Numerical and Experimental Study of the Thermal Efficiency of an Air-Soil Heat Exchanger in the Sahelian Zone

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Authors’ contributions
This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT
In the Sahelian zone, air conditioning in house by air-soil heat exchangers is an alternative in the context of insufficient of electrical energy. In this work, we carried out a numerical and experimental study of thermal efficiency of an air-soil heat exchanger. This study provided an estimation of thermal efficiency of an experimental air-soil heat exchanger during June, July and August 2016. Numerical results provided a better understanding of the influence of parameters such as tube length, air velocity and soil temperature on the thermal efficiency of this system.

Keywords: Sahelian zone; air-soil heat exchanger; cooling; thermal efficiency.

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1. INTRODUCTION

An Air-Soil Heat Exchanger (ASHE) is a geothermal system that uses the thermal inertia of the soil to heat or cool some of the renewal air of a habitat. The principle of the system consists in injecting into a habitat a flow of air coming from the outside that is forced beforehand to circulate in a pipe buried to a depth in the ground \[1,2\]. As a technology for renewable energy utilization, the ASHE presents various advantages such as economical and efficient energy utilization, no pollution, low operation cost, unrestricted by geological conditions. It is considered as a green energy technology of tremendous potential for building energy supply \[3,4\]. As the main equipment in the system for heat transfer, the ground heat exchanger transfers heat between fluids in the tube and surrounding soils \[5,6\].

The ASHE has been the subject of numerous numerical and experimental works. The work of Hollmüller \[7\] is one of the main references for the thermal of air-soil exchangers. Drawing on extensive theoretical modeling but also on numerous in-situ measurements, the author establishes simple rules for the dimensioning of air-soil exchangers. One of the references also in the field of air-soil exchangers is the work of Stéphane Thiers \[8\]. The author has produced a very advanced mathematical model which gives the temperature of the soil at any moment and at any depth, taking into account the thermal behavior of the soil. In Burkina Faso, Woodson et al. \[9\] carried out an experimental study of the evolution of soil temperature in the case of an air-soil exchanger. They showed that at a depth of 1.5 m, the soil temperature was approximately 30.4 °C. In the research work developed by David Amitrano \[10\], the author proposes objective criteria for the choice of parameters based on numerical simulations of thermal exchange by forced convection in a buried tube.

There is also work that is interested in studying the thermal performance of this system. To this end, the research carried out by David Bartolomeu et al. \[11\] is devoted to the performance of an air-soil heat exchanger. The study is carried out with the aim of a dimensioning of this system, necessary to optimize its performances which are analyzed throughout the year distinguishing the winter and summer seasons. In 2016, Hiresh Dubey et al. \[12\] also conducted an experimental study of the thermal performance of an air-soil heat exchanger used to improve the efficiency of heating, ventilation and air conditioning in a building. The soil temperature is considered constant and the soil is used as a cold source or as a hot source for the cooling or heating of the building \[13\].

This article treats the numerical and experimental study of the thermal performance of an air-soil heat exchanger used for the cooling of a habitat in the Sahelian zone. The numerical model is based on a mathematical approach by the nodal method. The experimental device is carried out in Ouagadougou (Burkina Faso).

2. METHODS OF MODELING AND EXPERIMENTAL DEVICE

2.1 Mathematical Modeling

The system we propose to study is an air-soil heat exchanger consisting of a tube buried in the soil at a given depth. It is described by the following Fig. 1.
For mathematical modeling, we use a one-dimensional model based on the nodal method. This method consists of a fictitious spatial division of the system into "slices" of thicknesses whose sections are perpendicular to the direction of flow. In each slice, the homogeneous variables are assumed and the energy balances are written in successive time intervals until the duration of study is exhausted. The transition from one slice to the next is carried out by retaining the output conditions of the slice (i) as input data of the slice (i + 1).

In general, we can say that the instantaneous variation of the energy rate within an element (i) is equal to the algebraic sum of the flux densities exchanged within this element. The basic equation for heat exchanges is therefore [14]:

\[ e_i \rho_i c_i \frac{dT_i}{dt} = D F S A_i + Q_{mi} + \sum_j \sum_x h_{ij}(T_j - T_i) \]  

\[ D F S A_i : \text{Density of solar flux absorbed by (i) (W m}\text{-2)} \]  
\[ Q_{mi} : \text{Mass flux density exchanged in (i) (W m}\text{-2)} \]  
\[ h_{ij} : \text{Coefficient of heat exchange between (i) and (j) (W m}\text{-2 K}\text{-1)} \]

We apply equation (1) to the various media of the system.

The heat efficiency [%] of the heat exchanger is a very important parameter that takes into account the temperatures of the air and that of the ground. Its expression is also given by [12]:

\[ \varepsilon = \frac{T_{out} - T_{in}}{T_{soil} - T_{in}} \times 100 \]  

\[ T_{in} \text{ is input air temperature, } T_{out} \text{ is output air temperature and } T_{soil} \text{ is the soil temperature.} \]

2.2 Numerical Simulation

For numerical simulation, we use an implicit finite difference method which gives stable results [15,16]. The numerical resolution of the system of equations is done by the Gauss method. The space pitch (\( \Delta X \)) chosen is 0.5 m for the horizontal part and 0.1 m for the vertical parts. With the implicit schema of finite differences, we retained a time step of 30 s. This choice is completed by the following initial conditions: the unknown temperatures are assumed to be equal to the ambient air temperature. The program is run using the FORTRAN calculation code.

2.3 Properties of Materials and Values of System Parameters

The following Table 1 shows the thermal properties of the various materials in the system.

The following Table 2 shows the values of the parameters used for the simulation.

2.4 Experimental Device

It is an air-soil heat exchanger consisting of a PVC pipe 18 m long, with an outside diameter 16 cm (5 mm thick) and placed 1.5 m deep in clay soil wet. Some parts of the system are described in the following Fig. 2.

### Table 1. Thermo-physical properties of the constituent materials of the system

<table>
<thead>
<tr>
<th>Materials of the system</th>
<th>Density (kg m(^{-3}))</th>
<th>Thermal conductivity (W m(^{-1}) K(^{-1}))</th>
<th>Thermal capacity (J kg(^{-1}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>1700</td>
<td>1</td>
<td>912</td>
</tr>
<tr>
<td>Tube</td>
<td>1380</td>
<td>0.15</td>
<td>900</td>
</tr>
<tr>
<td>Air</td>
<td>1.16</td>
<td>0.026</td>
<td>1006</td>
</tr>
</tbody>
</table>

### Table 2. Parameters values used for the simulation

<table>
<thead>
<tr>
<th>Physical parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube length</td>
<td>18 m</td>
</tr>
<tr>
<td>Tube diameter</td>
<td>0.155 m</td>
</tr>
<tr>
<td>Air velocity</td>
<td>Between 0.25 and 4.5 m/s</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>Between 300 and 304 K</td>
</tr>
<tr>
<td>Inlet air temperature</td>
<td>Between 308 and 319 K</td>
</tr>
</tbody>
</table>
This prototype is realized within the platform of Physic of the University Ouaga I Pr Joseph KI-ZERBO. The interchange is connected to a built-up creeper habitat of 32.818 m$^3$ (3.30 m x 3.25 m x 3.06 m). The sheath which connects the exchanger to the housing is insulated with glass wool to limit thermal losses. We opted for the PVC tube taking into account several considerations that are cost, waterproofing, rigidity and durability. Bojic et al. [17] and Bansal et al. [18] have shown that the nature of the tube has very little influence on the thermal performance of an air-soil heat exchanger. Our experimental work consists in measuring on the one hand the temperature of the air from the inlet of the exchanger to the outlet at steps of length 2 m and on the other hand the temperature of the soil at 1.5 m deep. These measurements are performed using K-type thermocouples connected to two programmable temperature recorders (MIDI LOGGER GL 220). The accuracy of these devices is 1% for temperatures between 20 °C and 50 °C. Measurements were made during the months of June, July and August 2016 to assess the thermal efficiency of the system.

3. RESULTS AND DISCUSSION

3.1 Experimental Results

Fig. 3 shows the evolution of the thermal efficiency of the exchanger on 22 and 23 June 2016 during the period from 11:20 to 15:30. We notice in Fig. 3 for each period that there is a fluctuation of the thermal efficiency between 11:20 am and 15:30 pm. It evolves in a decreasing way over time. On June 22 and 23, the average values were 63.89% and 58.39%, respectively. According to data for June 2016, the ambient temperature is higher on June 23 (maximum value of 39.5 °C) than on June 22 (maximum value of 38.8 °C). On the other hand, the soil temperature is identical (about 30.5 °C). Thus, for a given period, if the difference between the ambient temperature and the soil temperature is greater, then the thermal efficiency is higher. When the distance between the ambient temperature and the temperature of the air at the outlet of the exchanger is low, the thermal efficiency is low. According to [12], if the difference between the outside temperature and the soil is greater, then the efficiency of the exchanger is better.

Fig. 4 shows the evolution of the thermal efficiency of the exchanger on 14 and 15 July 2016 during the period from 12:10 to 14:50. We observe in Fig. 4 that during these three days, there is a fluctuation of the thermal efficiency between 12:10 am and 14:50 pm. During this period, thermal efficiency decreases over time. On July 14 and 15, the average values were 60.43% and 75.38%, respectively. According to data for July 2016, the ambient temperature is lower on 15 July (maximum value of 35.7 °C) than on 14 July (maximum value of 39.6 °C).

Fig. 5 shows the evolution of the thermal efficiency of the exchanger from 13 to 18 August 2016 during the period from 12:30 am to 16:30 pm. We note in Fig. 5 that there is a fluctuation of the thermal efficiency over time. For the period of August 13, 2016, the amplitudes are much larger with extreme values that are 100% at 12:40 am and then at 12:50 and 00 at 14:50 pm. On the other hand, on August 18, 2016, the amplitudes are smaller and the values of the thermal
efficiency are between 20% and 60%. On August 13 and 18, 2016, the mean efficacy values were respectively 56.09% and 41.36%. These values are low because the month of August is particularly rainy and the ambient air temperatures are relatively low (average value of 26.08 °C). Thus, during the period from 12:30 am to 16:30 pm, the cooling of the air is less important.
3.2 Numerical Results

3.2.1 Evolution of the thermal efficiency along the tube

We study the evolution of the heat efficiency of the exchanger along the inner wall of the tube. The result of the simulation performed is given in Fig. 6.

In Fig. 6, we note that the thermal efficiency increases logarithmically between 0 m and 16.5 m and then decreases slightly to 18 m. The thermal efficiency of our system is 91.18% at the output and its average value is 87.68%. These results reflect the good functioning of the system, because the system ensures good cooling of the air.

3.2.2 Influence of air velocity on thermal efficiency

We vary the air velocity between 0.25 and 4.5 m/s to study its influence on the evolution of thermal efficiency. We obtain Fig. 7.

In Fig. 7, we note that when the air velocity increases from 0.25 m/s to 0.75 m/s there is a sudden increase in thermal efficiency from 86.46% to 91.94%, then for air velocity ranging from 0.75 m/s to 4.5 m/s there is a slow decrease from 91.94% to 90.47%. When the air velocity increases, the cooling also increases for air velocity less than 0.75 m/s. But beyond this, the cooling of the air becomes weak and the air velocity has any influence on the heat
exchanges. We retained 2 m/s as the air velocity for our various simulations, because for this speed the corresponding thermal efficiency is 91.18%.

3.2.3 Influence of input temperature on thermal efficiency

We vary the input temperature and we follow the evolution of the heat exchanger efficiency. We obtain Fig. 8.

In Fig. 8, we note that when the input temperature increases, the heat efficiency of the exchanger increases. For an input temperature of 308 K, the corresponding thermal efficiency is 82.46%. On the other hand, for an input temperature of 319 K, the thermal efficiency is 94.45%. Indeed, when the input temperature increases, the cooling of the air increases. Since the soil temperature is fixed and is 303 K, the increase of the temperature difference between the air and the soil promotes a good heat exchange between the latter.

3.2.3 Influence of soil temperature on thermal efficiency

We vary the temperature of the soil between 300 K and 304 K, and then we simulate the evolution of the heat efficiency of the exchanger. We obtain Fig. 9.

Fig. 8. Evolution of the heat efficiency of the exchanger as a function of the air inlet temperature

Fig. 9. Evolution of the heat efficiency of the exchanger as a function of soil temperature
In Fig. 9 we note that when the soil temperature increases, the heat efficiency of the exchanger decreases. When we change the soil temperature from 300 K to 304 K, the thermal efficiency of the exchanger decreases from 93.19% to 90.21%. Indeed, when the temperature of the soil increases, the cooling of the air decreases. This again reflects the great influence of the soil temperature on the functioning of our system.

4. CONCLUSION

In this article, we analyzed the thermal efficiency of an air-soil heat exchanger (ASHE) for the cooling a habitat in Sahelian zone.

The experimental results show that, the thermal efficiency increases when the difference between the ambient air temperature and the soil temperature increases. During the warm periods of the day in June, July and August 2016, the average thermal efficiency of ASHE reached respectively 63.89%, 75.38% and 56.09%.

The numerical results show that the thermal efficiency increases logarithmically along the ASHE and can reach 91.18% at the output. The air velocity values (of the order of 4.5 m/s) do not favor the increase of the thermal efficiency. For a given soil temperature, when the input temperature increases (from 308 K to 319 K), the thermal efficiency of the exchanger increases significantly (from 82.46% to 94.45%). For a given input air temperature, increasing the soil temperature (from 300K to 304K) reduces the thermal efficiency of the exchanger (from 93.19% to 90.21%). In practice, the yields are between 20% and 70%. A good quality exchanger should have a performance of at least 50% in all operating conditions [18].

Our results suggest that during hot periods of the day, ASHE cools the air for the habitat. In addition, the choice of parameters (pipe length, air velocity and soil depth) makes it possible to improve the thermal efficiency of the air-soil heat exchanger.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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