an EAHE

The objective of using ground inertia for heating and cooling is not a new concept but rather a modified concept that goes back to the Ancients. This technology has been used from the ancient Greeks and Persians in the pre-Christian era until recent history (Santamouris and Asimakopoulos, 1996). It consists of a ground-buried pipe. During the summer, the air inside the buried tube is used for cooling outside buildings or storage systems. But in winter, the air inside the buried pipes is used for heating the exterior room, as shown in **Fig I. 4.**

The effective parameters of an EAHE are (13) :

D = Pipe diameter

L= Pipe Length

Np = Total number of pipes

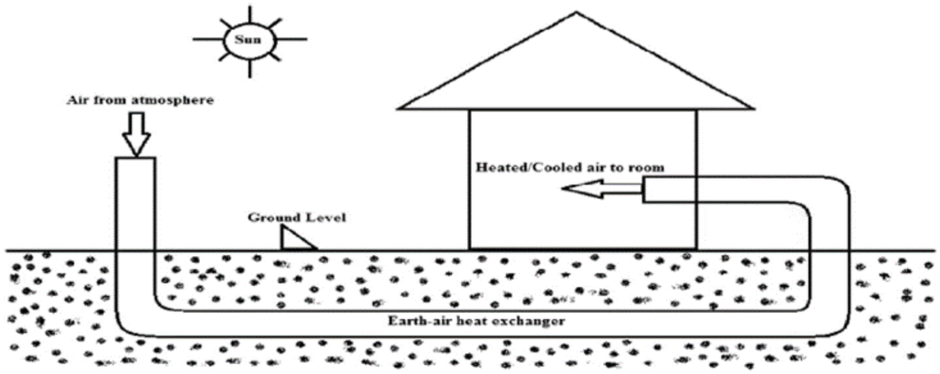


Fig I. 4: Function principle of EAHE (14).

b. Types of EAHE

The types of EAHE can be differentiated in two ways: by the loop types of the air movement inside the building or by the underground loop types.

Open loop: In an open loop, intake air comes through the inlet constantly; and passes through the tubes buried underground into the room to cool or heat a space and moves out through ventilation (**Fig I. 5**) (15).

Closed loop: The air is distributed frequently into the room through the underground pipe, no air exchanges with the outdoor air in this system. It is considered more viable than the open loop since the cooled/warm air is redistributed inside the buried pipes. As a result, the closed loop can reduce the pipe length used in the EAHE (**Fig I. 5**) (15).

The materials used for the loops are extraordinarily durable, which allows heat to transfer to the surroundings efficiently. The loop length depends on some crucial factors; loop configuration type, cooling and heating loads, soil conditions, and local climate (15).

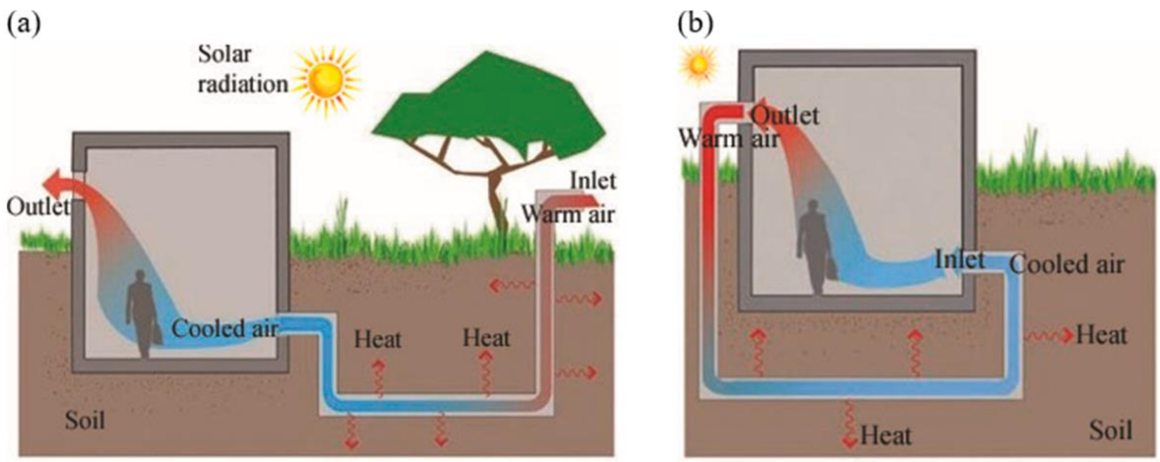


Fig I. 5: (a) EAHE with open loop, (b) EAHE with closed loop (15).

The underground loops can be set up in a vertical, horizontal, slinky, or pond loop as shown in **Fig I. 6.** The vertical configuration is more effective when there is limited space available; the horizontal loop is used when there is more free space, and soil conductivity and water holding capacity are significant, whereas the pond loop configuration gives the added advantage of extracting heat faster from the heated liquid (16).

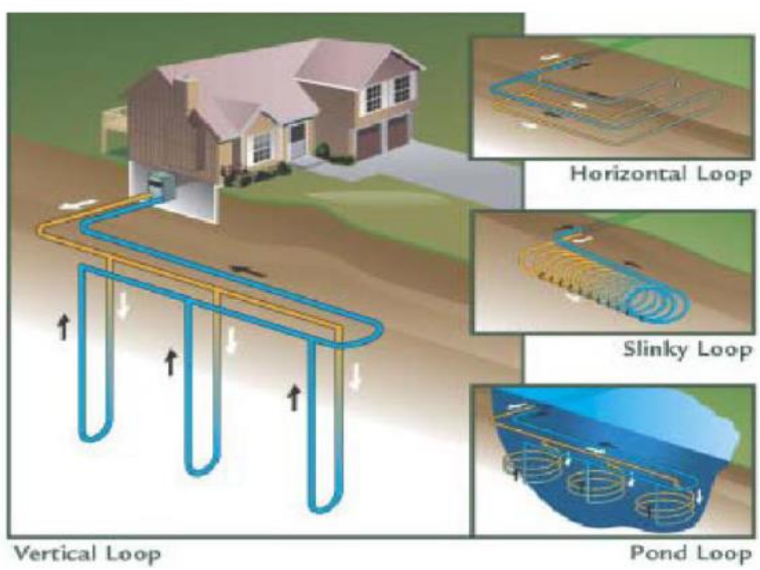


Fig I. 6: Underground loop types (16).

2. Passive cooling systems

Passive cooling uses free, renewable sources of energy such as the sun and wind to provide cooling, ventilation, and lighting needs. Also, it removes the need to use mechanical cooling. Applying passive cooling means reducing differences between outdoor and indoor temperatures, improving indoor air quality, and making the building both a better and more comfortable environment to live or work in. It can also reduce levels of energy use and environmental impacts such as greenhouse gas emissions. Interest in passive design for heating or cooling has grown recently – particularly in the last decade – as a part of a movement toward sustainable architecture. Well-designed envelopes maximize the cooling movement of air and exclude the sun in the summer season. Many passive cooling strategies are suggested for use in a hot arid climate (17).

2.1. Green roofing cooling system

Green roofs can offer a sustainable green surface by improving urban climate, minimizing heat island effects, and protecting biodiversity at once. Many studies have demonstrated that a green roof can reduce energy consumption by lowering thermal absorption and improving the internal comfort of buildings. By providing large surfaces with vegetation, they contribute to the boost of the thermal performance of buildings. Several properties of green roofs contribute to their thermal characteristics; direct shading of the roof, evaporative cooling from the plants and the growing medium, additional insulation values from both the plants and the growing medium, and the thermal mass effects of the growing medium. Differences in these factors have major effects on the roof's performance. A group of researchers from Japan has conducted field measurements of a roof lawn garden planted on nonwoven fabric on an actual three-story pre-cast reinforced concrete building. The measurements confirmed that the amount of heat coming into the room during summer was reduced by a roof lawn garden (18) see **Fig I.7**.

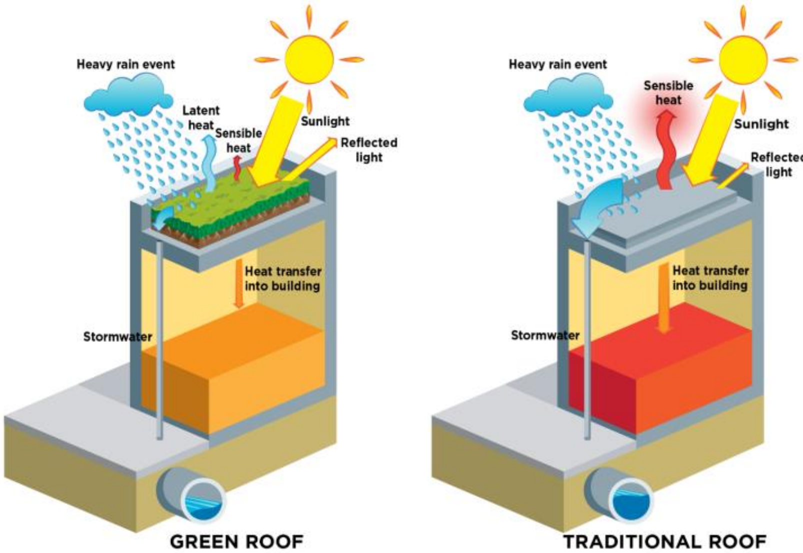


Fig I. 7: Heat exchange and water runoff of a green roof versus a traditional roof (19).

2.2. Evaporative cooling system

Evaporative cooling is a passive cooling technique in which outdoor air is cooled by evaporating water before it is injected into the building. Its physical principle lays in the fact that the heat of air is used to evaporate water, thus cooling the air, which in turn cools the living space in the building. However, passive evaporative cooling can also be indirect. The roof is cooled with a pond, wetted pads, or spray; and the ceiling is transformed into a cooling element that cools the space below by convection and radiation without raising the indoor humidity (20).

2.2.1. Function principle of evaporative cooling system

In an evaporative cooling system, hot outside air is forced through wet cooling pads by means of a motor-driven fan. The cooling pads are moistened continuously by a water pump that delivers water to the cooling pads. The cooled down air is then blown into the building. The outcoming air can then be cooled down between 60 and 90 % of the wet-bulb depending on the effectiveness of the evaporative media. The outcoming air is cooled down 10 to 15 °C but contains a high amount of humidity. Two-stage evaporative cooling, on the other hand, produces efficiencies up to 114% of the wet bulb, resulting in temperatures up to 7 °C lower, and due to the lower temperature, it contains 60% less humidity than direct evaporative cooling processes (3).

2.2.2. Types of evaporative cooling systems

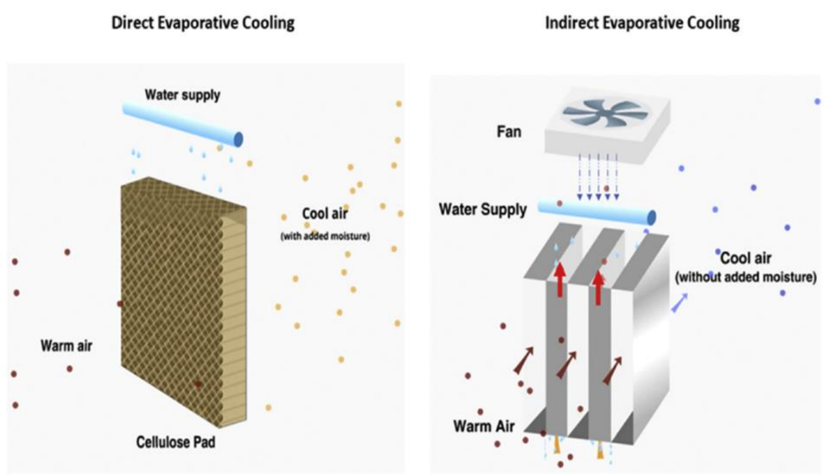
a. Direct evaporative cooling system (DEC)

Direct evaporative cooling (DEC), the easiest and oldest type of cooling, can provide comfortable conditions in hot and dry regions. This system has been operated successfully in various situations related to humans, such as residential and commercial buildings, for cooling and/or humidification control of the internal environment. Moreover, DEC can be used in other places that are not directly related to humans, like greenhouses, poultries, animal husbandries, vegetable stores, and fruit storage. However, the main application of evaporative cooling units is for air conditioning purposes. The evaporative cooler uses only water as cooling fluid rather than chemical refrigerants. DEC system has not had the same effect in cooling all types of buildings. Without considering architectural and psychological factors and with equal air velocities and human activities, the usages of DEC systems depend completely upon wet bulb temperature (4).

In the DEC system, the product air comes in direct contact with water to facilitate latent heat of vaporization. Hence, the evaporation of water lowers the air temperature. This system's effectiveness is very high but accompanied by increased humidity to yield possible thermal discomfort for occupants (21) see **Fig I.8**.

b. Indirect evaporative cooling system (IEC)

In an indirect evaporative cooling system, the air is cooled without introducing moisture content. In IEC, there are two separate channels for primary and working air. The initial air in the dry channel is sensibly cooled by the working air, which is cooled by the evaporated water in the wet channel. The working principle of the wet channel is similar to DEC where the working air is in direct contact with water. Without moisture exchange between these two channels, the humidity of primary air doesn't change. The limit of cooling the primary air is the wet bulb temperature of the inlet ambient air but typically reaches 50 – 80% of wet bulb efficacity (21) see **Fig I.8**.



(a) (b)

Fig I. 8: Direct (a) and Indirect (b) evaporative cooler (21).

2.2.3. Advantages and disadvantages of evaporative cooling system

a. Advantages:

- Energy efficient.
- Low installation and maintenance costs.
- Ideal choice for dry climates.
- Filters air effectively.
- Eco friendly.

b. Disadvantages:

- Drawbacks due to high humidity.
- Although an evaporative cooler requires minimal maintenance, there can be a buildup of salts and mineral deposits if your area has hard water.

Conclusion

This chapter discussed natural ventilation and its systems in addition to passive cooling systems. As it was shown, there is a variety of systems, the most used ones were: earth-air heat exchanger as a natural ventilation system and evaporative cooler as a passive cooling system. The combination between these two systems allow providing passive ventilation and cooling resulting thermal comfort to buildings. The next chapter will be devoted to a review of literature.

CHAPTER II:

Literature review

Introduction

According to what we mentioned in the first chapter, the earth-air heat exchanger system has the principle of cooling and heating, while the direct evaporator system works only on a cooling basis.

In this chapter, we will present a literature review of most of the latest researches on the EAHE and the DEC systems and their hybridization to give a general view of the technology of these systems.

1. Literature reviews

A research paper where **V. Bansal et al (22)** did a theoretical study of performance enhancement of earth air tunnel heat exchangers using evaporative cooling. It aimed to develop a thermal model to investigate the potential of using the storage capacity of the ground for cooling with the help of earth to air heat exchanger (EAHE) system integrated with an evaporative cooler. Parametric studies performed for this study illustrate the effects of buried pipe length, pipe diameter, the volumetric flow rate of air, number of pipes, and the results of the EAHE coupled with and without evaporative cooling are compared for different S/V ratio and bypass factor for predicting the temperature at the outlet of EAHE. Results showed that the length of the EAHE pipe is reduced significantly as much for obtaining desired temperature at the outlet of the EAHE by the integration of evaporative cooling with EAHE, and a reduction in the length of buried pipe is also noted with a decrease in bypass factor of evaporator cooler.

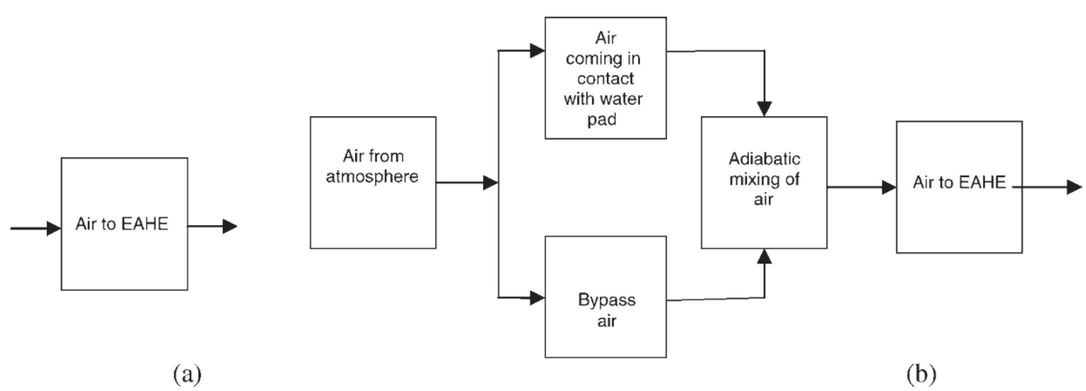


Fig II. 1: Schematic diagram of (a) EAHE without evaporative cooling. (b) EAHE with evaporative cooling.

Again, in India, **V. Bansal et al (23),** did a performance evaluation and analyzed the economic results of an integrated earth-air-tunnel heat exchanger to an evaporative cooling system to enhance the thermal comfort hours in summer conditions. The economics of this integrated system was analyzed by evaluating the internal rate of return (IRR) on investment. To estimate the energy savings obtained by using the EATHE system integrated into an evaporative cooler, they used a transient and implicit model based on computational fluid dynamics, they considered a few base cases of existing systems to carry out the economics analysis, in addition to three different types of blowers to evaluate the energy saving and financial viability of the system. The evaluation results of IRR showed that the replacement of the existing air conditioner and heaters with the proposed EATHE system is not a technically and economically viable option, they also noticed that the IRR value depends on the electric tariff and the energy efficiency of the blower type used in the EATHE system.

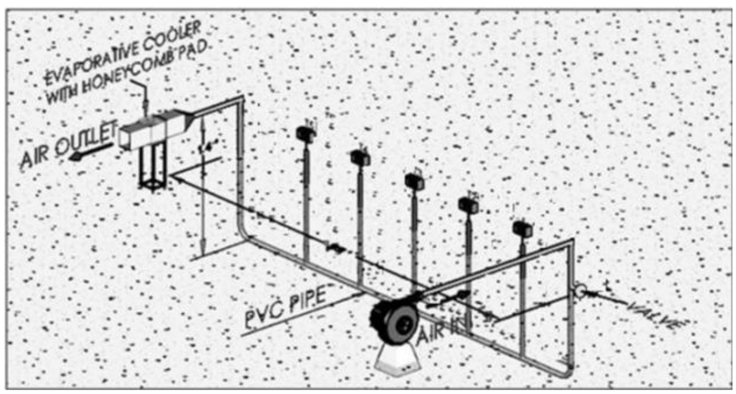


Fig II. 2: Experimental set-up of integrated EATHE–evaporative cooling system.

A research paper contained an experimental and numerical study of an Earth-to-Air Heat Exchanger (EAHE) for air cooling, have been done by **M. Khabbaz et al (24)**, the system is connected to a residential building located in Marrakech whose climate is a hot semi-arid one, it aimed to consists of summer monitoring of the EAHE via measurements of air temperature and humidity throughout the exchanger, as well as at its inlet and outlet to the building for two fixed values of the airflow rate. The results showed that the EAHE is a good semi-passive system for air refreshment; as the recorded blown air temperature into the building is quasi-constant although the outside temperature is high, and the reduction of daily and annual air temperature amplitudes is characterized by an exponential drop as a function of pipe length.

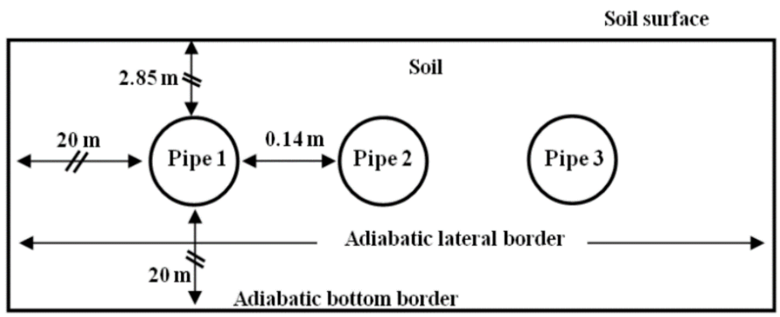


Fig II. 3: Schematic diagram of the physical model of the EAHE.

In this research paper **D. Belatreche et al (25),** did a theoretical study of an earth air heat exchanger (EAHE) employed as an air-conditioning device for buildings in the climate conditions of the south of Algeria. It aimed to present the modeling and simulation of the earth tubes buried in the ground. The appropriate depth of the buried pipes was calculated considering the physical properties of the soil in the region under study and a parametric analysis was carried out considering the length and the radius of the pipe and the velocity of the air in the pipes. The results showed that a simple EAHE system can provide 246.815 kWh in one year.

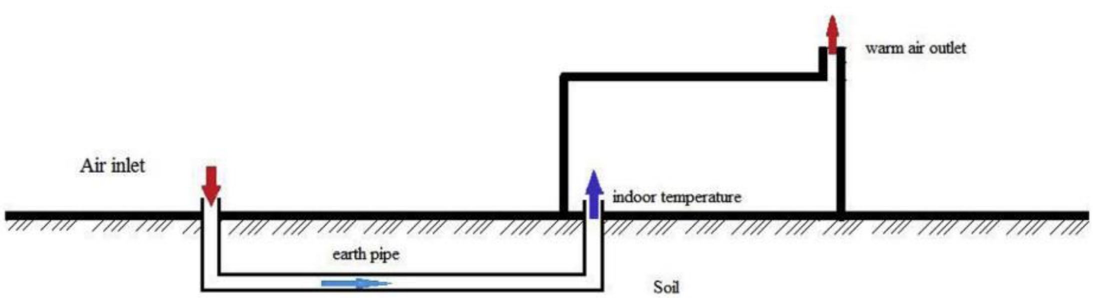


Fig II. 4: Schematic diagram of a passive air-conditioning system using earth air heat exchanger.

Another study where **Y. Belloufi et al (26),** did a numerical and experimental investigation on the transient behavior of an earth air heat exchanger in continuous operation mode. This study focused on investigation of the thermal performances of an earth air heat exchanger (EAHE) under transient conditions in cooling mode. Hence, a PVC pipe of a 53.16 (m) length and 110 (mm) diameter is buried at 3 (m) depth and used to do the experimental test that were carried out in non-stop operation of 71 (h) duration with high inlet temperatures. In addition to that, the performances of the EAHE were also studied numerically. It was determined that the operation duration doesn't affect the outlet air temperature in a remarkable way and also the EAHE performances. Furthermore, there was a good qualitative and quantitative agreement between the experimental and numerical results.

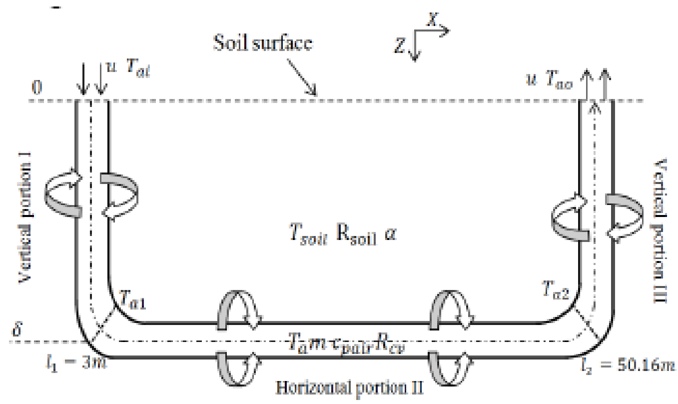


Fig II. 5: Descriptive scheme of EAHE.

This study paper where **S. Ahmadi et al (27),** did a cooling performance analysis of an integrated cooling system consisting of the earth-to-air heat exchanger EAHE and water spray channel to provide thermal comfort in the summer season in Tehran, Iran. The function principle of this system consists of cooling the inlet air temperature by passing through the EAHE and dissipating its heat to the soil. Then, the cooled air flows through a channel misting water and entering the living room. The results showed that this system meets the thermal comfort conditions in the summer season in Tehran, in addition to its high cooling effectiveness and its capability to decrease the ambient air temperature below the inlet ambient temperature of adiabatic saturation. The proposed hybrid system is considered an eco-friendly and energy-efficient system while it can be used as an alternative to conventional evaporative coolers or mechanical vapor compression systems.

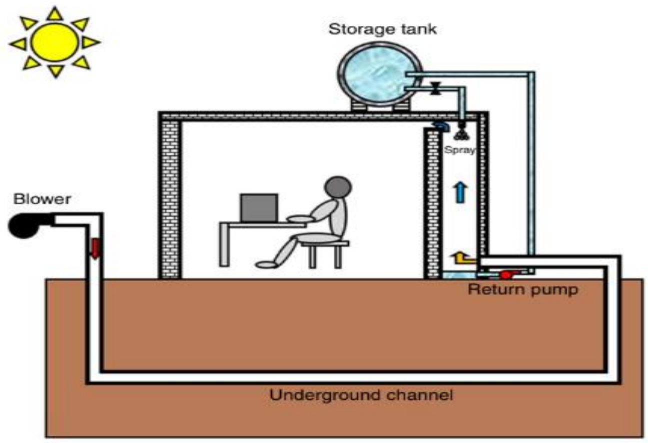


Fig II. 6: Schematic view of two-stage cooling system consisting of an earth-to-air heat exchanger (EAHE) and water spray channel.

Another research paper where **A. Abdelazeem et al (28),** did a theoretical study and analysis of indirect evaporative cooler performance under various heat and mass exchanger dimensions and flow parameters. It aimed to develop a mathematical model based on heat and mass transfer concepts, a developed mathematical model was verified using experimental and simulation results from recently published papers. The results were performed based on different operating and structural conditions affecting the outlet air temperature, cooling capacity, coefficient of performance, and wet-bulb efficiency. Results showed that the optimal dimensions that give good efficiency in climates with moderate humidity, such as for increasing the product air velocity, reduce the heat exchange period, which is undesirable, this analysis provides desirable operating conditions to achieve high operational efficiency as well as optimal dimensions for designing such a cooler.

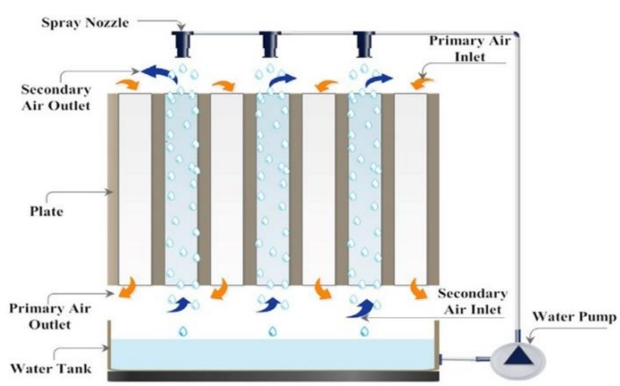


Fig II. 7: Scheme of the counter-flow indirect evaporative cooling system.

In a journal article where **N R. Shingala et al (14),** using Ansys 19.2 did a CFD analysis, which is the analysis of fluid flows using numerical solution techniques, to an earth air heat exchanger EAHE for storage system using an evaporative cooling system. The CFD analysis gave more effectiveness to assess mathematical and simulation data. They found that there was a remarkable accord between the experimental and simulation results of the EAHE system modeling with a deviation of 5 °C difference maximum. They also found that there is an inverse proportion between the rise of air temperature and the flow velocity. They brought this analysis to an end saying that the EAHE system is not affected by the disposition of the underground pipes and concluded from the CFD analysis of the EAHE is affected by the ambient conditions.

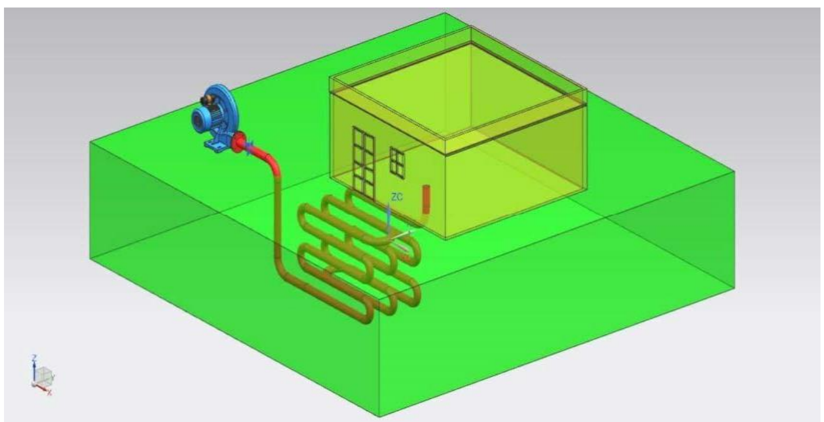


Fig II. 8: 3D diagram of EAHE.

A research paper containing a theoretical study of the efficiency and water consumption of a hybrid system combining an indirect evaporative cooler and an earth-air heat exchanger is presented by **N. Nemati et al (29)**. It aimed to study the performance evaluation of this innovative hybrid system. A developed numerical model was used to simulate the cooling performance of the indirect evaporative cooler and the earth-air heat exchanger systems using available data. Results showed that combining the earth-air heat exchanger with the indirect evaporative cooler led to an improvement in cooling performance and to a decrease in energy and water consumption in addition to the maintenance of the wanted thermal comfort level in the building.

Process 1-2: The ambient air temperature drops after passing through the buried pipe due to heat exchanging with the surrounding soil. Then, the outlet air from the earth-air heat exchanger enters the dry channels of the indirect evaporative cooler.

Process 2-3: The primary air temperature decreases without adding moisture, and then the product air enters the indoor space to provide comfortable conditions. On the other side, in a converse direction, the secondary air flows in the wet channels.

Process 4-1: the air with ambient temperature enters secondary (wet) channels and gets moisture from the hydrophilic walls of wet channels, which results in removing heat from the primary air in the dry canal.

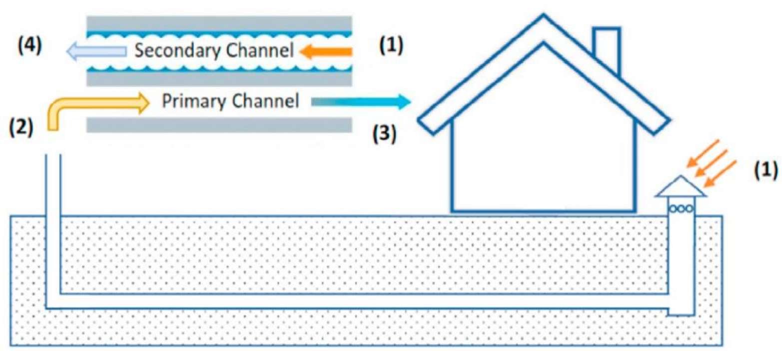


Fig II. 9: Hybrid system combining an earth-air heat exchanger and indirect evaporative cooler.

SF. Ahmed et al (15) This research paper contained a theoretical study of physical and hybrid modeling techniques for earth-air heat exchangers in reducing building energy consumption. It aimed to review the published research associated with the physical, and hybrid EAHE modeling techniques used in buildings, and highlight the prospects, benefits, progress, and challenges of these techniques. The results showed that hybrid modeling is more effective than physical models for accurate prediction. On the contrary, the hybrid models suffer from high complexity if EAHE operating conditions and all basic parameters are taken into consideration during the model development. They also provide valuable information regarding the physical and hybrid EAHE modeling techniques to the scientists, researchers, and so on adopting the most appropriate EAHE modeling technique for their climates.

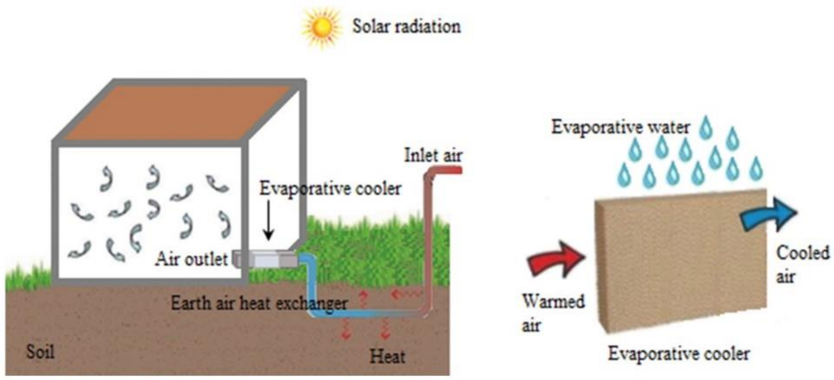


Fig II. 10: Schematic diagram of EAHE - Evaporative cooling process.

Conclusion

This chapter showed that many of the design techniques of the earth-air heat exchanger system operate in a cooling/heating manner. Hence, the evaporator system runs only in a cooling mode.

According to the literature review presented, it is noticed that the performance of EAHE system depends mainly on climatic conditions whereas the performance of the DEC system is generally affected by the pad thickness and the frontal air velocity.

CHAPTER III:

Experimental setup and mathematical formulation

Introduction:

This chapter is about a study that consists of a hybrid cooling system composed of a Direct Evaporative Cooler (DEC) and an Earth-Air Heat Exchanger (EAHE). An experimental setup was realized of a DEC attached to a 1 (m^3) room, it analyzed the inlet and outlet temperature of the DEC, exterior and interior relative humidity, and wet bulb temperature. Therefore, both systems (DEC & EAHE) were studied numerically using two numerical codes that were developed using Matlab software. The aim is to achieve thermal comfort inside the room and then apply the obtained results to residential buildings.

1. System description

A schematic design of the proposed system is shown in **Fig III.1** which is composed of a direct evaporative cooler (DEC) coupled with an earth-air heat exchanger and examined in this study. As it can be observed in the figure below, the air in ambient temperature enters the EAHE, and as it passes through, a heat transfer process occurs due to the temperature difference between the air inside the pipe and the surrounding soil which results in the airflow pre-cooling. After this, the pre-cooled air enters the direct evaporative cooler and passes through the wetted cooling pads inserted in the DEC and kept moist by continuously dripping water onto their upper edges. By exchanging heat and mass between the pre-cooled air and the wetted pads, the air temperature drops again while its relative humidity increases. After this process of evaporation, the cooled air enters the room. The water that wets the pads in the DEC is circulating in a closed loop, the water tank is assumed insulated and the heat transfer between it and the surrounding environment is negligible.

The present study analyzes the performance and feasibility of the proposed hybrid cooling system to prove that it can provide indoor thermal comfort.

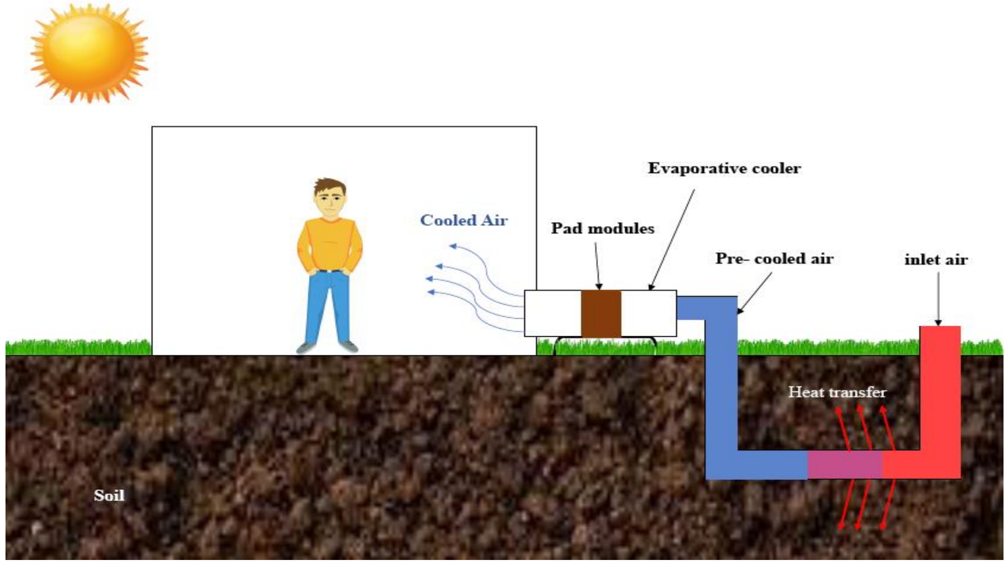


Fig III. 1: 2D scheme of the EAHE-DEC system.

2. Experimental setup description

An experimental setup was realized in the renewable energies laboratory number 15 at Kasdi Merbah University in Ouargla to carry on our study and experiments.

This experimental setup consists of a rectangular plexiglass channel with a square-cross section of area 0.09 (m^2) and a total length of 0.8 (m). A polystyrene layer of 20 (mm) thickness is used as insulation to reduce heat loss to the exterior.

Fig III. 2: 3D and real picture of the DEC system realized at Ouargla University.

The pad modules used in this study are placed at 45 (cm) from the inlet of the DEC channel, and they are made up of layers of date palm fibers, jute cloth, and cotton and different thicknesses of 15, 30, and 45 (mm); to achieve the 45 (mm) thickness, one of each pad of 15 and 30 (mm) thicknesses is inserted; with dimensions of 0.26 × 0.17 (m). The main reason for the choice of the materials mentioned above is that they are local natural fibers, also for their availability and durability, and recyclability, in addition to their significant water absorption and their strong water retention capacity, and finally their low price.

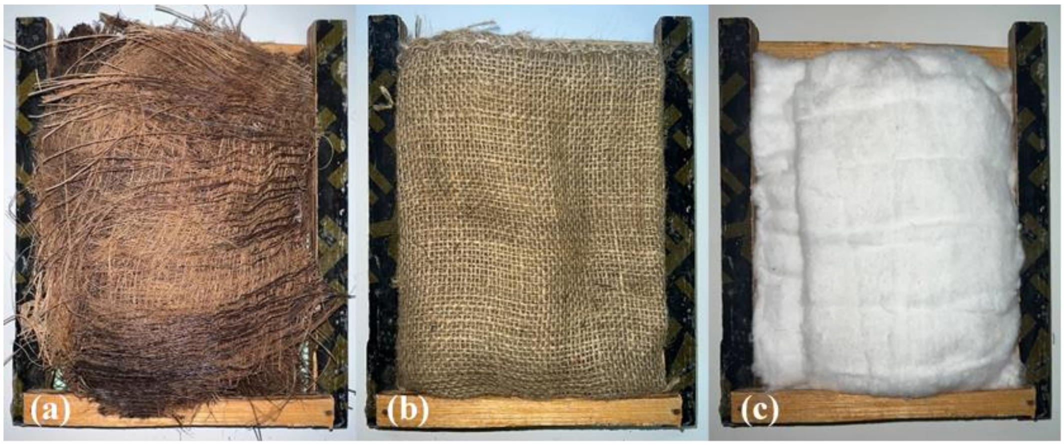
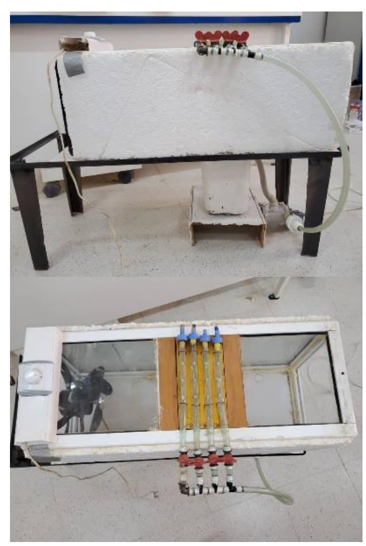


Fig III. 3: Used materials in the pad modules: (a) date palm fibers, (b) jute cloth, and (c) cotton.

3. Measuring instruments

Table III. 1: Technical specifications of the used elements and measuring instruments.

Element	Technical specifications	Picture
Direct Evaporative Cooler - DEC	Configuration: Horizontal rectangular tunnel. Tunnel material: Plexiglass (0.004 m thickness). Polystyrene (0.02 m thickness). Length of the rectangular tunnel: 0.8 (m). Width of the rectangular tunnel: 0.3 (m).	

	Height of rectangular tunnel: 0.3(m)	
Ventilator (air extraction)	Model: L300. Voltage: 220 (V). Power: 130 (W). Rotation speed: 1400 (r/min). Frequency: 50 (Hz). Dimensions: 0.3×0.3 (m^2).	
Water pump	Brand: HANYU. Model: B20-6. Voltage: 220 – 240 (V). Power: 30 (W). Frequency: 50 (Hz). Volumetric flow rate: 17 (L/min). Dimensions: 0.17×0.06×0.08 (m^3).	
Digital temperature panel (NTC) - (to obtain water temperature)	Brand: Eko. Model: TP3. Voltage: 220 (V). Power: ˂ 3 (W). Measuring range: -40 ~ 110 (°C). Accuracy: ±1(°C).	
Digital thermometer-hygrometer panel (to measure air relative humidity)	Brand: Elenxs. Model: GJ0596-01B-XY-5.3. Temperature range: -40 ~ 70(°C). Humidity range: 10% RH ~ 95% RH.	

	Humidity accuracy: ±2.5%.	
Resistance thermometer (to measure inlet and outlet DEC air temperatures)	Brand: Omega. Model: RDXL4SD. Resistance: 100 (Ω). Temperature range: -200 ~ 850(°C).	
Type K thermocouple	Temperature range: -200 ~ 1260 (°C).	
Anemometer (to measure airflow velocity)	Brand: UNI-T. Model: UT363. Wind speed: 0 ~30 (m/s). Resolution: 0.1 (m/s). Dimensions: 0.16×0.05×0.028 (m^3).	

4. Mathematical modeling of the DEC

The following mathematical model focuses on the heat and mass transfer of the DEC in which the cooling pads are made of local natural fibers. To clarify the heat and mass transfer process, the following hypothesis were taken into consideration:

1. The pad material is fully and continuously wetted.
2. The convective heat transfer (h_c) of moisture air on the surface of the water film is constant.
3. The thermal properties of water and air are constant.

4. The temperature of the water-air interface is assumed to be uniform and constant.
5. The surrounding heat flux transfers are neglected.
6. The air near the water-air interface is saturated, its temperature is assumed to be equal to that of the dripped water.
7. The air temperature changes only in the flow direction denoted by x.

4.1. Equations

4.1.1. Changes in air temperature equation:

The following equation presents the equation of air temperature changes **(Wu, J.M et al (30)):**

$$T_a = T_s + (T_1 - T_w) \, . \exp\left(- \frac{h_c \, .\xi \, .B \, .H \, .x}{G_a \, .C_p}\right) \quad \text{(Eq III.1)}$$

Where T_s is the air wet bulb temperature in (°C);

T_1 is the entering air dry bulb temperature, $Ta = T_1$ at $x = 0$;

T_w is the water film temperature in (°C), in our study the water film temperature T_w is considered approximately equal to T_s;

B & H are the width and length of the used pad module in (m), ξ is the pore surface coefficient in (m^2/m^3);

C_p is the specific heat of the air in (J/Kg.K);

h_c is the convective heat transfer coefficient in ($W/m^2.K$), and it is calculated as follows:

$$h_c = \frac{Nu \times \lambda}{\delta}; \quad \text{(Eq III.2)}$$

Nusselt number:

$$Nu = 0.1 \times Re^{0.8} \times Pr^{\frac{1}{3}}; \quad \text{(Eq III.3)}$$

Reynolds number:

$$\mathrm{Re} = \frac{\rho \times V \times D_h}{\mu}; \quad \text{(Eq III.4)}$$

Prandtl number:

$$Pr = \frac{C_P \times \mu}{\lambda};$$ (Eq III.5)

G_a is the air mass flow rate in (Kg/s) and it is calculated as follows:

$$G_a = V \times \rho \times B \times H;$$ (Eq III.6)

4.1.2. Changes in humidity ratio of moisture air equation:

The equation below defines humidity ratio of moisture air:

$$f_a = f_s - \frac{C_p}{r} . (T_1 - T_s) . \exp\left(- \frac{h_c .\xi .B .H .x}{G_a .C_p}\right)$$ (Eq III.7)

Where f_a is the air humidity ratio, f_s is the saturated air humidity ratio and r is the latent heat of water vaporization.

4.1.3. Cooling efficiency equation:

$$\eta = \frac{T_1 - T_2}{T_1 - T_s} \times 100\%;$$ (Eq III.8)

Where T_2 is the leaving air dry bulb temperature.

5. Mathematical modelling of the Earth Air Heat Exchanger

5.1. Estimation of air temperature

According to the assumptions mentioned below, the EAHE modelling was constructed as follows:

1. Thermo physical properties of air are constants;
2. Air flow is uniform along the length of the buried pipes;
3. The air flow is considered one-dimensional;
4. Soil around the heat exchanger is homogenous;
5. Soil properties are isotropic and there is a perfect contact between the soil and the pipe;
6. The pipe and the soil are assumed to be subdivided into many layers of length (Δx) arranged in series;
7. In each layer, the heat flux between air and soil is assumed to be constant for the full current time step.

For a j^th^ layer, the energy balance is written by the following relation:

$$\dot{m}_a\, Cp_a\, \frac{dT_a}{dx} = -\frac{(T_a - T_s)}{R_{tot}} \qquad \text{(Eq III.9)}$$

Where: T_a, Cp_a and $\dot{m}_a$ are respectively the air temperature, air specific heat and air mass flow rate.

R_{tot} is he sum of the thermal resistances of air: R_{cv}, pipe resistance R_p, and R_s of the disturbed soil surrounding the j^{th} layer.

The air outlet temperature of the j^{th} layer is given by solving analytically the differential Eq III.10 as follows:

$$T_{a(j)}^{out} = \left(T_{a(j)}^{in} - T_{s0}\right) \exp\left(\frac{-\Delta_x}{R_{tot}\dot{m}_a\, Cp_a}\right) + T_{s0} \qquad \text{(Eq III.10)}$$

After a specified period of time (t_1) has passed, the length of the layer is taken as follows: **Δx = 1 (m).** Then the inlet air temperature is assumed as the outlet air temperature of the layer for the current j^{th} (j-1) layer, and from it write equation Eq III.11 as follows:

$$T_{a(j+1,i)} = \left(T_{a(j,i)} - T_{s0}\right) \exp\left(\frac{-1}{\rho_a Cp_a S V_a R_{tot(j,i)}}\right) + T_{s0} \qquad \text{(Eq III.11)}$$

From the previous equation, it is expressed in stable state by assuming that the thermal properties are fixed for the soil for the full-time step. The calculation of air temperature for the next step of time is also repeated with the new (soil temperature, soil thermal resistance) by using the RBM model.

5.2. Estimation of soil temperature

The total thermal resistance relationship between air, pipes and soil surrounding j^{th} layer of the EAHE is written as follows:

$$R_{tot} = R_{CV} + R_P + R_S \qquad \text{(Eq III.12)}$$

$$R_{CV} = 1/(h_a 2\pi r_{int}) \qquad \text{(Eq III.13)}$$

$$R_p = log(r_e/r_{int}) \Big/ \left(2\pi\gamma_p\right) \qquad \text{(Eq III.14)}$$

$$r_\delta = r_e + \delta \qquad \text{(Eq III.15)}$$

$$\acute{q}_{(j,i)} = \frac{\left(T_{a(j,i)} - T_{s0}\right)}{R_{s(j,i-1)}} \qquad \text{(Eq III.16)}$$

Where $T_{a(j,i)} = T_{a(j-1,i)}^{out}$ (Eq III.17)

$$R_{s(j,i-1)} = \frac{1}{2\pi\lambda_s} \, log\left(\frac{r_{\delta(j,i-1)}}{r_e}\right) \qquad \text{(Eq III.18)}$$

Where r_δ is the soil radius and δ is the disturbed soil thickness.

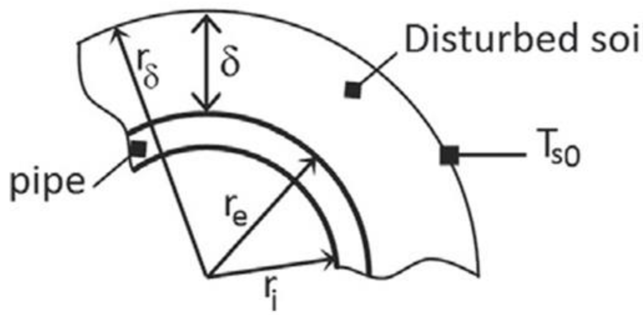


Fig III. 4: Scheme shows the disturbed soil thickness δ, and the soil radius r_δ (31).

Finally, the equation of the transient temperature of the soil surrounding the pipe:

$$T_{s(k,j,i)} - T_{s0} = \frac{\acute{q}_{(j,i)}}{\pi\lambda_s r_\infty^2} \sum_{n=1}^{\infty} \frac{1 - e^{-\alpha_s \beta_n^2 t_i}}{\beta_n^2} \frac{J_0(\beta_n r_k) J_0(\beta_n r_e)}{J_1^2(\beta_n r_\infty)} \qquad \text{(Eq III.19)}$$

6. Organizational chart of the EAHE-DEC model

For a good understanding of the previous calculations, the different steps described previously in the calculations are summarized in the organizational chart presented below in **Fig III.5**.

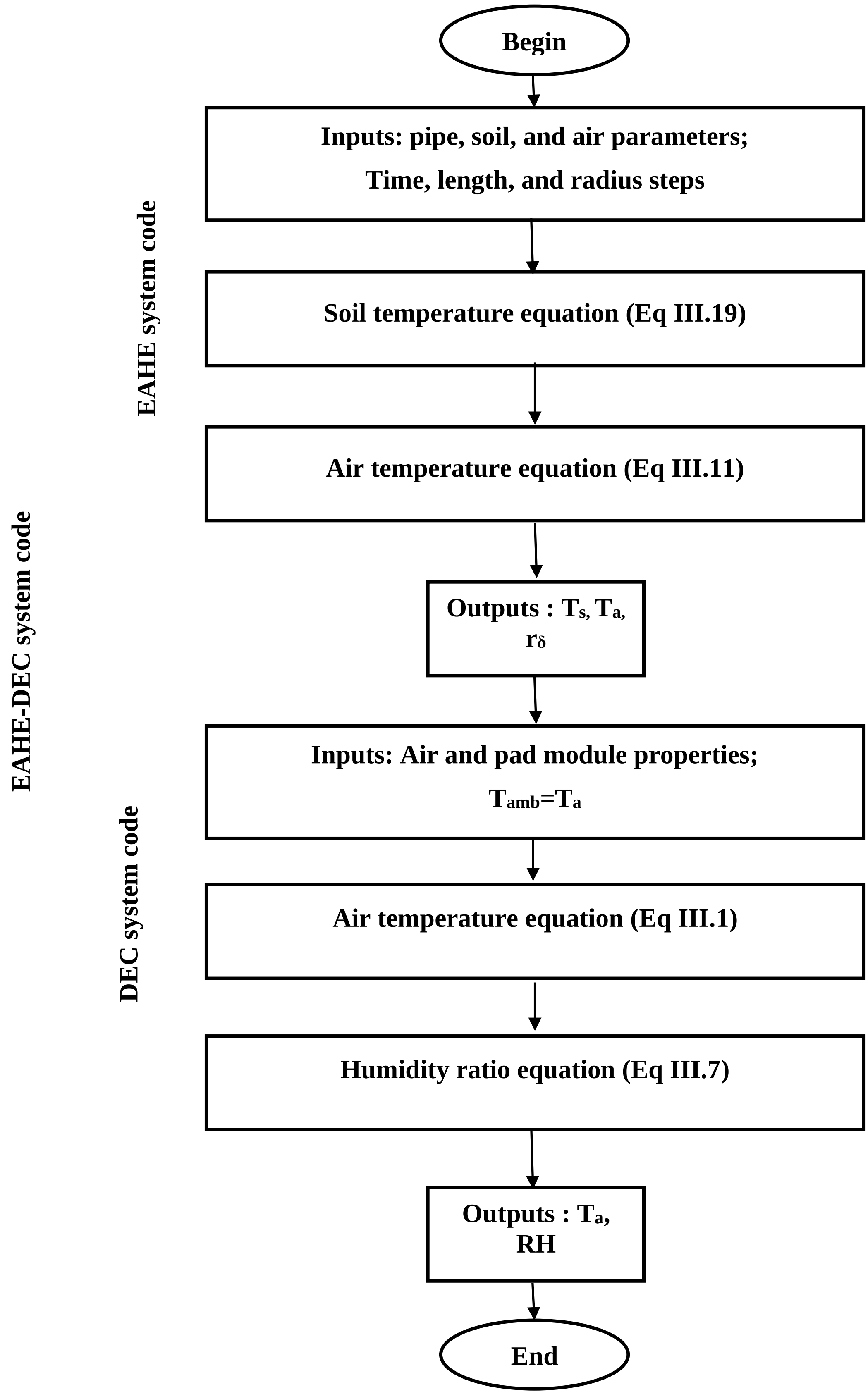


Fig III. 5: Organizational chart of the EAHE-DEC module.

Conclusion

In this chapter, the realized setup of the direct evaporative cooler and its numerical modeling study were presented, as well as a numerical modeling of an earth air heat exchanger. The purpose is to predict the air temperature circulating inside the EAHE pipes, at the same time, the evolution of the soil temperature, as well as the temperature at the outlet of the DEC. Therefore, considering the experiments done and what have been withdrawn from the equations of both systems mentioned above in this chapter, the principal norms to focus on that affect the performances of the proposed hybrid system generally are the outdoor ambient temperature, air velocity, material type used in the pad module, and its thickness, Henceforward, the next chapter will be devoted to analyze and interpret the obtained results from this chapter.

CHAPTER IV:

Results and discussions

Introduction

This chapter presents the obtained results within the framework of this thesis. First, the obtained experimental results of the DEC system integrated into a room of 1 (m^3) volume are presented. Then, as mentioned in the previous chapter, two numerical codes were developed using Matlab software to study both systems in analytical and semi-analytical ways. Finally, a case study is done to test the applicability of the system in the region of Ouargla, Algeria.

1. Numerical models validation

1.1. DEC system model validation

The specific characteristics of the inserted pad module in the experimental setup realized within the frame work of this thesis that were used to achieve our DEC system numerical model validation are shown in **Table IV.1** below.

Table IV. 1: Specific characteristics of pad module.

Parameter	**Value**
Pad length	0.26 (m)
Pad width	0.17 (m)
Pad thickness	0.045 (m)
Air velocity	2 (m/s)

The comparison between the validation model results and the experimental results obtained on April 26th 2023 is shown in **Table IV.2**, the calculated temperatures at the outlet of the DEC system show a good agreement with the experimental outlet temperatures with a 12 % maximum error. Hence, the validity of the developed code of the DEC system and its applicability in more upcoming analysis is confirmed.

Table IV. 2: Experimental parameters.

Time	**T_{in} (°C)**	**T_{out} (°C)**	**T_{out} (numerical model) (°C)**	**T_{water} (°C)**	**Efficiency (%)**	**Relative error (%)**
10:00	34.6	30.2	30.0	28.5	29	-1
10:15	35.4	27.5	30.4	28.7	54	11
10:30	36	29.8	30.5	28.7	43	2
10:45	35.7	28.5	30.6	28.9	49	7
11:00	35.9	29.6	30.8	29.1	43	4
11:15	36.7	27.5	30.9	28.9	60	12
11:30	37.9	27.7	30.9	28.5	65	11
11:45	37.6	28.3	30.8	28.5	57	9
12:00	38.1	27.7	30.6	28	67	10

The columns graph of the cooling efficiency of the DEC system using a pad module of 45 (mm) thickness and an air velocity equal to 2 (m/s) is displayed in **Fig IV.1**. As it can be observed, the efficiency of the DEC system is significantly high with a maximum efficiency of 67%. Thus, this efficiency valor discerns the viability of the system in decreasing the temperature value as well as attaining thermal comfort.

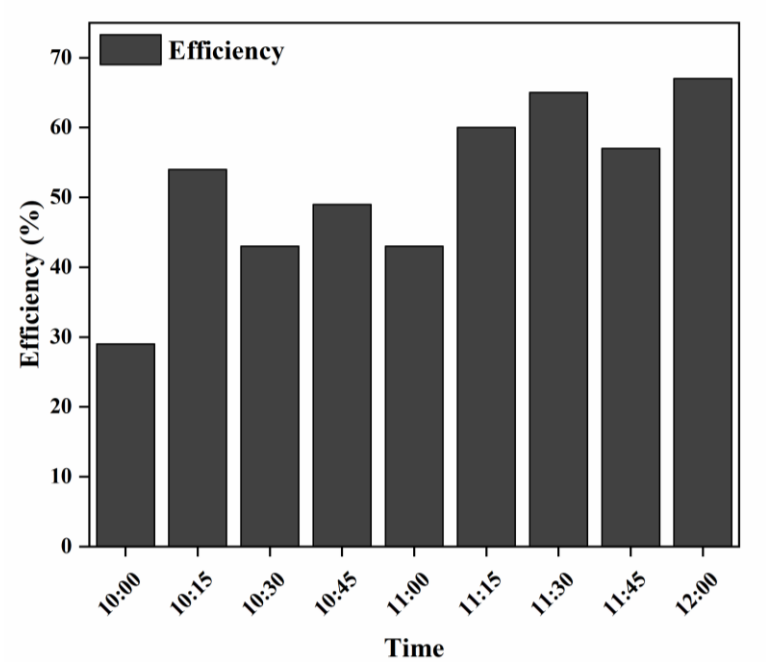


Fig IV. 1: Cooling efficiency of the DEC system.

1.2. EAHE system model verification

To attain the validation of the developed numerical model for the EAHE system, we employed the experimental results realized by **Belloufi et al –** that show the variation of air temperature all along the EAHE. The inlet parameters that were employed to do the comparative validation are mentioned in **Table IV.3** below, whereas the comparison results are displayed as a graph (**Fig IV.2).**

The variation of air temperature all along the EAHE for the experimental results of **Belloufi et al (26)** and the predicted temperatures using our numerical model is shown in **Fig IV.2**. As remarked, there is a good accordance between the obtained results. The maximum relative error is about 1.3% for a 50 (m) pipe length and a 3.5 (m/s) air velocity. The slight difference between the results may be due to personal fallacies during the experimental measurements. Therefore, it can be concluded that the numerical model can correctly predict the thermal performances of an EAHE system and then can be used for further analysis.

Table IV. 3: Inlet parameters of the EAHE.

Parameter	**Value**
T_{in} (°C)	35.98
T_{soil} (°C)	26
Pipe inner radius (m)	0.055
Pipe outer radius (m)	0.0575
Pipe thermal conductivity (λ_{pipe}) (W/m.°C)	0.17
Air velocity (m/s)	3.5
Soil thermal conductivity (λ_{soil}) (W/m.°C)	1.25
Soil density (ρ_{soil}) (kg/m^3)	1800
Soil specific heat capacity (Cp_{soil}) (J/kg.°C)	1340

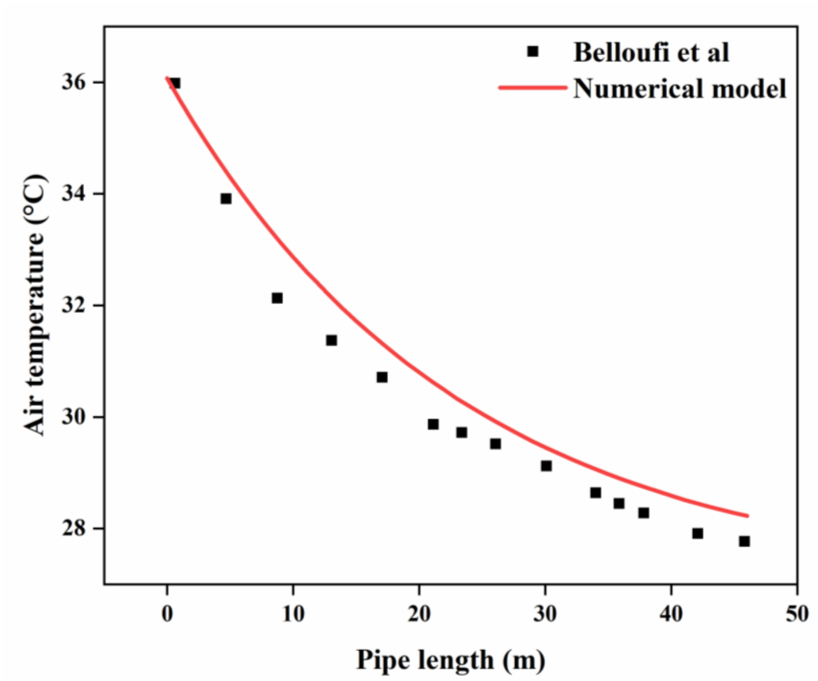


Fig IV. 2: model verification comparison with the work of **Belloufi et al**.

2. Experimental study of the DEC system

2.1. Different materials effect on cooling performances

To study the performance of different materials used in the DEC system, tests on three different natural fibers (date palm fibers, jute cloth, and cotton) are elaborated to choose which one has better efficiency. **Table IV.4** shows the measured parameters and the obtained results for all three materials on March 16th 2023.

Table IV. 4: experimental results for three different materials (cotton, date pam fibers, and jute cloth).

Used material: Cotton							
Time	**T_{in} (°C)**	**T_{water} (°C)**	**RH_{in} (%)**	**T_{wb} (°C)**	**T_{out} (°C)**	**RH_{out} (%)**	**Efficiency (%)**
10:50	25.3	26	21.9	13.7	25.4	25.2	1
11:05	25.7	26	20.4	13.4	25.4	23.9	3
11:20	26.3	26.5	19.8	14.0	26.1	24.4	2
11:35	26.6	25.1	18.4	13.6	26	22.5	5
11:50	27.3	25.8	18.8	14.4	26.8	23.6	4
12:05	28	25.7	18.8	14.1	26.9	21.9	9
12:20	28.9	26.3	18.9	15.4	27.4	26.6	13
12:35	29.4	26.8	18.6	15.5	27.8	25.4	13
12:50	29.8	27	17.6	15.7	28.2	25.1	13
Used material: Date palm fibers							
13:00	30.2	26.4	18.1	16.0	27.7	28.3	21
13:15	30.9	27.1	17.4	16.2	27.7	29.8	28
13:30	31	27.1	16.8	15.8	27.7	27.6	28
13:45	31.1	26.9	16.3	15.6	27.6	26.9	29
14:00	31.5	27.2	15.5	15.8	27.5	28.2	34
14:15	31.9	27.2	16	15.8	27.8	27.2	34

14:30	32	27	15.9	15.5	27.7	26	35
14:45	31.5	27	15.2	15.3	27.9	24.5	29
15:00	29.8	26.9	15.7	14.0	28	18.6	13
Used material: Jute cloth							
15:35	31.3	26.5	15.7	15.5	27.8	25.5	28
15:50	31.7	26.9	15.5	15.3	27.7	25.1	32
16:05	32.5	27.3	14.9	15.2	27.9	23.7	36
16:20	30.7	26.8	15.1	14.1	28	19	19
16:35	31	26.4	15.3	14.6	27.5	22.5	2
16:50	31.3	26.5	14.8	14.1	27.1	21.6	32
17:05	30.4	26.3	15.3	13.8	26.8	21.2	28
17:20	28.1	25.5	16.5	14.1	27.1	21.6	8
17:35	26.7	25.1	17.4	12.8	25	22	14

The underneath **Fig IV.3** shows a comparison of outlet parameters as a function of inlet parameters and the efficiency comparison bars graph. As it can be observed, the highest disparity between the inlet and outlet temperature is 4 degrees using date palm fibers, the same as in the relative humidity graph where the highest disparity is 12,7% using date palm fibers. From the efficiency bars graph, we can clearly see that date palm fibers material has an overpower in terms of bars number with high-efficiency values. In other terms, date palm fibers are a very effective material to be used as wetted pad modules in evaporative cooling because of their great potential and high-water retention.

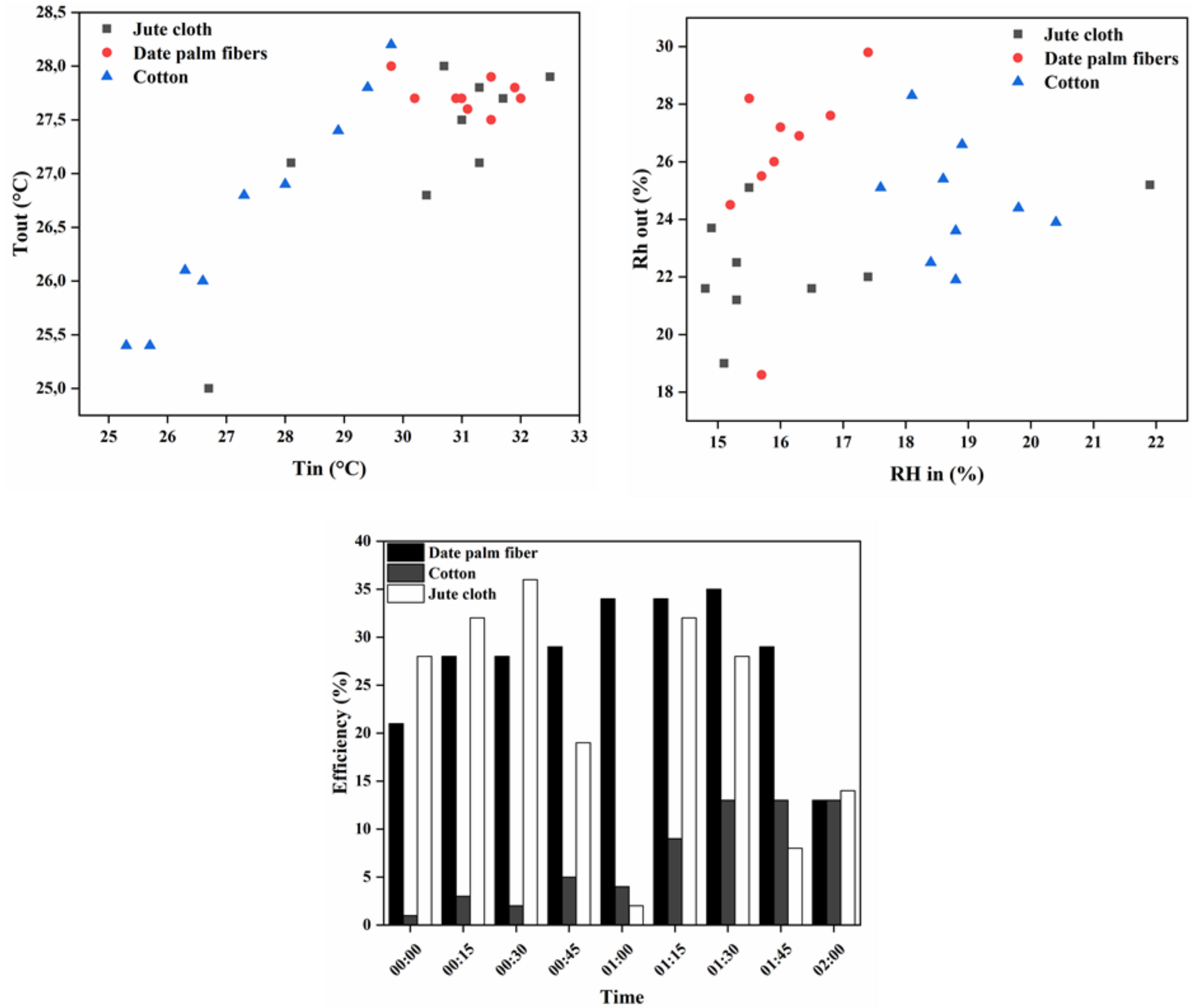


Fig IV. 3: Comparison graphs between three different materials in terms of temperature, relative humidity and efficiency.

2.2. Effect of thickness of pad module on the cooling performance

After studying different materials' performance, it's found that date palm fibers have better performance. In this section, the effect of thickness of the pad module's on the performance of the DEC system is studied. **Table IV.5** below shows the experimental results of three different thicknesses (15, 30, and 45 (mm)) obtained on April 18th 2023.

Table IV. 5: Experimental results of the three different pad module thicknesses.

Thickness: 15 mm							
Time	**T_{in} (°C)**	**T_{water} (°C)**	**RH_{in} (%)**	**T_{wb} (°C)**	**T_{out} (°C)**	**RH_{out} (%)**	**Efficiency (%)**
10:00	28.3	25.8	19.4	13.9	24.1	25	29
10:15	27	25.1	18.6	13.4	24.4	25	19
10:30	26.8	24.9	17.6	13.1	25	24	13
10:45	27	24.6	15.8	12.5	25.3	22	12
11:00	27.2	24.4	15.1	12.1	26.2	21	7
11:15	27.6	24.3	14.6	12.1	26.3	21	8
11:30	28.1	24.2	14.1	12.0	27.1	21	6
11:45	28.5	24.1	14.5	11.7	27.3	20	7
12:00	29.7	23.9	14.2	11.6	28.5	20	7
Thickness: 30 mm							
12:00	29.7	23.9	14.2	11.6	28.5	20	7
12:15	29.6	24.1	15	12.3	27	23	18
12:30	29.9	23.8	15.1	11.9	27.7	22	14
12:45	30.1	23.6	15.9	11.8	28	22	13
13:00	30.5	23.5	15.4	11.7	28.6	22	11
13:15	30.4	23.6	15.2	11.8	28.3	22	13
13:30	30.3	24.1	15.2	11.9	29.1	21	7
13:45	30.6	24.1	15.4	11.9	29	21	9
14:00	30.8	24.3	15.6	12.1	29.1	21	10
Thickness: 45 mm							
14:00	30.9	24.6	15.2	12.5	28.7	22	12
14:15	31.2	24.1	15	12.1	28.9	22	12
14:30	30.9	23.2	15.1	11.3	28.5	21	12
14:45	31.9	23.6	15	11.6	29.2	21	13
15:00	31.6	24	15.1	11.9	29.1	21	13

15:15	31.4	24	15.1	12.1	28.9	22	13
15:30	31.9	24.1	15.2	12.1	29.1	22	14
15:45	31.6	24.1	15	11.9	29	21	13
16:00	31.2	24.3	15	12.1	29.1	21	11

The comparison of outlet temperature as a function of inlet temperature and a bar graph of efficiency for three different thicknesses of the date palm fibers pad module is exhibited in **Fig IV.4** below. It is very clear from the temperature graph that the highest differences between inlet and outlet temperatures are obtained by the 45 mm thickness pad with a value of approximately 3 degrees. Hence, for the efficiency bars graph, it is definitely remarked that the values of efficiency are mostly close, and the controlling values are those of the 45 mm pad thickness. It can be concluded from the results of **Fig IV. 4** that increasing pad thickness yields higher cooling efficiency and that's due to increasing the heat transfer flux section by increasing the pad thickness.

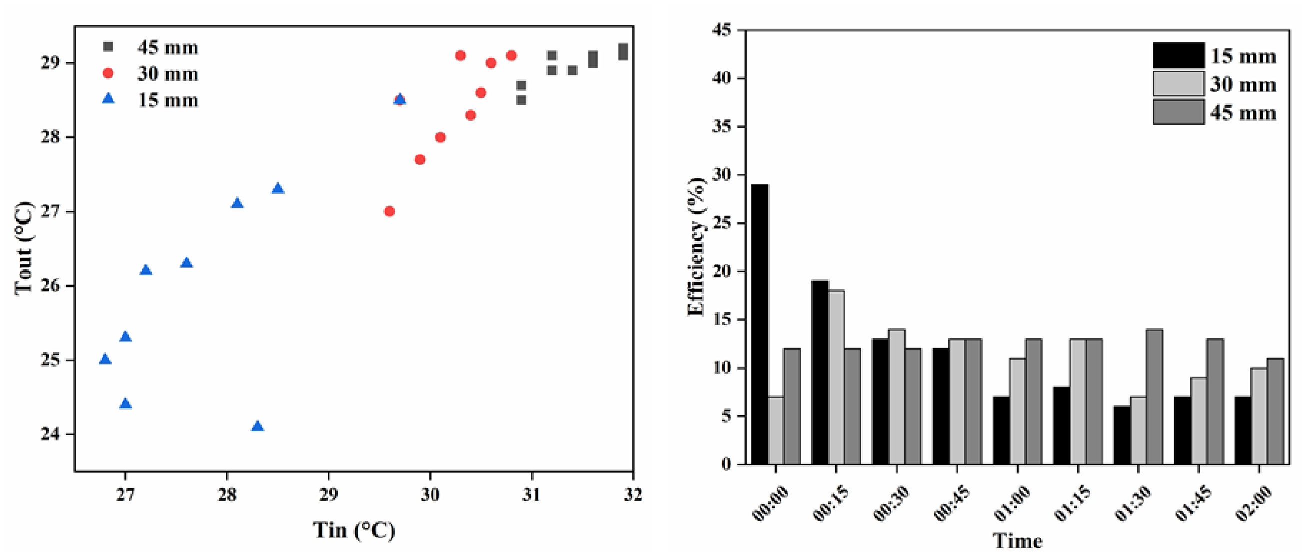


Fig IV. 4: comparison of outlet temperatures as a function of inlet temperatures and cooling efficiency for three different pad thicknesses

2.3. Air velocity effect on the cooling performances

After finding the best pad module material and the thickness that lends good performance efficiencies, this part of the study presents the cooling performance examination of three different air velocities (1, 2, and 5 m/s). **Table IV.6** displays the experimental results of three different air velocities.

Table IV. 6: experimental results of three different air velocities.

Time	**T_{in} (°C)**	**T_{water} (°C)**	**RH_{in} (%)**	**T_{wb} (°C)**	**T_{out} (°C)**	**RH_{out} (%)**	**Efficiency (%)**
Air velocity: 1 m/s							
10:00	28.3	25.3	24	13.6	26.3	25	14
10:15	28.3	25.3	25	13.0	26.3	22	13
10:30	28.3	25.3	23	12.8	26.3	21	13
10:45	28.3	25.3	22	12.7	26.3	20.7	13
11:00	32.1	19.7	18.5	9.1	30.1	22	9
11:15	33.1	19.4	18	9.0	30.8	23	10
11:30	34.1	21	18.2	10.2	30.1	23	17
11:45	35.7	22.4	18.7	11.5	30.3	25	22
12:00	34.9	24.1	18.8	12.5	30.9	24	18
Air velocity: 2 m/s							
14:00	30.9	24.6	15.2	12.5	28.7	22	12
14:15	31.2	24.1	15	12.1	28.9	22	12
14:30	30.9	23.2	15.1	11.3	28.5	21	12
14:45	31.9	23.6	15	11.6	29.2	21	13
15:00	31.6	24	15.1	11.9	29.1	21	13
15:15	31.4	24	15.1	12.1	28.9	22	13
15:30	31.9	24.1	15.2	12.1	29.1	22	14
15:45	31.6	24.1	15	11.9	29	21	13
16:00	31.2	24.3	15	12.1	29.1	21	11
Air velocity: 5 m/s							
12:00	34.9	24.1	18.8	12.5	30.9	24	18
12:15	35.6	26.2	19.3	14.0	29.5	24	28
12:30	34.9	26.5	17.5	14.2	29.6	24	26

12:45	35.7	26.3	19.4	14.1	29.9	24	27
13:00	34.7	26.2	17.5	14.0	29.3	24	26
13:15	35.4	26.8	17.3	14.4	29.8	24	27
13:30	36.1	26.3	16.5	14.1	30	24	28
13:45	36.6	26.6	17.9	14.1	29.7	23	31
14:00	36.5	26.1	15.6	13.7	30.1	23	28

The comparison of outlet parameters as a function of inlet parameters and the efficiency bars graph is presented in **Fig IV.5**. It is shown that the disparity between the inlet and outlet temperature is a 7 degrees difference marked for the 5 m/s air velocity. Same as for the relative humidity where we observe that the highest difference is given by the 5 m/s velocity.

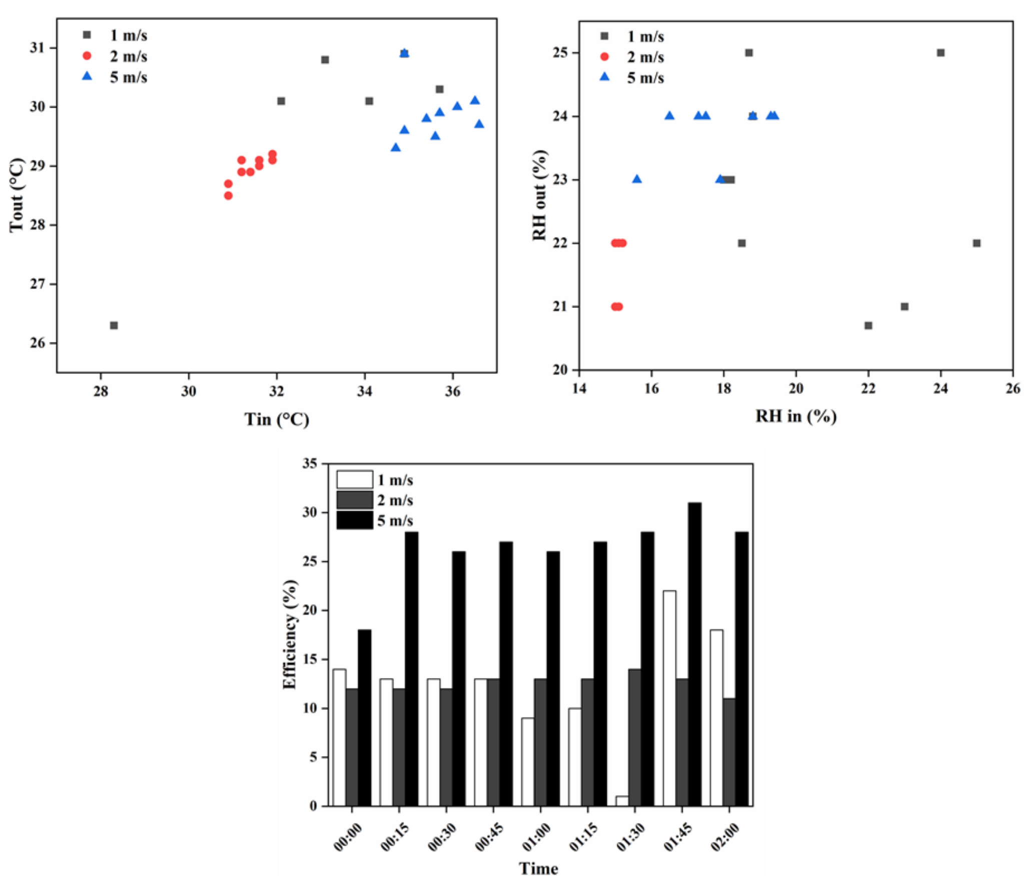


Fig IV. 5: Comparison of outlet parameters as a function of inlet parameters and efficiency comparison for three different air velocities (1, 2 and 5 m/s).

3. EAHE parametric study

The used parameters in the numerical model are indicated in **Table IV.7** below.

Table IV. 7: Numerical model validation parameters.

Parameter	**Value**	**Unit**
air specific heat (**Cp_a**)	1000	[J/kg.°C]
air density (**ρ_a**)	1.2	[kg/m^3]
air thermal conductivity (**λ_a**)	0.0242	[W/m.°C]
Air velocity (**V_a**)	3.5	[m/s]
soil specific heat (**Cp_s**)	1340	[J/kg.°C]
soil density (**ρ_s**)	1800	[kg/m^3]
soil thermal conductivity (**λ_s**)	2.5	[W/m.°C]
pipe specific heat (**Cp_p**)	1046	[J/kg.°C]
pipe density (**ρ_p**)	1380	[kg/m^3]
pipe thermal conductivity (**λ_p**)	0.17	[W/m.°C]
pipe length (**L**)	50	[m]
pipe interior diameter (**D_i**)	0.11	[m]
pipe exterior diameter (**D_e**)	0.115	[m]
pipe depth	2.5	[m]
dynamic viscosity (**μ**)	1.8×10^{-5}	[Pa s]
Air ambient temperature (**T_{amb}**)	51.3	[°C]
Soil initial temperature (**T_{s0}**)	21.5	[°C]

3.1. Operation duration effect on the soil temperature

The effect of operation duration and the distance from the pipe surface on the soil temperature is shown in **Fig IV.6**. The performances were studied for 24 hours. The results in the figure show that the soil temperature increases by distance divergence and time passing, and that's due to the continuous heat transfer between the soil and the air inside the pipe.

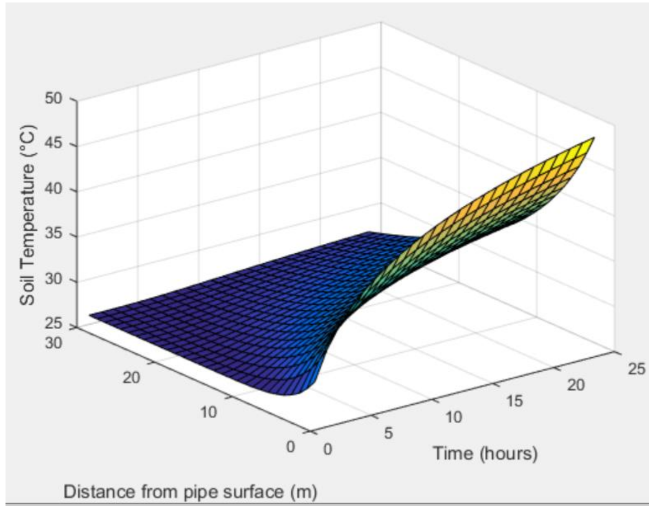


Fig IV. 6: effect of the operation duration and distance from the pipe surface on the soil temperature.

3.2. Pipe diameter effect on the air temperature

Fig IV.7 shows the variation of air temperature as a function of pipe length for three different pipe diameters (110 mm, 200 mm and 315 mm).

It is noticed that there is a notable decrease in air temperature all along the pipe for the 110 mm diameter and a slight decrease in air temperature for the 200 mm and 315 mm diameters. This is due to the inverse relation between the pipe diameter and heat transfer speed, where the larger the pipe diameter the slowest the heat transfer process between the pipe and the soil and the smaller the pipe diameter the faster the heat transfer occurs and more the effect on air temperature is noticeable.

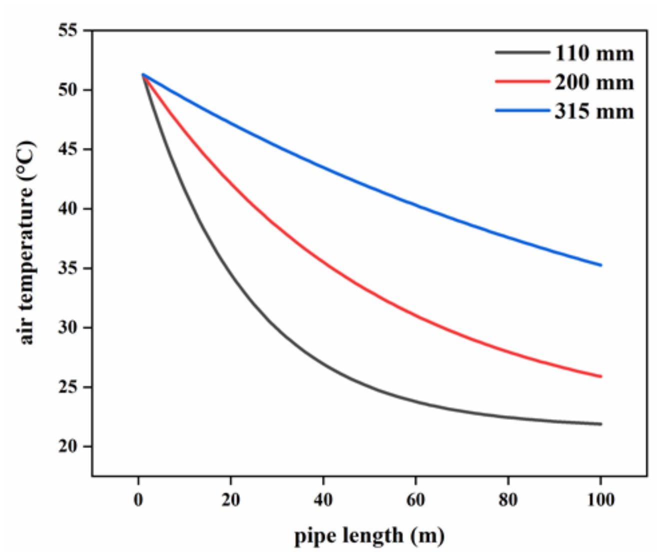


Fig IV. 7: Variation of air temperature as a function of pipe length for three different pipe diameters (110, 200 and 315 mm).

3.3. Air velocity effect on air temperature

Fig IV.8 displays the drops of air temperature as a function of pipe length for three different air velocities (1.5 m/s, 3.5 m/s and 5 m/s) to study the effect of changes of air velocity on the thermal performances of the EAHE.

It is spotted that the increase of air velocity causes a decrease in air temperature drop, and that is owing to the decrease of the staying time of the flowing air inside the EAHE. Thus, the performances of the EAHE degenerates proportionally with the increase of air velocity. From **Fig IV.8**, it is concluded that low airflow velocity doesn't affect the thermal performances of the EAHE during the operation duration.

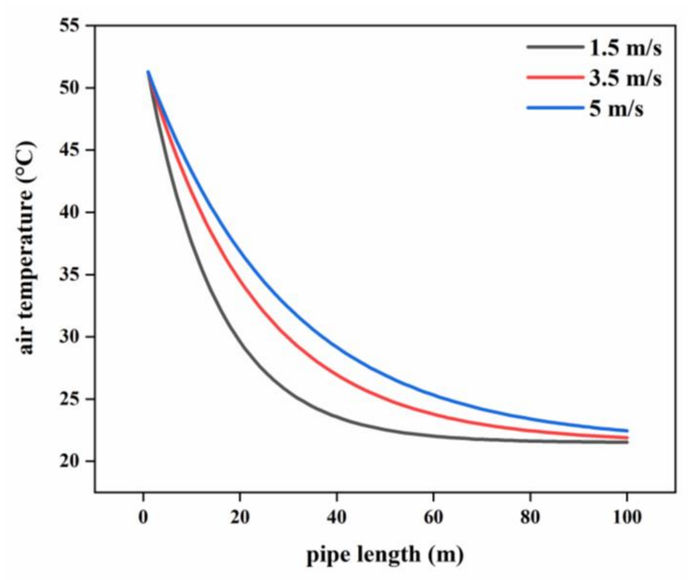


Fig IV. 8: Air temperature drops as a function of pipe length for three different air velocities (1.5, 3.5 and 5 m/s).

4. Case study: Hybrid system (EAHE-DEC)

In this section, the applicability and the feasibility of the proposed system in the region of Ouargla. To maintain these tests, the maximal air ambient temperature is chosen from the last ten years in addition to the soil temperature in the same region at a 2.5 (m) depth.

From the meteorological data of the maximum temperature during the period between 2012-2022, it was found that the extreme temperature of the past years is equal to 51.3 °C (32), see **Fig IV.9**. Therefore, this temperature will be considered as the temperature of the air at the inlet of the EAHE.

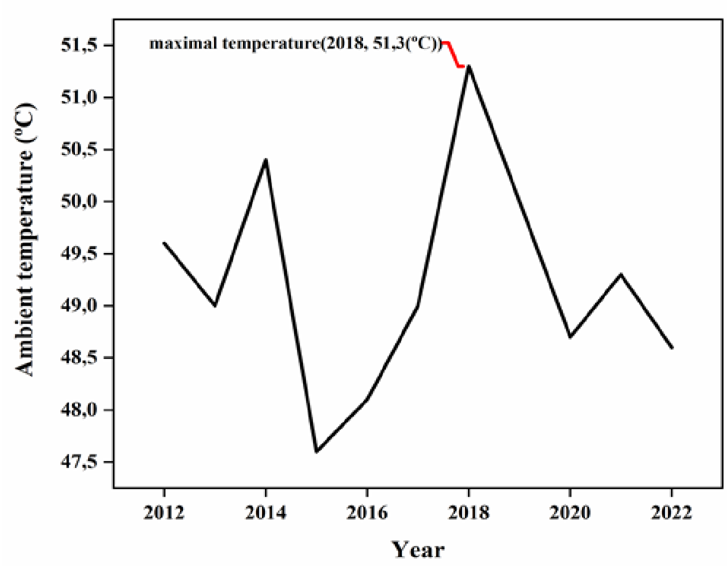


Fig IV. 9: Ambient air temperature changes as function of years in the region of Ouargla.

Table IV.8 presents the experimental results of soil temperature at different depths (1, 1.5, 2 and 2.5 m) in the region of Sidi Khouiled- Ouargla. The results display that the average soil temperature at a wanted depth of 2.5 (m) is at an order of 21.5 °C. This temperature is considered as the initial soil temperature in this study.

Table IV. 8: Experimental results of soil temperature at different depths.

	Soil Temperature (°C)								**$T_{average}$ (°C)**
Depth (m)	**09:00**	**10:00**	**11:00**	**12:00**	**14:00**	**18:00**	**19:00**	**20:00**	
1	23.3	23	23.1	23.2	25	25.1	24.2	24.4	24
1.5	22..5	22.1	22.4	22.3	23.8	23.8	23.2	23.7	23
2	21.5	21.6	21.8	21.5	22.3	23.5	23.7	23.9	22.5
2.5	20.7	21.1	20.5	20.8	21	22.3	22.7	22.7	21.5

Table IV. 9: numerical model of the hybrid system (EAHE-DEC) obtained temperatures.

EAHE system		Pipe length (m)	Air temperature (°C)
Pipe length (m)	Air temperature (°C)	19	30.19
1	51.30	20	29.62
2	49.31	21	29.08
3	47.47	22	28.58
4	45.75	23	28.11
5	44.15	24	27.67
6	42.65	25	27.27
7	41.25	26	26.88
8	39.95	27	26.53
9	38.73	28	26.20
10	37.59	29	25.88
11	36.52	30	25.60
12	35.53	**DEC system**	
13	34.60	Pad thickness (mm)	Air temperature (°C)
14	33.74	10	24.10
15	32.93	20	22.91
16	32.17	30	22.06
17	31.47	40	21.46
18	30.81	45	21.23

(°C) to 25.6 (°C) in a duration of 1 hour. The incorporation of the DEC system helped to decrease the temperature to 21.23 (°C). The combination of the two systems into one (EAHE-DEC) succored to decrease the air temperature and improved to achieve low temperature value.

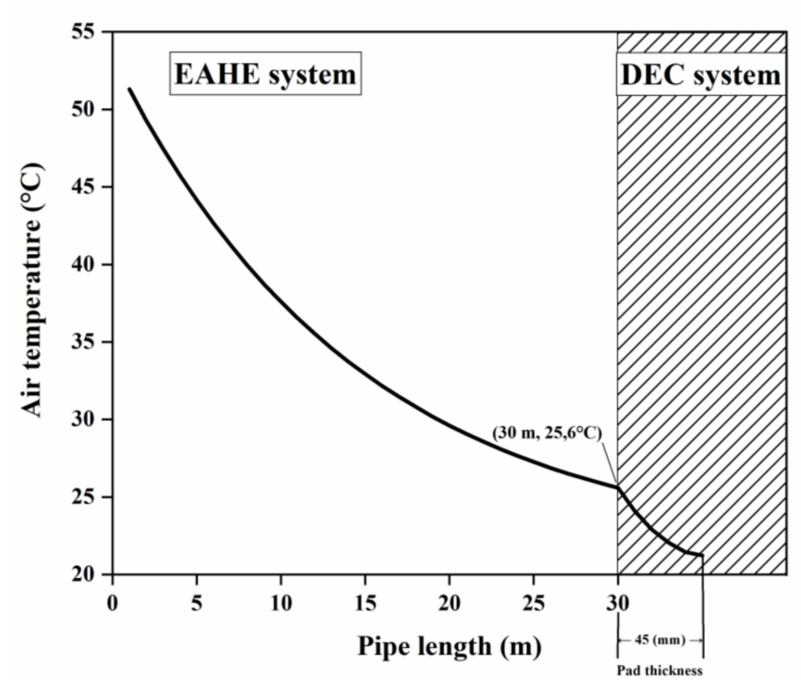


Fig IV. 10: Air temperature drops as a function of pipe length and pad thickness using the EAHE-DEC hybrid system.

Conclusion

In this chapter and based on the analyzes and the results that we obtained in the vital conditions of the hot and dry regions, particularly in the area of Ouargla, we attained very positive results that gave us a good impression of the possibility of applying the proposed cooling hybrid system in our region, given all the environmental conditions. Among the obtained results we mention: date palm fiber is the highest efficiency material, in addition to a thickness of 45 (mm), in the EAHE the air velocity needs to be low to make its performance higher.

GENERAL CONCLUSION

General Conclusion

In this research paper, we studied a new hybrid system combining a direct evaporative cooler with an earth-to-air heat exchanger. This system was proposed as an eco-friendly alternative to classic cooling systems.

The objective of this study is to examine the experimental and numerical evaluations of the thermal performances of the proposed system in hot arid and dry regions where the ambient temperatures sometimes exceed 51 °C.

In this work:

At first, we did a general review on the ventilation and cooling of existing passive systems, and we based it on the earth air heat exchanger and evaporative cooling systems. Moreover, we did a literature review of the former studies on the earth air heat exchanger, evaporative cooling, and the combination of both systems (EAHE-EC). We found out that many researchers from all around the world are interested in studying and expanding the idea of employing the hybrid system (EAHE-EC) in dry and hot climatic conditions, especially Indian researchers.

After that, we did an experimental study on the DEC system and numerical validation of both DEC and EAHE systems, where the purpose was to estimate the air temperature circulating inside the EAHE pipes and that at the outlet of the DEC in addition to the effective parameters on the system's performance.

Finally, we presented the analyses and interpretation of the obtained results and the verification of the numerical results by doing a case study in the region of Ouargla.

From the analyses of the obtained results, we came to:

- Comparing the three used materials in the DEC system, we found out that date palm fibers have higher efficiency, and that's due to their capacity in retaining water.
- The efficiency of the DEC system is proportionally direct with the pad module thickness.
- Long operation duration of the EAHE affects the soil temperature, still the soil is saturated with heat that it continuously emerges.
- The pipe diameter affects the air temperature at the outlet of the EAHE, so lowering the pipe diameter affects positively the performance of the EAHE.

- Air velocity affects the performance of EAHE, in view of the fact that more the air movement is slow, more it takes its time to exchange heat with soil.

Finally, the EAHE-DEC system is more effective when the ambient temperatures are high. It is very energy efficient and does not present any polluting emissions to the environment. This system can be used as an efficient alternative to conventional air conditioning systems at lower operating costs in hot and dry climate areas.

For the perspectives, we look forward to test the proposed system (EAHE-DEC) in real scale.

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Abstract

The objective of this thesis is to study a hybrid cooling system combining an earth-air heat exchanger and a direct evaporative cooler (EAHE-DEC). An experimental setup of the DEC system was realized at the University of Ouargla to evaluate its thermal performance. However, a numerical model is developed using Matlab to examine the effect of different parameters, namely the EAHE pipe’s diameter, air velocity, and the used material in the pad’s tampon, on the performances of the proposed system. The model was verified using experimental data that handed good concordance. Results showed that the proposed hybrid system is able to decrease the temperature from 51.3 °C to 21.23 °C, which approves the feasibility of the EAHE-DEC system to attain thermal comfort in residential buildings.

Keywords: Thermal comfort, earth-air heat exchanger, direct evaporative cooler, renewable energy, cooling, ventilation.

ملخص

الهدف من هذه المذكرة هو دراسة نظام تبريد هجين يجمع بين مبادل حراري أرضي هوائي ومبرد مبخر مباشر (EAHE-DEC). تم اجراء إعداد تجريبي لنظام DEC في جامعة ورقلة لتقييم أدائه. اضافة الى ذلك ، تم تطوير نموذج رقمي باستخدام Matlab لدراسة تأثير مختلف العوامل ، مثل قطر أنبوب EAHE ، وسرعة الهواء ، والمواد المستخدمة في وسادة التبريد ، على أداء النظام المقترح. تم التحقق من النموذج باستخدام بيانات تجريبية، والتي أعطت توافقًا جيدًا. أظهرت النتائج أن النظام الهجين المقترح قادر على خفض درجة الحرارة من 51.3 درجة مئوية إلى 21.23 درجة مئوية ، مما يؤكد جدوى نظام EAHE-DEC لتحقيق الراحة الحرارية في المباني السكنية.

الكلمات المفتاحية: الراحة الحرارية، مبادل حراري، مبخر مائي، طاقة متجددة، تبريد، تهوية.

Résumé

L’objectif de cette thèse est d’étudier un système de refroidissement hybride combinant un échangeur de chaleur air-sol et un refroidisseur à évaporation directe. Une installation expérimentale du système d’évaporation directe a été réalisée à l’Université de Ouargla pour évaluer sa performance thermique. Cependant, un modèle numérique est développé à l’aide de Matlab pour examiner l’effet de différents paramètres, à savoir le diamètre du tuyau de l’échangeur air-sol, la vitesse de l’air et le matériau utilisé dans le tampon de l’evaporateur, sur les performances du système proposé. Le modèle a été vérifié à l’aide de données expérimentales qui fournissaient une bonne concordance. Les résultats ont montré que le système hybride proposé est capable de réduire la température de 51,3 °C à 21,23 °C, ce qui approuve la faisabilité du système hybride pour atteindre le confort thermique dans les bâtiments résidentiels.

Mots-clés : Confort thermique, échangeur de chaleur air-sol, refroidisseur à évaporation directe, énergie renouvelable, refroidissement, ventilation.