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Numerical study of the thermal environment in a habitat: Materials analysis

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Abstract
The use of air-soil heat exchangers (ASHE) for cooling a habitat has developed considerably in recent years. An air-soil heat exchanger (ASHE) is a geothermal system that uses the thermal inertia of the soil to heat or cool part of the air to renew a habitat. The principle of the system is to inject into a habitat, air flow from outside that is forced beforehand to flow in a pipe buried at a certain depth in the soil. Air-soil heat exchangers have been the subject of numerous numerical and experimental works.In this work, we conducted a numerical study of the evolution of air temperature in a habitat coupled with an air-soil heat exchanger in Ouagadougou. This work evaluated with the physical parameters (such as the type of habitat material, the roof, the rate of air renewal and the height of the wall) the influence of the ASHE on the temperature of the air in the habitat. Our results show that there is an influence of the ASHE on the thermal environment in the habitat during the hot periods of the day. Taking these parameters into account could contribute to the improvement of thermal comfort in the habitat in Sahelian zone.

1. Introduction
The building sector is one of the top three energyconsumers in the world, with transportation andindustry [1]. The share of energy consumption inbuildings amounts to 40% of world energy [2] and 50% of this consumption is devotedgenerally to heating, ventilation and airconditioning systems [3]. The thermal design of abuilding influences the thermal performance ofthe building, which also affects energy consumption [4]. The thermal performance of a buildingcan be improved by acting either on its physicalform, its solar protections [5,6] and its orientation [7], or on the composition of the materials of itsenvelope (improvement of the thermal inertia).
An air-soil heat exchanger (ASHE) is a geothermal system that uses the thermal inertia of the soil to heat or cool part of the air to renew a habitat. The principle of the system is to inject into a habitat, air flow from outside that is forced beforehand to flow in a pipe buried at a certain depth in the soil [8,9].
ASHE have been used generally to utilize shallow geothermal energy. 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 [10,11].
As the main equipment in the system for heat transfer, the ground heat exchanger transfers heat between fluids in the tube and surrounding soils [12,13].

The air-soil heat exchangers have been the subject of many works, both numerical and experimental. Numericalworks are based on different models. Among them are thediffuse model and the model which assumes given thetemperature of the soil. Among the various worksexplicitly dealing with conduction in the soil, a good partonly allows the study on a single tube of the system.

These are the cases of [14, 15] and [16]. Whereas in thefirst case [14], the conduction equation is resolvednumerically in soil cut into horizontal slices at uniformtemperatures. At the surface of the soil, the radiations andconvections are retained and the lower part assumed to be

adiabatic. The other work [15] assumes cylindrical soil layers as well as horizontal segmentation along thetube (iterative calculation, air temperature at output of asegment serving as input to the next segment). In this case an adiabatic condition is assumed to be applied ata large radial distance from the tube (thus not taking intoaccount the mutual influence of parallel tubes) and the coupling with the free surface is done in a not veryexplicit way via the analytical solution of seasonal diffusion in undisturbed soil [15]. In the second case [16], the concentric cylinders aresubdivided into three portions (adjustable proportions),each subject (at adjustable distance) provided at theadiabatic or isothermal edge. There are also works that areinterested in studying the thermal performance of this system. To this end, the research work carried out by [17] is devoted to the performance of an air-soil heatexchanger. The study is carried out with the aim of adimensioning of this system, necessary to optimize itsperformances which are analyzed throughout the yeardistinguishing the winter and summer seasons.

In 2016, [18] also conducted an experimental study of the thermalperformance of an air-soil heat exchanger used to improvethe efficiency of heating, ventilation and air conditioningin a building .

The work of Hollmuller [19] is today one of the main references for the heat of air-ground heat exchangers. Based on a thorough theoretical modeling but also on many in-situ measurements, the author establishes simple rules for the design of air-ground heat exchangers. One of the references also in the field of air-ground heat exchangers is the work of Stéphane Thiers [20]. The author has made a very advanced mathematical model that gives the soil temperature at any time and at any depth, taking into consideration the thermal behavior of the soil. In Burkina Faso, Woodson et al. [21] carried out an experimental study of the evolution of the soil temperature in the case of an air-ground heat exchanger. They showed that at 1.5 m depth, the soil temperature was approximately 30.4°C. In the research work developed by David Amitrano [22], the author proposes objective criteria for the choice of parameters based on numerical simulations of heat exchange by forced convection in a buried tube.

B. Kaboré et al. [23] carried out an analytical study of the functioning of an ASHE in the meteorological conditions of the city of Ouagadougou for the year 2014. The results made it possible to understand the influence of certain parameters (the soil depth, the length of the tube and the air flow) on the annual operation of the ASHE. These results also showed that ASHE responds favorably to Ouagadougou meteorology.

In 2017, B. Kaboré et al. [24] showed that a nodal approach is effective for the study of air-soil heat exchangers. This method leads to acceptable results in view of the literature and with respect to experimental measurements. This study has shown that in the Sahelian zone, with an exchanger about 15 m of length and buried at 1.5 m deep in the soil, we can cool the air during hot periods of the day. The experimental exchanger makes it possible to stabilize the air temperature beyond 4 m to 6 m in length in the tube, whatever the temperature of inlet and for all periods. Decreases in air temperature along the system can reach 13°C in June, 12°C in July and 8°C in August. These experimental results show that the cooling of the air is all the more important as the period is warmer.

The objective of our work is to evaluate with the physical parameters (the type of material of the habitat, the roof, the rate of air renewal and the height of the wall) the influence of the ASHE on the air temperature in the habitat.

2. Description of the air-soil heat exchanger and the habitat

2.1. The air-soil heat exchanger (ASHE)

The air-soil heat exchanger consists of a poly vinyl chloride (PVC) pipe (U-type) of horizontal length 15 m, diameter 16 cm and placed at a depth of 1.5 m (slope of approximately 2%) in the soil. We will study the following cases: cement block habitat, compressed earth block (BTC) habitat and adobe habitat. **Figure 1** describes the ASHE-habitat system.

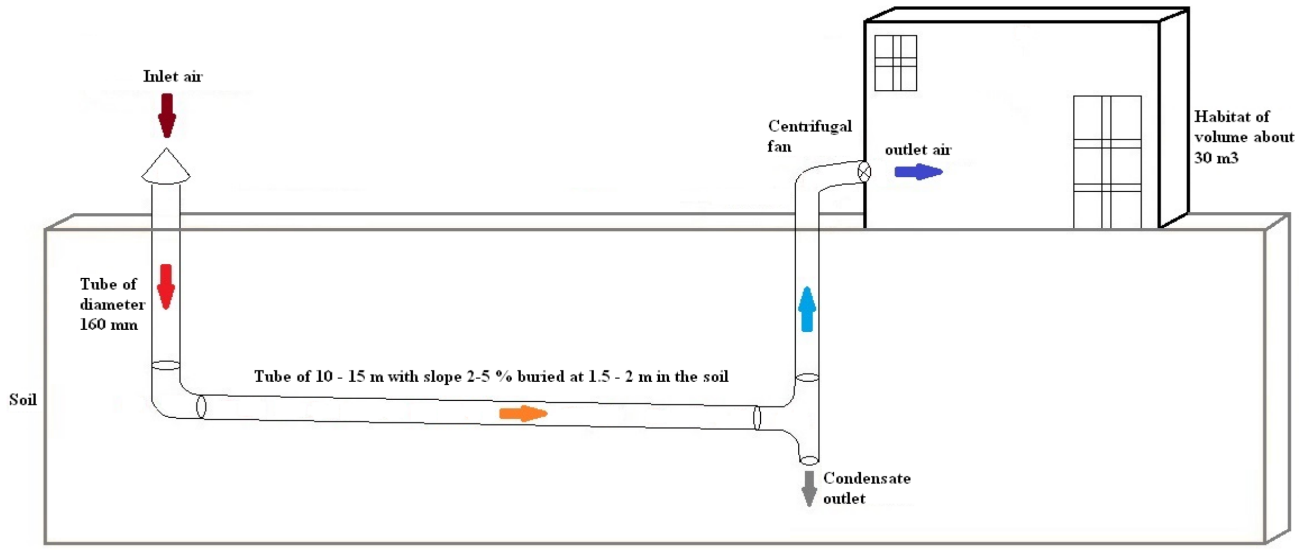

Figure 1. Scheme of the system ASHE-habitat.

2.2. Description of the materials used for the habitat

a- Brick made with cement block:

The brick of cement called cinderblock or agglomerated (**figure 2.a**), is a block of manufactured cement which makes it possible to erect the walls and the habitats. Cement makes it possible to have a habitat that withstands bad weather over time. It is fixed thanks to a mortar made of cement and sand.
In Burkina Faso, cement block is used in large urban centers for the construction of modern buildings. These buildings not being adapted to the local climate, very often cause excessive loads for the air conditioning equipment.

b- The compressed earth block (BTC):

The compressed earth block (**Figure 2.b**) is a modern evolution of the adobe block. These are small parallelepiped-shaped masonry elements whose common dimensions, however, differ from molded earth blocks or fired bricks and vary according to the type of press and the modules that are adapted to them.
The compressed earth blocks are made from moist earth and compacted in a press. They can be stabilized and stabilization is the stage in the manufacturing process to stabilize performance over time.
Energy saving and comfort in the building being a priority, the BTC could be an alternative to the cinder block. This natural material has the particularity of absorbing the excess moisture contained in the

ambient air and that. The BTC block restores this moisture during the dry phases. Thanks to the inertia, no need for air conditioning.

c- The adobe brick:

The adobe brick (**Figure 2.c**) commonly called "banco" brick is an element of masonry. It is obtained by molding the earth in the wet state in a wooden mold and rectangular shape. The mold obtained is then dried in the open air.

In Burkina Faso, the construction of houses with adobe is done without foundation and without measures of protection of the foot of the wall. This construction technical leads to habitats that are less resistant to bad weather and therefore less durable. In the rural zones of Burkina Faso, the majority of habitats walls are based on adobe materials.

Figure 2a. Brick made of cement block

Figure 2b. The compressed earth block (BTC)

Figure 2c. The adobe brick

Figure 2. Materials used for habitat [25]

Table 1 gives the thermal and physical properties of the previous materials.

Table 1. Thermal and physical properties of materials of habitat [26] [27] [28]

Materials	**Density ($kg\ m^{-3}$)**	**Thermal conductivity ($W\ m^{-1}\ K^{-1}$)**	**Thermal capacity ($J\ kg^{-1}\ K^{-1}$)**
Air	1.250	0.023	1000
Cement block	1000	0.83	1000
BTC	1960	0.671	1492
Adobe brick	1394	0.450	1213
Roof	7800	50	450

3. Mathematical modeling and numerical simulation

The scheme of thermal exchanges in the habitat is described in **Figure 3**.

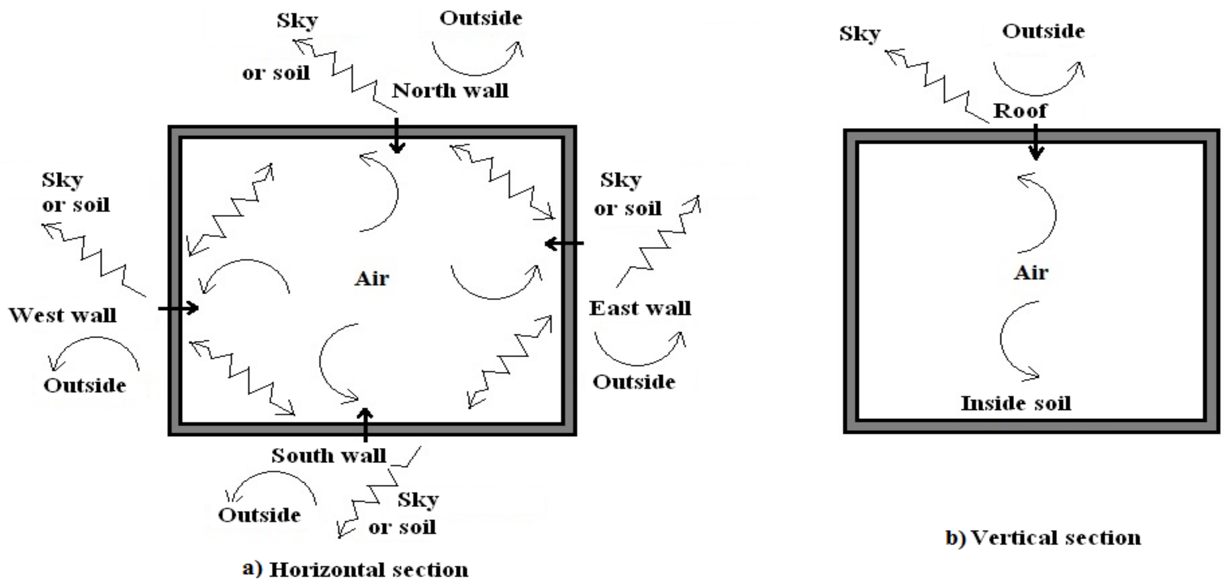

Figure 3. Scheme of thermal exchanges in the habitat.

For modeling, we use the nodal method. This method involves a fictitious spatial division of the system into "slices" of thickness whose sections are perpendicular to the direction of the flow. In each slice, the homogeneous variables are assumed and the energy balances are written in successive time intervals until the duration of the study is exhausted. The transition from one slice to the next is performed by retaining the output conditions of the slice (i) as input data of the slice (i + 1).

3.1. Equations of thermal exchanges in habitat

In a general way, we can say that the instantaneous variation of the rate of energy within an element (i) is equal to the algebraic sum of the flux densities exchanged within this element.

The basic equation of thermal exchanges is in **Eqn. 1**[29] [30] [31]:

$$e_i \rho_i c_{pi} \frac{dT_i}{dt} = DFSA_i + Q_{mi} + \sum_j \sum_X h_{Xij} (T_j - T_i) \quad (1)$$

We apply equation (1) to the various environments of our system. Mass transfers are not counted.

In order to solve the equations obtained previously, we determine the heat transfer coefficients appearing in each second member [24].

3.2. Simulation of thermal behavior of habitat

We use a finite difference method implicit as in the case of the air-soil heat exchanger. In order to reduce the calculation time, we choose 300 seconds like time step. We solve the difference equations by the method of Gauss, choosing a precision equal to 10^{-3}.

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. We perform a habitat coupling with an air-to-ground heat exchanger (ASHE) for cooling the air. This allows us to study the influence of the heat exchanger on the thermal behavior of the habitat during a year. The meteorological data used concern the average hourly ambient air temperature for the city of Ouagadougou from 2014. These data are measured in the meteorological station. They are integrated into the simulation program. Thus, we are interested in the month of April considered as the hottest month in Burkina Faso.

Figure 4 describes the algorithm of the simulation program. The numerical study is based on this program.

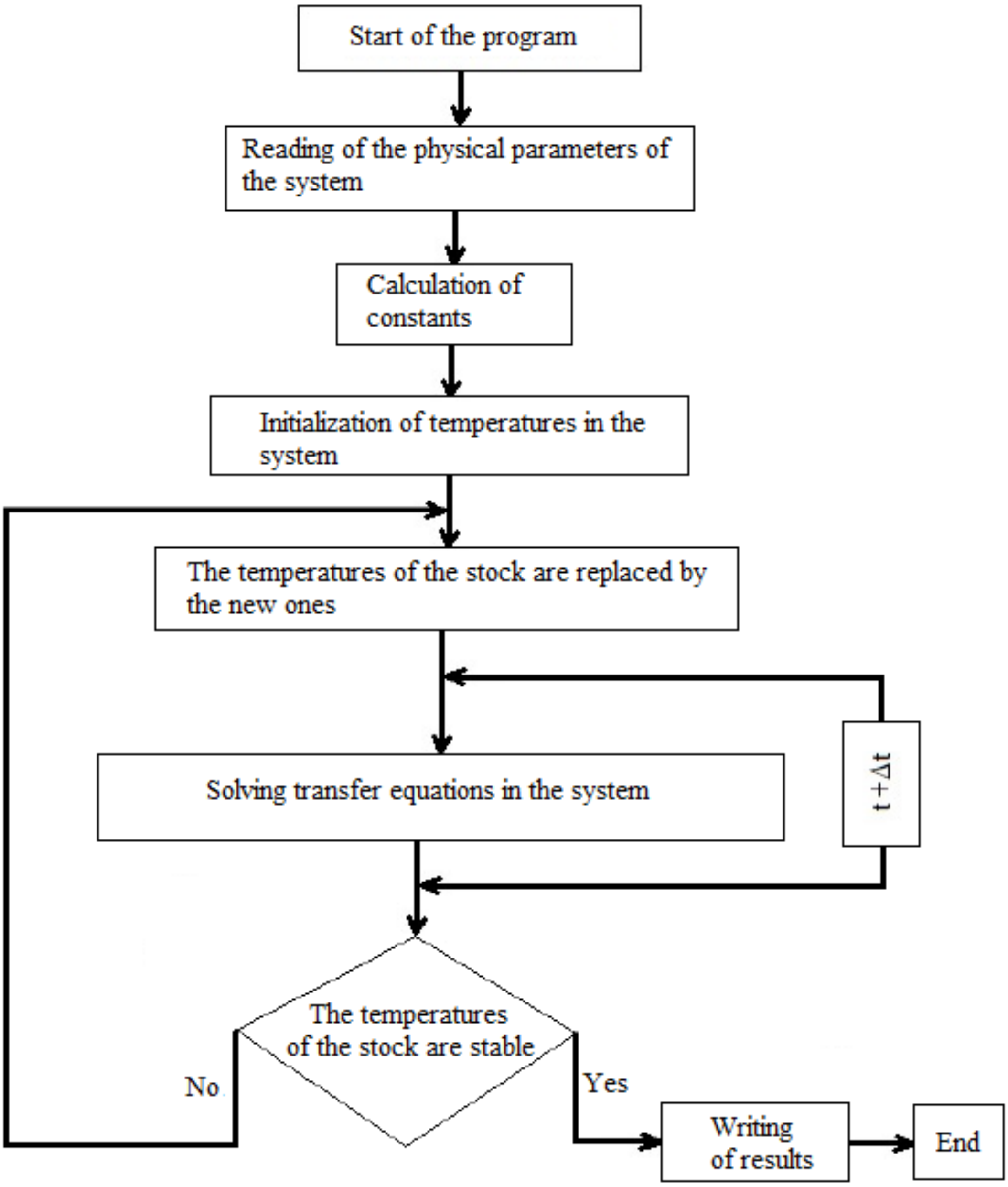

Figure 4. Algorithm of simulation program

4. Results of numerical simulations

4.1. Influence of the exchanger on the air temperature in different types of habitat

To better understand the influence of the ASHE on the air temperature in the habitat, we made a simulation in two cases:

- *Case 1: Habitat without ASHE*

This simulation is carried out with several types of habitat, according to the nature of the wall(cement block, BTC or adobe). After simulation, we obtain **Figure 5**. We observe that the temperature of the air is almost identical over time in all habitat types considered (cinder block, BTC or adobe). Whatever the type of habitat, the air temperature is high than that of the ambient air during the hot periods of the day, especially from 10 am to 5 pm. For example, at 1 pm, the air temperature in each type of habitat is about

39.4 °C and that of the ambient air at the same time is about 37.3 °C. This shows the need to bring an air of renewal for cooling in these different types of habitats.

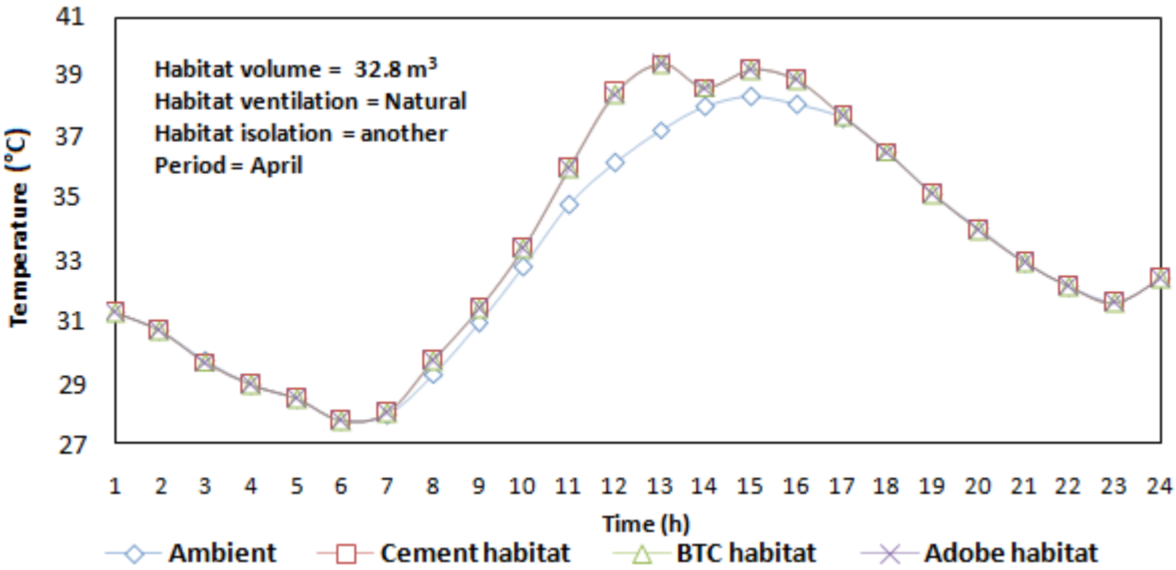

Figure 5. Evolution of air temperature in different types of habitat without ASHE

- *Case 2: Habitat with ASHE*

We repeat the previous simulation considering this time that the habitat is coupled to an ASHE for cooling purposes. After simulation, we obtain **Figure 6**.

On **Figure 6**, we observe that the temperature of the air is almost identical over time in all habitat types considered (cinder block, BTC or adobe). Whatever the type of habitat, the air temperature is low than that of the ambient air during the hot periods of the day, especially from 10 am to 5 pm. For example at 2 pm, the air temperature in each type of habitat is about 33.6 °C and at the same time that of the ambient air is about 38 °C. Thus, under the effect of the heat exchanger there is a significant decrease in air temperature in each habitat compared to the previous case (habitat without ASHE). In the case of the cement block habitat, at 2 pm the drop in air temperature is about 5 °C.

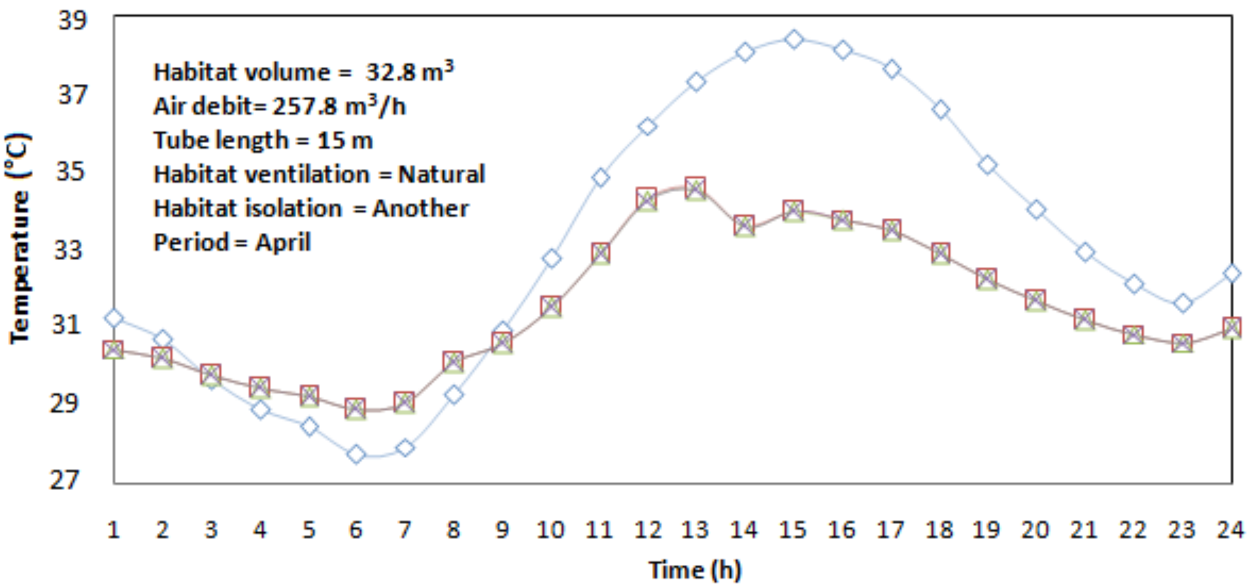

Figure 6. Evolution of air temperature in different habitat types with ASHE

4.2. Influence of the roof on the air temperature in different types of habitat

In this part, we first consider that the roof of the habitat is isolated. Then, we vary the type of habitat. We obtain the following result on **Figure 7**.

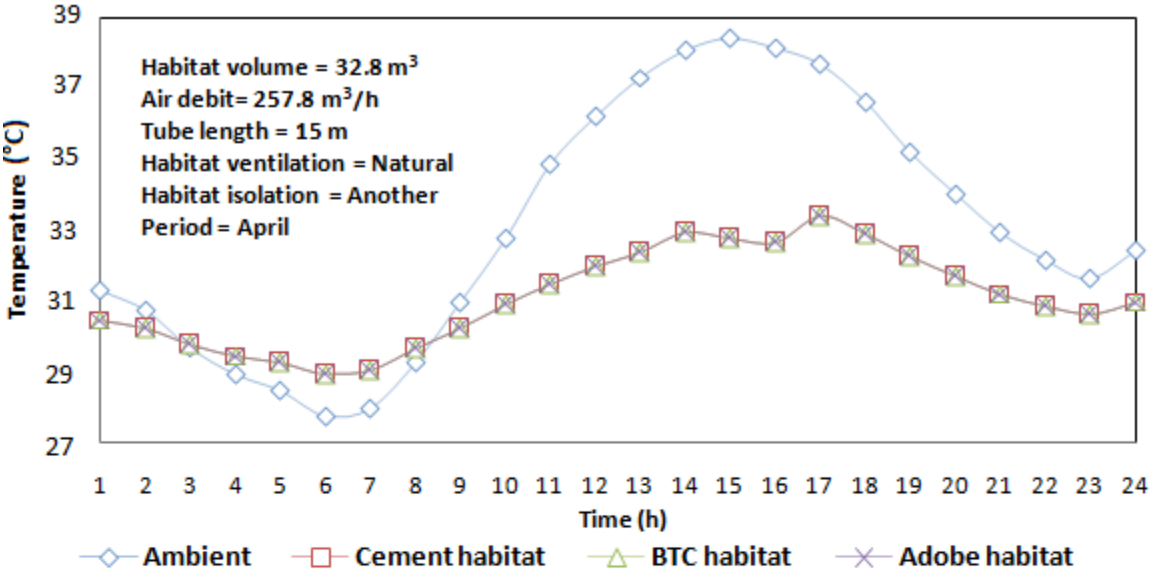

Figure 7. Evolution of air temperature in different types of habitat with insulated roof

On **Figure 7**, the curves of temperature are similar to those of Figure 5. But, a difference is observed in the air temperature values in each habitat type. Indeed, the roof being insulated, it cancels the thermal contribution. This explains the slight decrease in air temperature in each type of habitat during the hot periods of the day. For example at 2 pm, in the cement block habitat without insulated roofing, the temperature is 33.6 °C. At the same time, in the cement block habitat with insulated roofing the temperature is 32.9 °C. The analysis that we make is that in practice the insulation roof is difficult to achieve certainly, but it is possible to find materials (roofing) that are able to reduce the heat input of the roof. It is in this perspective that we vary the type of roof, and then we simulate the evolution of air temperature in the breeze block habitat. We obtain the following results on **Figure 8**.

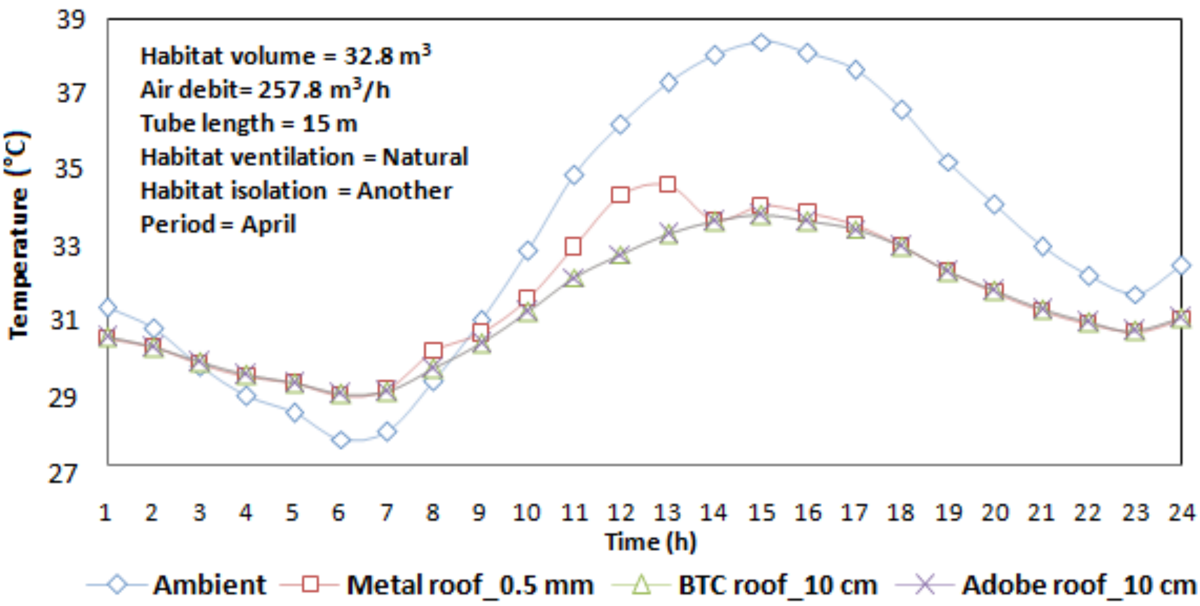

Figure 8. Evolution of the air temperature in habitat for different roofs

On **Figure 8**, the curves are plotted by considering the cement block habitat in three cases:

- Metal roof 0.5 mm thick; - BTC roof 10 cm thick; - Adobe roof 10 cm thick.

On **Figure 8**, we observe that during the hot periods of the day, especially from 10 am to 5 pm, the air temperature in the habitat with metal roof is slightly higher than that of the air in the other two cases (BTC roof and adobe roof). For example at 12 am, the temperature difference is about 1.6 °C. This is explained by the fact that the metal roof leads more than the roofs in BTC and adobe. Thus, the metal roof contributes more to the heating of the air in the habitat. It would therefore be wise to avoid these types of roofing in the construction of habitats.

4.3. Influence of the renewal rate of air on the air temperature in habitat

The supply of renewal air in the habitat is ensured by the ASHE, it is essential to control its rate in order to optimize the cooling. We vary the air renewal rate provided by the ASHE to the cement block habitat. The simulations lead us to **Figure 9**.

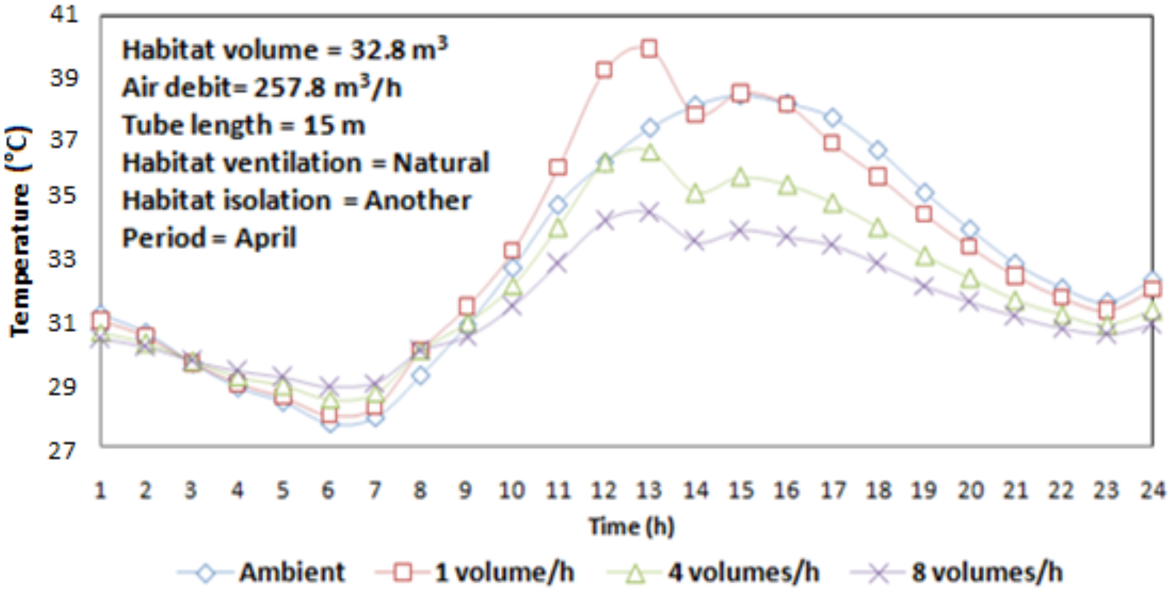

Figure 9. Evolution of the air temperature in the habitat for different renewal rates

On **Figure 9**, we observe that during the hot periods of the day (between 10 am and 5 pm) when the renewal rate of air increases the temperature of the air in the habitat decreases.

For example at 1 pm, the ambient air temperature is 37.3 °C and for renewal rates of 1 volume / hour, 4 volumes / hour and 8 volumes / hour, the air temperatures in the habitat are respectively 39.9 °C, 36.6 °C and 34.5 °C. Our analysis of these results is that for a turnover rate of 1 volume / hour, ASHE does not cool the air in the habitat because the air is warmer than the ambient air. On the other hand, for a renewal rate of 4 volumes / hour and 8 volumes / hour, the ASHE cools the air in the habitat with a decrease of respectively 0.7 °C and 2.8 °C compared to the temperature of ambient air.

It is therefore necessary to use an aspirator whose power allows the ASHE to deliver a sufficient airflow for cooling air in the habitat.

4.4. Influence of the Wall height on the air temperature in habitat

We are also interested to the geometry of the habitat. For this, we vary the height of the wall to study its influence on the temperature of the air in the habitat. We obtain **Figure 10**.

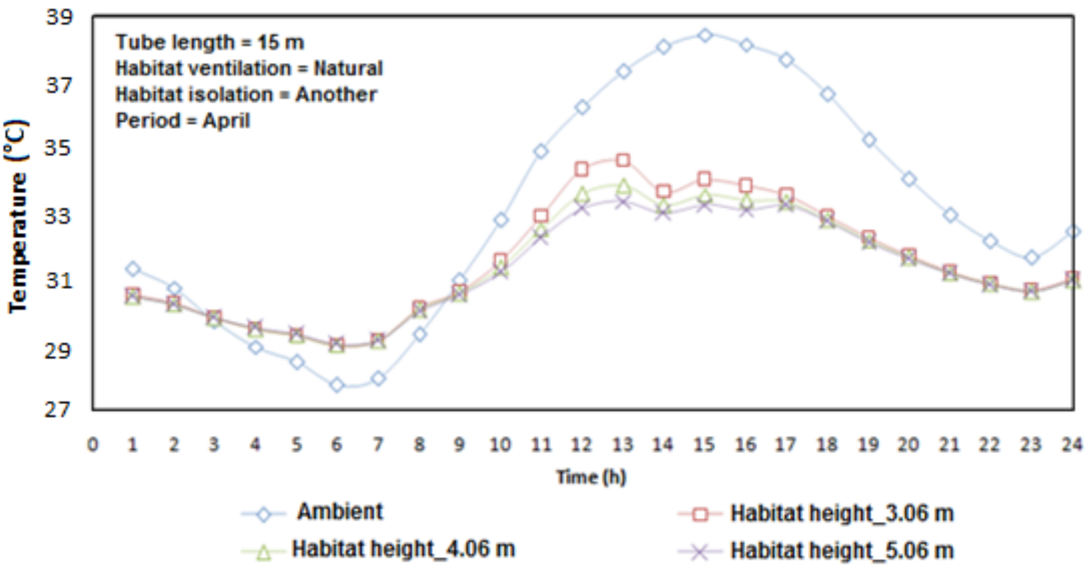

Figure 10. Evolution of the air temperature in habitat for different heights of the wall

On **Figure 10**, we observe that during the hot periods of the day, especially between 10 am and 5 pm, when the height of the wall increases, the air temperature in the habitat decreases. For example, when the height of the wall goes from 3.06 m to 5.06 m, the air temperature in the habitat at 1 pm decreases by 1.2 °C. As the height of the wall increases, that reduces radiation heat transfer between the roof and other internal parts of the habitat.

Conclusion

In this paper, we conducted a numerical study of the evolution of air temperature in a habitat (cement block, BTC or adobe) coupled to an air-soil heat exchanger in Sahelian zone. For modeling, we used the nodal method and the implicit finite difference method. For the simulation we used the FORTRAN calculation code.

This work evaluated from the physical parameters (such as the type of habitat material, the roof, the air change rate and the height of the wall) the influence of the ASHE on the temperature of the air in the habitat.

Our results show that during the hot periods of the day, especially between10 am and 5 pm:

- Whatever the type of habitat (without ASHE), the air temperature is high than that of the ambient air;
- As a result of ASHE, there is a significant decrease in air temperature in each habitat type(up to 5°C) compared to air temperature in habitat without ASHE;
- The temperature of the air in the habitat with metal roof is slightly higher than that of the air in the other two cases (BTC roof and adobe roof);
- When the renewal rate of air increases the temperature of the air in the habitat decreases;
- When the height of the wall increases, the air temperature in the habitat decreases.

All of these results show that there is an influence of the ASHE on the thermal environment in the habitat during the hot periods of the day. Taking these parameters into account could contribute to the improvement of thermal comfort in the habitat.

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