Parametric Study and Energy Performance of an Earth-Air Heat Exchanger for a Poultry House in Morocco

Azzeddine Laknizi[1,2‡], Mustapha Mahdaoui[3], Kamal Anoune[1,2], Mohamed Bakhouya[2], Abdelatif Ben Abdellah[1,2], Hamza Oussous[2]

[1]Laboratory of Engineering, Innovation,and Management of Industrial Systems (LEIMIS), Faculty of Science and Technology of Tangier (FST), AbdelmalekEssaâdi University (UAE), Ziaten. BP: 416, Tangier, Morocco.

[2]Laboratory of Renewable Energies and Advanced Materials (LERMA), International University of Rabat (UIR), Sala Al Jadida 11000, Morocco

[3]Equipe de Recherche en Transferts Thermiques & Énergétique - UAE/E14FST Département de Physique FST, Université Abdelmalek Essaâdi Tanger – Maroc

(eng.azzeddinelaknizi@gmail.com,mustapha_mahdaoui@yahoo.fr, benabdellah.abdellatif@gmail.com, kamal.anoune@gmail.com)

‡AzzeddineLaknizi, Tel: +212 06 48 21 73 38, eng.azzeddinelaknizi@gmail.com

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Abstract- In this paper, an earth-air heat exchanger is modeled and evaluated for cooling and heating a poultry house. A parametrical study was conducted to investigate the effects of the velocity of the air, the physical properties and the diameter of the tube on the thermal performance of the system. Furthermore, an environmental evaluation of the earth-air heat exchanger was conducted. The results showed that a heat exchanger of polyethylene material and diameter of 100 mm and length of 30 m with a velocity of 2 m/s gives a higher coefficient of performance with a higher efficiency. The energy performance of the system under the climate conditions of Marrakech-city shows that the system has the potential to save annually 146.38 MWh and 104.3 MWh in heating and cooling modes respectively. The environmental benefit in the reduction of greenhouse gases is estimated at an amount of 32.2 tCO2.

Keywords earth-air heat exchanger; cooling; heating; poultry house; energy performance; environmental.

1. Introduction

Population growth and its food security have been the driving forces behind the development of the poultry sector in many regions of the world. According to the Food and Agriculture Organization (FAO), lower prices have helped make poultry the meat of choice for consumers compared to red meats, which is expected to cover 50% of world meat consumption by 2025 [1].

Poultry sector in Morocco is making a great contribution to the national economy and is considered one of the most dynamic sectors. According to the poultry federation of Morocco's statistics [2], the turnover of the poultry sector for 2017 is estimated at 29.1 billion MAD for total investments of 11.3 billion MAD. The sector currently provides 120 000 direct jobs and 280 000 indirect jobs related to the marketing and distribution system. The sector has 7627 licensed poultry houses producing 550 000 tons of chicken meat.

Weather conditions and energy consumption are the main problems facing the Moroccan poultry sector, especially with the occurrence of hot and cold waves, which cause heat and cold stress. These stressful conditions result in a high mortality rate and high energy consumption by using ventilation, cooling, and heating systems. This high energy consumption leads to high costs since it uses electricity network and butane gas, which represent another item of expenditure for farmers. In order to adapt the indoor temperature to the comfort temperature for chicken with reduced cost two broad options are possible. The first option is to use more efficient systems, while the second option is to use renewable energy source for producing electricity.

Existing solutions for ventilation, cooling, and heating are numerous. For the ventilation, there is mechanical and natural ventilation, for each type there are many configurations, such as tunnel ventilation. The limitation of the ventilation systems is that they are recommended in hot periods and in cold periods it contributes to energy losses [3]. For heating, there are gas-fired radiant heating, convective heating, and Unit Heaters. These solutions are based on the combustion of the fuel, which leads to green gas emissions. For cooling, the widely used solutions are based on evaporative cooling (e.g., evaporative pad cooling [4]), misting and fogging system. These systems are highly efficient and are eco-friendly [5, 6] but their limitation is ineffective at high relative humidity [7].

Passive solutions based on renewable energy can reduce the energy consumption in the poultry sector. In this context, Okonkwo and Akubuo in [8] have conducted an experimental investigation on a poultry house, which is equipped with solar Trombe wall in order to provide ventilation, heating, and cooling to the poultry house. They found that the system maintained the temperature in the range of 28°C -35°C, the average body weight is 586 grams, the feed conversion ratio is 1.87% and the rate of mortality is around 3% [8]. Fawaz et al. in [9] evaluated the performance of a solar-assisted localized ventilation system; their results show that the system can cover 74% to 92% of the energy demand.

Biogas production by anaerobic digestion is a good alternative to recover energy from the agriculture product such as fruit and vegetable [10] and olive-mill [11] or from the animals waste such as poultry [12] and cattle manure [13]. Ali and Al-Sa'ed in [14] develop and deploy a pilot-scale anaerobic digester for farm heating. Their experimental results showed that the total biogas production is about 39.95 m3, the methane content ranged between 46- 68% and the heat generated from the produced biogas is 788 MJ.

Renewable energy resources are also good alternatives for the production of energy in agriculture sector [15]. The use photovoltaic panels [16] for pumping groundwater is an example of the potential of renewable energy in the satisfaction of the energy demand of the farmers. Fahmy et al. [17] studied a hybrid PV-biomass gasifier system to be used for poultry house. They used HOMER software tool for the simulation and optimization. The authors showed that the obtained optimal configuration is sustainable, techno-economically viable with a minimum amount of greenhouse gases emissions. Kapica et al. [18] evaluated the reduction of CO2 by using a solar-wind hybrid system for heating a poultry house, and they found that a larger system provides a higher CO2 reduction.

Geothermal heat pump is a good and efficient solution in space heating and it is a well proven system in residential sector[19]. Choi, Salim et al. [20] have investigated a geothermal heat pump for heating of broiler house. In comparison with the conventional heater, the geothermal heat pump increases the body weight gain, the mortality rate is not affected, the indoor air quality is improved, fuel consumption was reduced, and the electricity consumption is increased. In fact, the geothermal heat pump allows a lower cost of heating, improved production performance with lower amount of gases emissions.

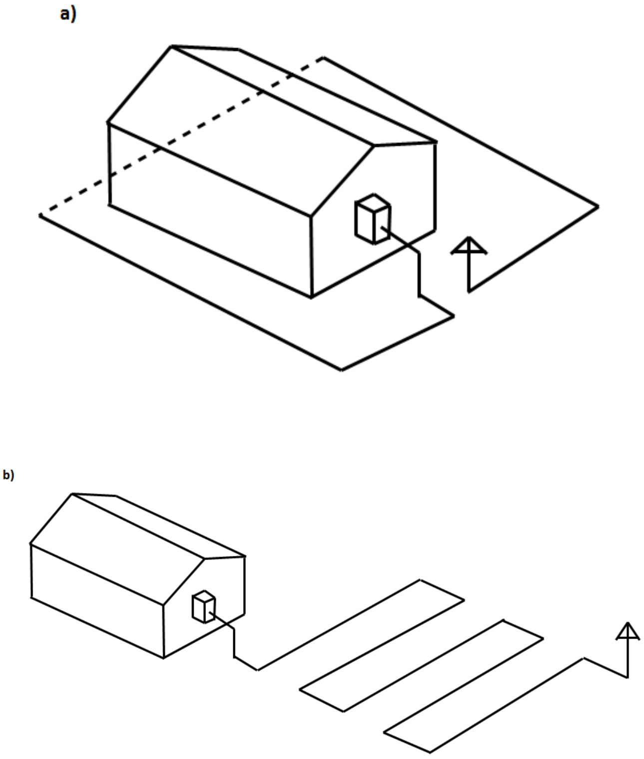
The aforementioned literature shows that solutions based on renewable energy and passive technologies are widely studied and recommended in the poultry sector. Our current work follows the same trend by proposing an Earth-Air Heat Exchanger (EAHE) for heating and cooling a typical poultry house in Morocco. The proposed system was modeled and studied parametrically in order to find the optimal geometry and operating conditions accordingly. The influence of the velocity and thermo physical properties of EAHE is studied. The results of the parametric study are considered as input parameters for the hourly simulations. An analysis of the energy and environmental performance was carried out under the climatic conditions of the city of Marrakech-Morocco.

The reminder of this paper is structured as follows. Section 2 gives an overview of existing EAHE layouts. In section 3, the mathematical modeling of the EAHE is developed. The effects of the design parameters are discussed in Section 4. Obtained simulations results are discussed in the Section 5. Conclusions and perspectives are given in Section 6.

2. An Overview of EAHE

This section overviews EAHE and describes commonly used layouts. In fact, an EAHE is a geothermal system used to heat or cool the air and consists of buried tubes coupled to a fan. The role of the tubes is to ensure the thermal contact between the outside air and the soil. The tube material is a non-metallic material (i.e., plastic material), such as polypropylene (PP) and PVC, which are the widely used for EAHE.

The tubes' layouts depend on the available area. The widely used ones are circular layout, meanders (serpentines) and Tichelmann grid as depicted in Fig.1 [21].



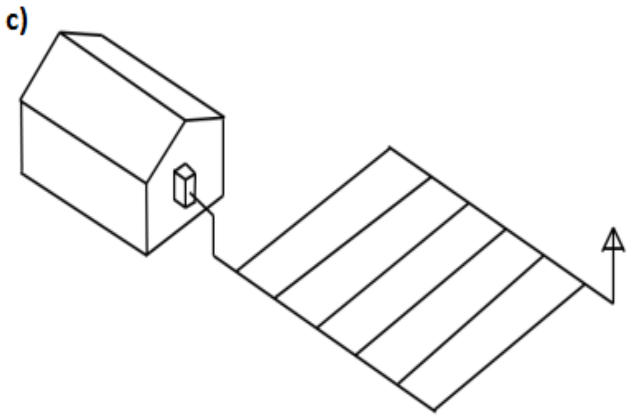


Fig. 1. The most widely used tubes' layouts: a) circular, b) meander, c) Tichelmann

The Tichelmann layout consists of a set of hydraulically balanced tubes of the same length and diameter. When a high air flow rate is required, it is recommended to use the Tichelmann layout rather than the circular and meander layouts. The available area, the cost and simplicity of the installation, pressure drops, air flow rate are the factors that could be used for selecting the best layout. A minimum slope of 3 % in the downstream direction should be also insured [22].

3. EAHE Modeling

In this section, we introduce the mathematical model, which is used for our design space exploration study in order to select the best suitable design for minimizing energy consumption while maintaining a good comfort.

3.1. Heat transfer in a buried tube

The heat transfer inside the tube is a convective heat transfer and conductive through the thickness of the tube with constant wall temperature, which is taken equal to the soil temperature at the fixed depth. The following assumptions are made:

i) The heat exchange is steady-state,
ii) The soil temperature is taken constant,
iii) The thermo-physical properties of the air are taken constants, which are listed in Table 1.

The air temperature at the outlet of the earth-air heat exchanger is calculated by using the following equation:

$$T_o = T_s + (T_i - T_s)e^{-\left(\frac{1}{\dot{m}C_pR_{tot}}\right)} \qquad (1)$$

The thermal resistance is the sum of the convective and conductive resistances as follows:

$$R_{tot} = R_{conv} + R_{cond} = \frac{1}{\bar{h}\pi D_i L} + \frac{\ln\left(\frac{D_e}{D_i}\right)}{2\pi K_t L} \qquad (2)$$

where T_s is the soil temperature, T_i is the inlet temperature, which represents the outdoor temperature, D is the diameter of the tube (m), L is the length of the tube (m), h is the convection heat transfer coefficient (W/m2.K), $\dot{m}$ is the air flow rate (kg/s), and c_p is the specific heat capacity (J/kg. K). The convection heat transfer coefficient can be computed as follows:

$$\bar{h} = \frac{\overline{Nu}_D k}{D_i} \qquad (3)$$

The Nusselt number is given by Colburn correlation[23]:

$$\overline{Nu}_D = 0.023\ Re^{0.8}Pr^{0.33} \qquad (4)$$

The Reynolds number is:

$$Re = \frac{4\dot{m}}{\pi D_i \mu} \qquad (5)$$

The Prandtl number is:

$$Pr = \frac{\mu c_p}{k} \qquad (6)$$

Table 1: The thermo-physical properties of the air [24]

The Thermo-physical properties	Value	Unit
Density	1.2	kg.m-3
Dynamic viscosity	18.46×10^{-6}	kg.m^{-1} s^{-1}
Thermal conductivity	0.0263	W. kg $^{-1}$ K^{-1}
Specific heat capacity	1005	J.m^{-1} s^{-1}

3.2. Pressure drop

The calculation of pressure drop allows us to design the earth-air heat exchanger by choosing the proper length, the diameter of the tubes and the blower (fan) to be coupled to the said heat exchanger. The total pressure drop is the sum of linear losses and singular losses and is calculated using the following equation:

$$\Delta P_{tot} = \sum f\frac{L}{D_i}\frac{\rho v^2}{2} + \sum \xi\rho\frac{v^2}{2} \qquad (7)$$

where, *f* is the friction factor, *L* is the length of the tube (m), D_i is the inner diameter (m), *V* is the velocity (m/s), ε is the roughness of the tube (mm), and ξ is constant coefficient depends on the type of singularity.

The friction factor is calculated using the Colebrook's equation [25]:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D_i} + \frac{2.51}{Re\sqrt{f}}\right) \tag{8}$$

The singular losses occur in tees, elbows, and in the filter. The pressure drop in the filter is obtained from the datasheet of the manufacturer. Figure 4 shows the pressure drop as a function of the flow rate.

3.3. Fan

The system requires a fan to supply air to the local. The fan must be selected in such a way to ensure the required flow rate and to overcome the pressure drop generated by the passage of the air inside the tubes. The power consumption of the fan is calculated by the following equation:

$$P_{fan} = \frac{\dot{m}\Delta P_{tot}}{\rho\eta_{fan}\eta_{motor}} \tag{9}$$

where $\dot{m}$ the mass flow rate (kg/s), $\Delta P_{tot}$is the pressure drop in the circuit (Pa), η_{fan} and $\eta_{motor}$are the efficiency of the fan and the motor respectively, and ρ is the density of the air (kg/m3). The motor and fan efficiencies are taken equal to 80%, the most used value for existing commercial equipment.

After modeling the main components of an EAHE, the aim is to select the best suitable dimensions and measure the system's efficiency. Two metrics have been considered as follows.

The coefficient of performance described as the ratio of the heating or the cooling performance to the electrical power consumption of the fan. It is calculated by the following formula.

$$COP = \frac{\dot{m}cp(T_o - T_i)}{P_{fan}} \tag{10}$$

The system's efficiency is another performance metric, which is described as the ratio of the actual heating or cooling performance to the maximum heat that could be exchanged. It is calculated by the following formula.

$$\eta = \frac{T_o - T_i}{T_s - T_i} \tag{11}$$

where T_s is the soil temperature, $T_i$is the inlet temperature which represents the outdoor temperature, T_O is the outlet temperature, which represents the indoor temperature.
In order to explore the design parameters and compute the performance metrics we have developed a program using MATLAB as depicted in Figure 5. The input parameters for this program are: i) the dimension and the consecutive material of the EAHE, ii) the weather conditions of the located city namely the outdoor temperature and soil temperature. The outputs are the outlet temperature, the electric power consumption of the fan, the COP and the efficiency.

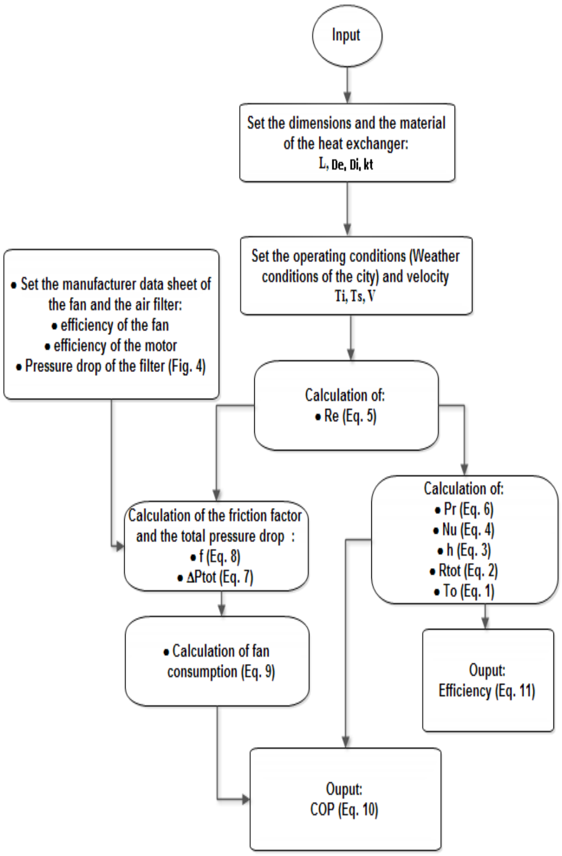


Fig. 2. Flowchart of the design space exploration program

4. Design Space Exploration Methodology

From the mathematical modeling, we can see that the design of the EAHE is controlled by many parameters as also mentioned in Figure 2. In this section, a parametric study was conducted to evaluate the following effects on the performance of the system as follows: i) the velocity of the air, ii) physical properties of tube material and the diameter of the tube. The characteristics of the considered tubes are summarized in Table 2.

Table 2: The characteristics of the considered tubes [26]

Material	Roughness (mm)	Thermal conductivity (W/m/K)
Polyvinyl Chloride PVC	0.0015	0.2
Polypropylene PP	0.003	0.28
Polyethylene PE	0.001	0.49

4.1. The air velocity effects

The velocity is varied between 2m/s and 5m/s, while the diameters are taken equal to 100 mm, 200 mm, 250 mm, 315 mm and 400 mm. Figure 3 shows the effect of the velocity of the air on the coefficient of performance and the efficiency. It can be seen that the COP and efficiency decrease with increasing velocity. This is due to the fact that at low velocity, the Reynolds number is lower. This allows the air to have enough time of heat exchanging with the soil, which consequently results in higher outlet temperature, energy gain, and efficiency. Also at low velocity, the flow rate and pressure drop are less, which lead to less electrical consumption of the fan and consequently a higher coefficient of performance.

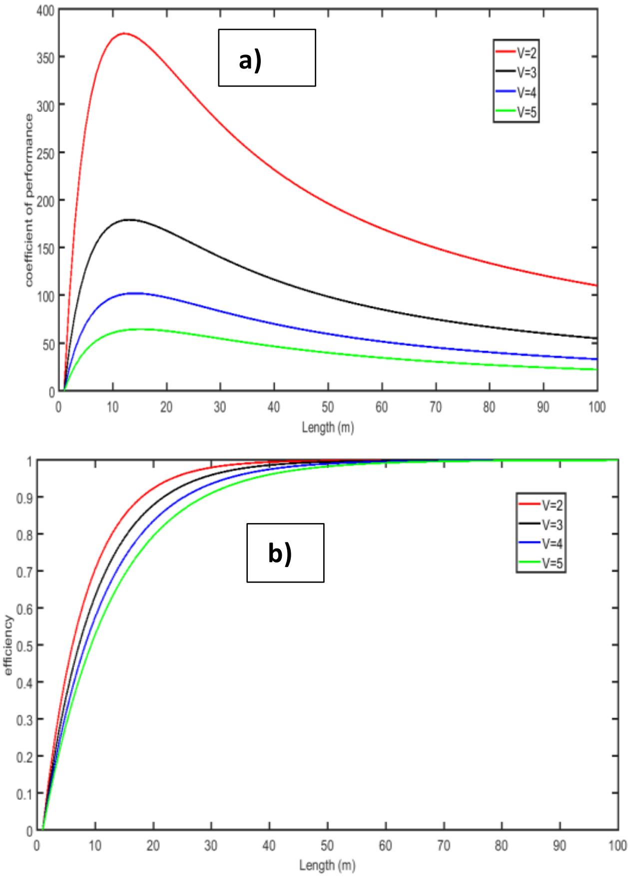


Fig. 3. The effect of the velocity of the air on: a) the coefficient of performance, b) the efficiency

4.2. The tube diameter effects

Figure4 shows the effect of the diameter of the tube on the coefficient of performance and the efficiency. It can be shown that the coefficient of performance decreases by increasing tube diameter. This is explained by the increase of the flow rate and the fan consumption at larger diameters and fixed velocity. It also shows that the diameter has more influence on the efficiency, which is related to the heat transfer coefficient. At a higher diameter, this coefficient is lower, which affects directly the outlet temperature and indirectly the efficiency.

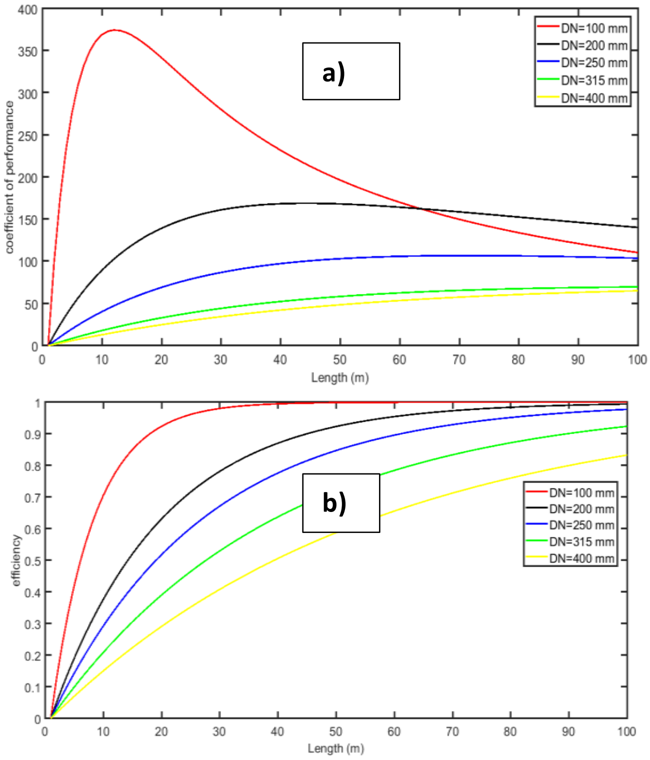


Fig. 4. The effect of the diameter of the tube on: a) the coefficient of performance, b) the efficiency

4.3. The tube thermal conductivity effects

From Figure 5 the coefficient of performance and the efficiency change slightly to respect to the thermal conductivity of the tube this is due to that the investigated materials are plastics material and their thermal properties are close. Polyethylene material gives the higher coefficient of performance.

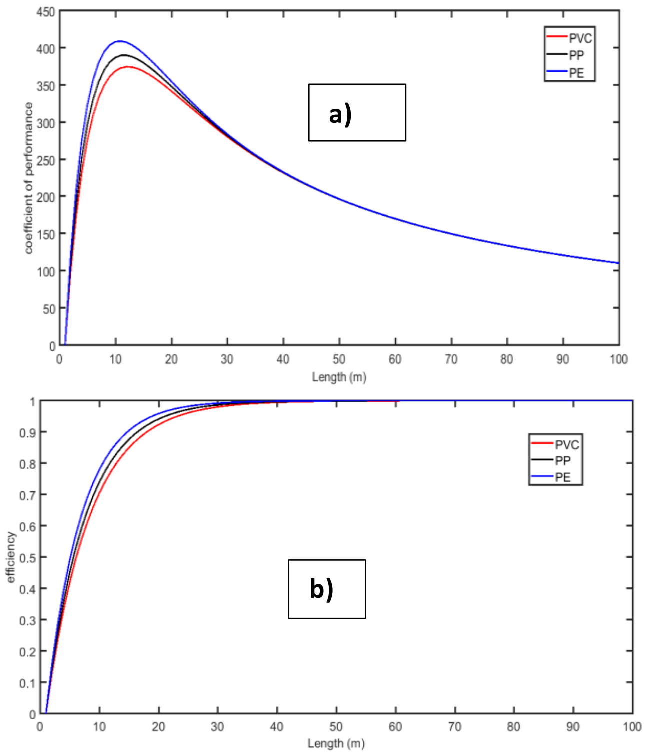


Fig. 5. The effect of the thermal conductivity of the tube on: a) the coefficient of the performance, b) the efficiency

From this abovementioned parametric study, we can conclude that the diameter has more influence on the thermal performance than the velocity and the thermal conductivity of the tube. A significant change in the results is obtained when the length is increased from 20 to 30 m. Moreover, increasing the length from 30 m to 40 m does not lead to an important change in the results. Accordingly, we conclude that the length of 30 m gives sufficient performance.

Based on the obtained results an EAHE of PE material, the diameter of 100 mm and length of 30 m operating at a velocity of 2 m/s is recommended in order to obtain optimal performance. These design parameters, which have been selected, are used to conduct simulations under the considered climate conditions as presented in the next section.

5. Simulations and Results

This section presents the simulations we have conducted under Marrakech climate conditions for typical poultry house.

5.1. Simulations parameters and evaluation metrics

In poultry breeding sector, generally, chickens need 42 days to reach slaughter weight. During this study, the agriculture year is divided into 7 cycles (growing periods) of 42 days and between two successive cycles; there is a period of 7 days for cleaning and disinfection. For the dimensions of the EAHE are set at 0.1 m in diameter and 30 m in length. The operating conditions are the weather conditions of Marrakech-Morocco. Figure 6 shows the ambient temperature and relative humidity in Marrakech. The minimum temperature is 2.4°C the maximum temperature is 44.6 °C. The indoor required temperatures are giving by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) [27]recommendations Table 3.

Table 3: Indoor required temperature during the growing period

Week	Indoor temperature
1st	33°C
2nd	30°C
3rd	27°C
4th	24°C
5th	21°C
6th	18°C

An hourly simulation was conducted using a developed MATLAB program to solve the heat transfer equations. The aim is to evaluate the energy performance of the earth-air heat exchanger. The input data of this program are the aforementioned conditions of weather data and the indoor required temperature.

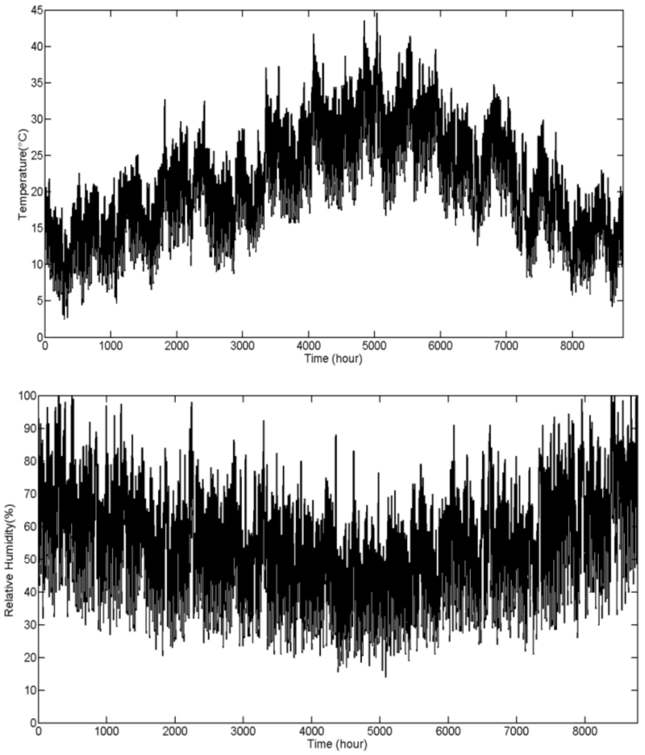


Fig. 6. Climate conditions in Marrakech: a) ambient temperature, b)relative humidity

For system's evaluation, we have conducted extensive simulations by focusing mainly on energy gain and comfort (i.e., temperature). For a significant analysis, the first and fifth cycle temperature profiles are presented, which coincide with the period where the higher heating demand (winter) and the higher cooling demand (summer) occur respectively.

5.2. Simulations results

Figure 7 shows the temperature profiles during the first and fifth cycles. As it can be seen from this figure, the outdoor temperature is lower and higher than the required temperature (indoor temperature), which results in high heating demand in the first cycle and in high cooling demand in the fifth cycle. This is expected because the first and fifth cycles coincide with the coldest and the hottest months respectively in Marrakech. The contribution of the EAHE in satisfaction of this heating/cooling demand can be explained by this figure. In fact, the air has a temperature, which increases and decreases to the required temperature or to a temperature in order to improve the indoor conditions, and consequently contribute in reducing the load on the existing heating and cooling system.

According to the obtained results, the system lowered and heat up the temperature of the poultry house, which confirms the system's performance in terms of reducing the energy demand as depicted in Figure 8.

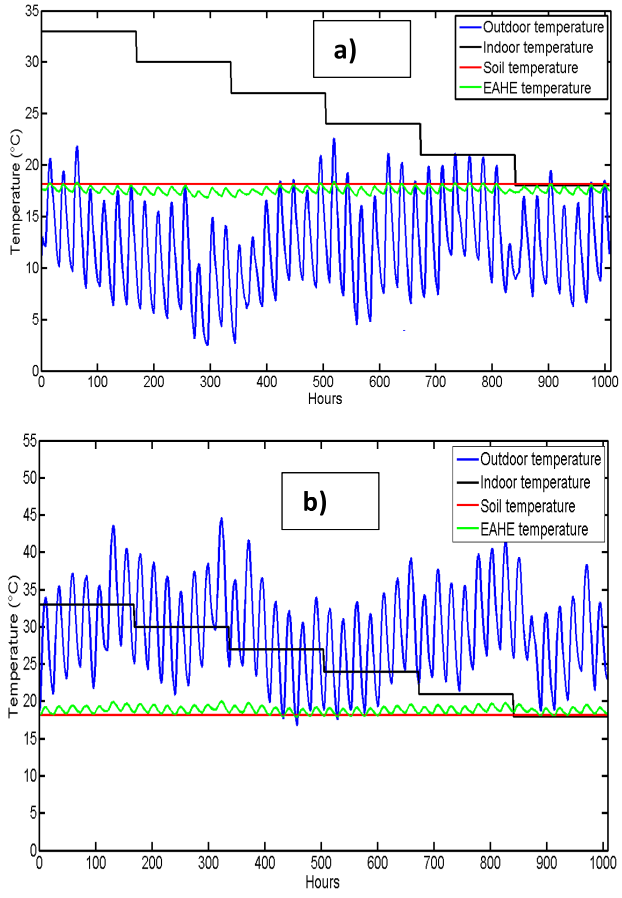


Fig. 7. Temperature profiles during: a) the first cycle, b) fifth cycle

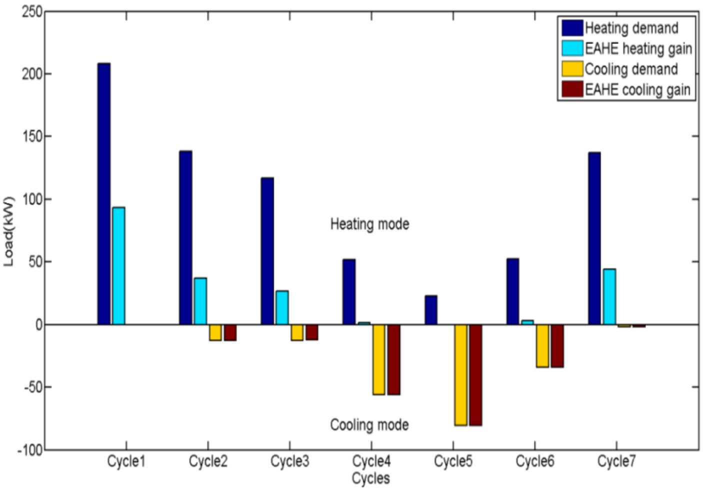


Fig. 8. The energy gain during the whole year

In this Figure, we can see that the heating demand is present during each cycle. A high demand in the first cycle, coincides with the coldest month, while the cooling demand is present in the cycle 4, 5 and 6, which coincides with the summer period. Mainly, the contribution of the EAHE in heating and cooling demand is summarized as follow. The annual heating demand is 418.38MWh, while the use of EAHE can cover 146.38 MWh, which represents 35%. The annual cooling demand is 104.46MWh, while the use of an EAHE can cover 104.30MWh, which represent 99.84%.

In heating mode, butane gas is widely used by the Moroccan farmer. The energy gain by the proposed system is estimated to 146.38MWhequivalent to 11.71 tons of butane gas based on it Lower Heating Value (LHV) of 12.5 kWh/kg. By using this system the framer will be less dependent on butane gas that represents a heavy burden on the country's budget due to subsidy policy. If we generalize this study to all the Moroccan poultry houses (i.e., 7293 poultry houses [2]), the energy saving will be more promising and can be reducing the energy bill of the industrial sector, which represent 43.6% of the national consumption [28].

Regarding the environmental impact, the greenhouse gas (GHG) emissions mitigation, from energy saving due to the use of the EAHE, calculated with respect to butane gas and electricity in heating and cooling mode respectively. The following equation gives the amount of GHG emissions:

$$M_{\text{emission mitigated}} = (C_{CO2} + C_{CH4} + C_{N2O})E_s \qquad (12)$$

where $M_{\text{emission mitigated}}$ is the amount of the greenhouse gas emisssions in kg. C_{CO2} , C_{CH4} and C_{N2O} are the emission factors (Emissions per kWh of electricity generated), E_s is the annual energy saving in kWh. For Morocco, the emission factors are equal to C_{CO2} =7.31E-01kg CO2/KWh for dioxide of carbon, C_{CH4}=1.30E-05kg CH4/kWh for methane and C_{N2O}=9.45E-06 kg N2O/kWh for dioxide of nitrogen [29]. For the butane gas, this factor equals to 0.22 kgCO2/kWh [30].

Table 4. Mitigation of greenhouse gas emissions.

	Operating hours (Hour/Cycle)		Energy saving (KW/Cycle)		CO2 mitigated(kg)	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Cycle1	913	11	93.5833	0.0927	18797.14	0.745616
Cycle2	562	194	36.8982	12.658	4562.093	1795.615
Cycle3	468	196	26.6246	12.494	2741.269	1790.637
Cycle4	82	527	1.2987	55.763	23.42855	21488.53
Cycle5	9	693	0.0697	80.619	0.138006	40852.43
Cycle6	130	410	3.1180	34.091	89.1748	10220.55
Cycle7	621	77	43.8425	2.0472	5989.762	115.2641

The issue of greenhouse gases in poultry house was addressed by many researchers [31, 32]. Based on the energy gain results and the national emissions factors, the system can mitigate 32.2 tons of CO_2 in heating mode and 76.26378 tons of CO_2 in cooling mode.

6. Conclusions and Perspectives

One of the main goals of this study was to evaluate the potential of EAHE in saving energy and corresponding greenhouse gas emissions. To achieve this goal, first, a parametric study was conducted for design space exploration in order to determine the optimal geometry and operating conditions. Second, an hourly simulation was conducted for each growing period of the whole year. The results of the parametric study show that an earth-air heat exchanger of PE material with the diameter of 100 mm and length of 30 m operating at a velocity of 2 m/s is recommended in order to obtain optimal performance. Using the selected design parameters in a typical poultry house and under specific climate conditions, the thermal performance of the system showed that the air temperature inside the poultry house could be lowered in the hot period and heated up in cold period, which significantly reduces the impact of the heat/cold wave. The system can reduce the annual energy bill of the poultry house at the rate of 250.675 MWh, with 146.3773 MWh in heating mode and 104.2978MWh in cooling mode, which demonstrates the efficiency of the system in both heating and cooling. Another benefit of the using EAHE is the environmental issue. The system can mitigate the GHG emissions by an amount of 108.4668 Tons of CO_2 annually.

Further research should be undertaken to investigate the effect of EHAE in reducing the rate of mortality by creating comfortable indoor conditions for animals.

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Nomenclature

Latin symbols

c_p	specific heat capacity, J/(kg K)
D_i	internal tube diameter, m
D_e	external tube diameter, m
h	average heat transfer coefficient, W/(m²K)
k_t	Thermal conductivity of the tube, m²/s²
L	tube length, m
f	friction factor
$\dot{m}$	mass flow rate, kg/s
Pr	Prandtl number
ΔP_{tot}	total pressure drop, Pa
Re	Reynolds number
Nu	Nusselt number
T_i	inlet temperature, °C
T_o	outlet temperature, °C
v	velocity, m/s

Greek symbols

η	Efficiency, %
ε	Roughness of the tube , m
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m3

ξ	Singular pressure drop coefficient

Subscripts

i	Inlet, Internal
o	Outlet
e	External
s	Soil
tot	Total

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