Numerical and experimental study of an air-soil heat exchanger for cooling habitat in Sahelian zone: case of Ouagadougou

Boureima Kaboré[1*], Sié Kam[1], Germain Wende Pouiré Ouedraogo[1], Belkacem Zeghmati[2], Xavier Chesneau[2], Dieudonné Joseph Bathiébo[1]

[1] Laboratory of Renewable Thermal Energy, University Ouaga I Pr Joseph KI-ZERBO, Burkina Faso.
[2] Laboratory of Mathematics and Physics, University of Perpignan, France.

Abstract— *The use of air-soil heat exchangers for the cooling home has developed considerably in recent years. In this work, we have leaded the numerical study of an air-soil heat exchanger by using a nodal approach. We have also presented our experimental prototype implemented in Ouagadougou. This study has allowed determining the evolution of air temperature along the exchanger and also validating our numerical results with those of the literature and the experiment.*

Keywords— *Air-soil heat exchanger, Numerical study, Nodal approach, Experimental prototype.*

I.   INTRODUCTION

An air-soil heat exchanger is a geothermal system that uses the thermal inertia of the soil to heat or cool some of the air renewing a habitat. The principle of the system consists to inject into a habitat a flow of air coming from the outside that is forced beforehand to circulate in a pipe buried at a depth in the soil [1].

Air-soil heat exchangers have been the subject of numerous numerical and experimental works. Numerical works are based on different models. Among them are the diffuse model and the model which assumes given the temperature of the soil. Among the various works explicitly dealing with conduction in the soil, a good part only allows the study on a single tube of the system. These are the cases of [2, 3] and [4, 5]. Whereas in the first case [2], the conduction equation is resolved numerically in soil cut into horizontal slices at uniform temperatures. At the surface of the soil, the radiations and convections are retained and the lower part assumed to be adiabatic. The two other works [3, 4] assume cylindrical soil layers as well as horizontal segmentation along the tube (iterative calculation, air temperature at output of a segment serving as input to the next segment). In the first case [3] an adiabatic condition is assumed to be applied at a large radial distance from the tube (thus not taking into account the mutual influence of parallel tubes) and the coupling with the free surface is done in a not very explicit way via the analytical solution of seasonal diffusion in undisturbed soil.

In the second case [4], the concentric cylinders are subdivided into three portions (adjustable proportions), each subject (at adjustable distance) provided at the adiabatic or isothermal edge. There are also works that are interested in studying the thermal performance of this system. To this end, the research work carried out by [6] 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, [7] 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 cooling or heating the building. Thermal efficiency is assumed to be a function of the number of transfer units. They have mainly studied the influence of speed on changes in the temperature of the air at the outlet of the exchanger and the thermal efficiency of the system. [8], is one of the main references for the thermal efficiency of air-soil exchangers. The author sets out 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 [9]. 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, [10] 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.

The objective of this work is the numerical and experimental study of an air-soil heat exchanger used for the cooling habitat in the Sahelian zone. Our numerical study is based on a mathematical approach by the nodal

method. We present the results concerning the evolution of the air temperature in the horizontal part of the exchanger and their validations by results of the literature and also of our experimental measurements.

Fig. 1: Diagrams of the model of air-soil heat exchanger

II. MATHEMATICAL MODELING

The system we propose to study is an air-soil heat exchanger consisting with one tube buried in the soil at a given depth. It is described in Fig.1.
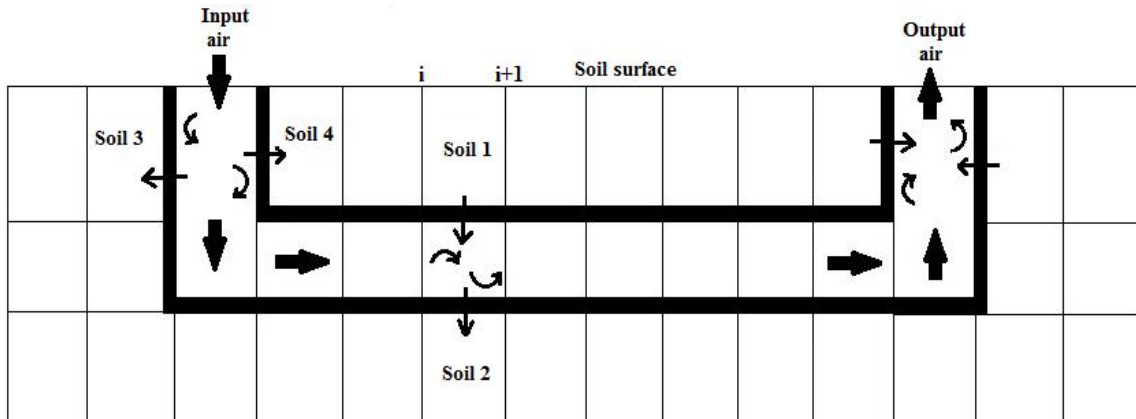
For mathematical modeling, we are interested to the "horizontal part" of the system (Figure 2). We use a one-dimensional model for heat exchanges. For modeling, we use the nodal method. This method consists of a fictitious spatial division of the system into "slices" of thicknesses whose sections are 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 exhaustion of the duration of study. 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).

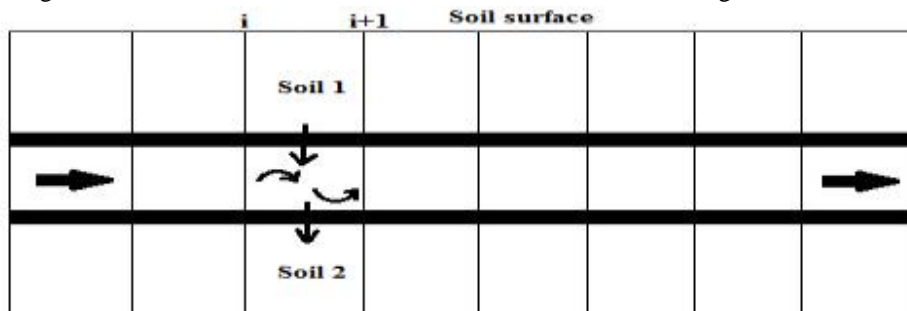The following Fig. 2 describes the horizontal part of the air-soil heat exchanger.

Fig. 2: Diagram of the horizontal part of the system

Generally, 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 (1) of heat exchanges is [11]:

- In soil surface :

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

$DFSA_i$: Density of solar flux absorbed by (i) (W m^{-2})

Q_{mi} : Mass flow density exchanged in (i) (W m^{-2})

h_{Xij} : Coefficient of heat exchange between (i) and (j) (W m^{-2} K^{-1})

We apply equation (1) to the various media of the vertical input part. The thermo-physical properties of materials are assumed homogeneous and constant.

- In soil surface :

$$e_s \rho_s c_{ps} \frac{dT_{ss}}{dt} = DFSA_{ss} + -h_{cae}(T_{ss} - T_{ae}) - h_{ds}(T_{ss} - T_{sol1}) + -h_{rssvc}(T_{ss} - T_{vc}) \tag{2}$$

- In soil 1 :

$$e_s \rho_s c_{ps} \frac{dT_{sol1}}{dt} = -h_{ds}(T_{sol1} - T_{ss}) + -h_{ds}(T_{sol1} - T_{ptSE}) \tag{3}$$

- At the outer superior wall of the tube :

$$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptSE}}{dt}=$$
$$-h_{ds}(T_{ptSE}-T_{sol1})+ \qquad (4)$$
$$-h_{dpt}(T_{ptSE}-T_{ptSI})$$

- At the inner superior wall of the tube :

$$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptSI}}{dt}=$$
$$-h_{dpt}(T_{ptSI}-T_{ptSE})+ \qquad (5)$$
$$-h_{cat}(T_{ptSI}-T_{ath})$$

- In the air into the tube:

$$\frac{Vol_{at}}{S_{pt}}\rho_{a}c_{pa}\frac{dT_{ath}}{dt}=$$
$$-h_{cat}(T_{ath}-T_{ptSI})+ \qquad (6)$$
$$-h_{cat}(T_{ath}-T_{ptII})$$

- At the inner inferior wall of the tube :

$$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptII}}{dt}=$$
$$-h_{cat}(T_{ptII}-T_{ath})+ \qquad (7)$$
$$-h_{dpt}(T_{ptII}-T_{ptIE})$$

- At the outer inferior wall of the tube :

$$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptIE}}{dt}=$$
$$-h_{dpt}(T_{ptIE}-T_{ptII})+ \qquad (8)$$
$$-h_{ds}(T_{ptIE}-T_{sol2})$$

In order to solve the previously obtained equations, we determine the coefficients of transfer by conduction, convection and radiation.

– Radiation between soil surface and the vault of heaven:

$$h_{rssvc}=\varepsilon_{ss}\sigma(T_{ss}^{2}+T_{vc}^{2})(T_{ss}+T_{vc}) \quad (9)$$

With : $\sigma=5,67.10^{-8}Wm^{-2}K^{-4}$, constant of Stefan-Boltzmann ; T_{ss} , soil surface temperature ; $\varepsilon_{ss}=0,85$, soil emissivity.

The temperature of vault of heaven is given by Swinbank expression [12]:

$$T_{vc}=0,0552\times T_{ae}^{1,5} \qquad (10)$$

T_{ae} is the ambient air temperature.

– The coefficient of convection between soil surface and ambient air [12]:

$$h_{cae}=2,8+3,3\times V_{ae} \qquad (11)$$

V_{ae} is ambient air velocity.

- Soil conduction coefficient [11] :

$$h_{ds}=\frac{\lambda_{s}}{e_{s}} \qquad (12)$$

λ_{s} is thermal conductivity of soil and e_{s} is the thickness of the soil.

- Tube conduction coefficient [11] :

$$h_{dpt}=\frac{\lambda_{pt}}{D_{E}\times\frac{e_{pt}}{D_{I}}} \qquad (13)$$

λ_{pt} is the thermal conductivity of the tube ; D_{E} is the outer diameter of the tube ; D_{I} is the inner diameter of the tube ; e_{pt} is the thickness of the tube.

– Coefficient of forced convection of the air in the tube [9]:

$$h_{cat}=\frac{Nu\times\lambda_{a}}{L}=$$
$$\frac{(0,023\,\mathrm{Re}^{0,8}\times\mathrm{Pr}^{n})\times\lambda_{a}}{L} \qquad (14)$$

$$\mathrm{Re}=\frac{V_{a}\times D_{i}}{\nu_{a}} \quad ; \quad \mathrm{Pr}=\frac{\mu_{a}\times C_{pa}}{\lambda_{a}} \quad ;$$

$$\mu_{a}=\nu_{a}\times\rho_{a}$$

If $T_{ath}>T_{sol}$ (cooling) then n = 0.3 or if $T_{ath}<T_{sol}$ (heating) then n = 0.4.

The characteristic length L is equal to the inside diameter D_{I} of the tube; T_{ath} is the temperature of the air in the vertical tube; T_{sol} is the soil temperature. Nu is the number of Nusselt; λ_{a} is the thermal conductivity of the air; Re is the Reynolds number; Pr is the number of Prandtl; V_{a} is the velocity of the air in the tube; μ_{a} is the dynamic viscosity of the

air ; V_a = 15,6 .10^{-6} m² s^{-1} is the kinematic viscosity of

the air; ρ_a is the density of the air.

For numerical simulation, we use an implicit finite difference method [13, 14]. The numerical resolution of the system of equations is done by the Gauss method. The selected space step (ΔX) is 0.1 m. This value allows obtaining an acceptable number of iterations and precision. With the implicit schema of finite differences, we retained a time step of 30 s. At the initial instant, we assume the 6 unknown temperatures

$(T_{ss}, T_{sol1}, T_{ptSE}, T_{ptSI}, T_{ptII}, T_{ptIE})$ equal to the soil temperature and the unknown temperature T_{ath} equal to the ambient air temperature. The temperature of the air at the inlet of the exchanger is equal to that of the ambient air. The calculation code used for the simulation is Fortran.

Table 1 shows the thermo-physical properties of the materials of the system.

Table.1: Thermo-physical properties of the constituent materials of the system [1]

System materials	Density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Thermal capacity (J kg^{-1} K^{-1})
Soil	1700	1	912
Tube	1380	0.15	900
Air	1.16	0.026	1006

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

Table.2: Values of the parameters used for the simulation

Physical parameter	Values
Tube length	15 ; 50 m
Tube diameter	0.1 ; 0.35 m
Air velocity	2 ; 5 m/s
Soil temperature	297 ; 304 K
Input air temperature	313 ; 317 K

III.   EXPERIMENTAL DEVICE

This device is an air-soil heat exchanger consisting with one PVC tube of 15 m of length, of 16 cm of diameter (5 mm thickness) and buried in the soil at 1.5 m of depth in a moist clay soil. Some parts of the system are described in following Fig. 3.

Fig. 3: Description of some parts of the system

This prototype is carried out within the platform of the Laboratory of Physics of the University Ouaga I Pr Joseph KI-ZERBO. The interchange is connected to a habitat of 32.82 m^3 of volume.

The sheath which connects the exchanger to the habitat is insulated with glass wool to limit thermal losses. We opted for the PVC tube taking into account several considerations that are cost, tightness, rigidity and durability. [2, 15] 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 input of the exchanger to the output 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. We conducted measurements during the months of June, July and August 2016 to study the thermal behavior of the system.

IV.   RESULTS

4.1.   Experimental results

Figs. 4, 5 and 6 present evolution of air temperature along the horizontal part of the tube respectively in June, July and August 2016.
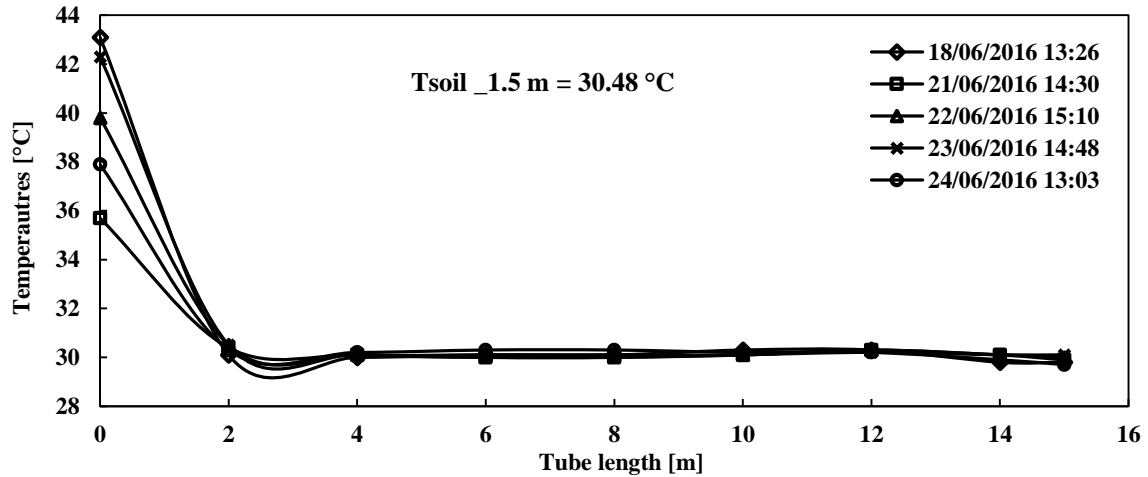
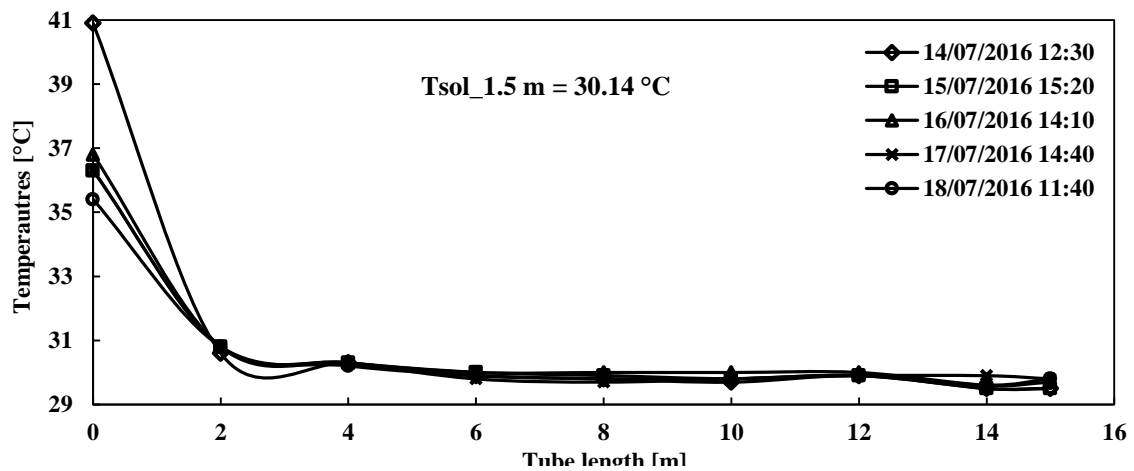*Fig. 4: Evolution of air temperature in the horizontal part in June 2016*

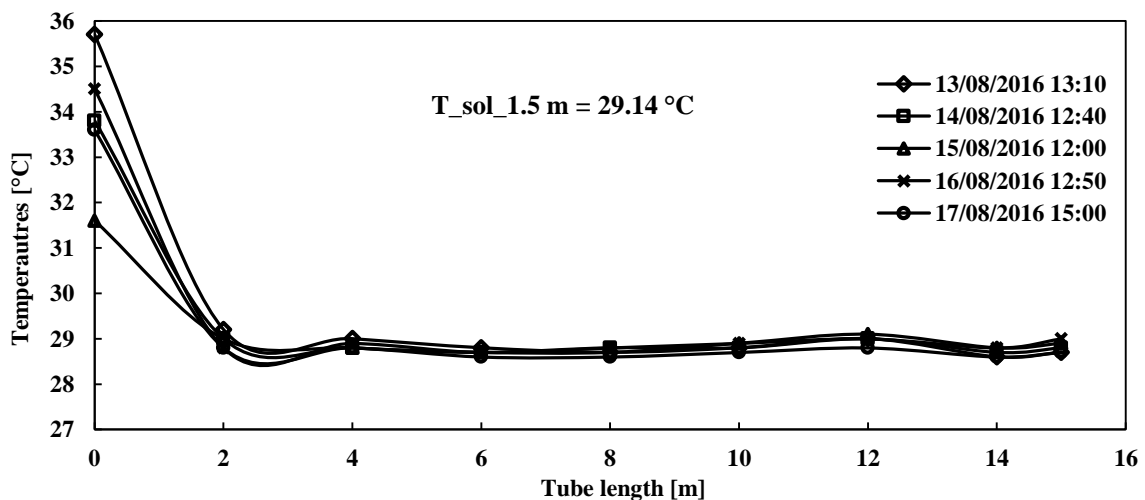*Fig. 5: Evolution of air temperature in the horizontal part in July 2016*

Fig. 6: Evolution of air temperature in the horizontal part in August 2016

In the previous Figs. 4, 5 and 6, we observe that, whatever the month in question, the temperature of the air decreases along the tube. There is therefore a cooling of the air along the exchanger. In general, the air temperature stabilizes above 4 m to 6 m length of the tube. For this purpose, according to [9], beyond a certain length, the lengthening of the tube does not improve the heat exchange. Similarly, work by [16], showed that the drop in air temperature is abrupt in the first 10 meters and subsequently moderates. For the month of June (Fig. 4), we note a significant decrease in temperature between 6 °C and 13 °C. On June 18th at 13:26 pm, the input temperature is 43.1 °C while at the output it is 29.8 °C. For the month of July (Fig. 5), the drop is between 6 °C and 12 °C. On July 14th at 12:30 pm, we note at the input 40.9 °C and output 29.5 °C. As for August (Fig. 6), the drop is between 4 °C and 8 °C. On August 13th at 1:10

pm, we note at the input 35.7 °C and the output 28.7 °C. Temperatures are relatively low during the month of August as it is a particularly rainy month in Burkina Faso. We note that the soil temperature is lower in August (mean value of 29.14 °C) than in June (average value of 30.48 °C) and July (mean value of 30.14 °C). Our values are in agreement with the results of [10], which showed that in Burkina Faso at 1.5 m depth in soil the temperature is about 30.4 °C. Our results justify the important role played by the soil in the functioning of the system. The soil dampens considerably the temperature of the air along the exchanger and that whatever the temperature of the air at the input or even the period.

4.2. Numerical results

Fig. 7 describes evolution of air temperature along the horizontal part of system for different values of input air temperature.
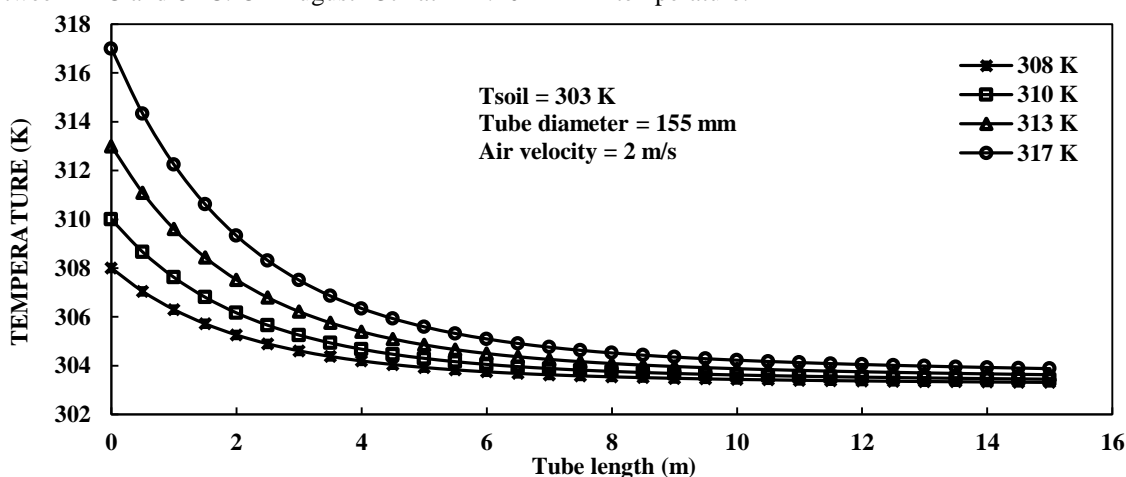

Fig. 7: Evolution of air temperature in the horizontal part for different values of input air temperature

In Fig. 7, we note that whatever the input temperature there is a cooling of the air along the tube. For an input temperature of 317 K, the temperature of the output air is 303.88 K (decrease of 13.12 K). For an input temperature of 317 K, the drop is 13.12 K and for an input temperature of 308 K, the decrease is 4.69 K. Indeed, the temperature of the soil being set at 303 K, when the temperature gradient between the soil and the input air is higher, the heat exchange is greater.

To test the reliability of our model, we validate our simulation results with those of models published in the

literature and also with our experimental work. For the evaluation of errors, we use the RMSE (Root Mean Square Error) statistical correlation.

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}\left(X^{*}_{\exp,i} - X^{*}_{pre,i}\right)^{2}}$$

(15)

4.3. Validation with numerical model of [16]

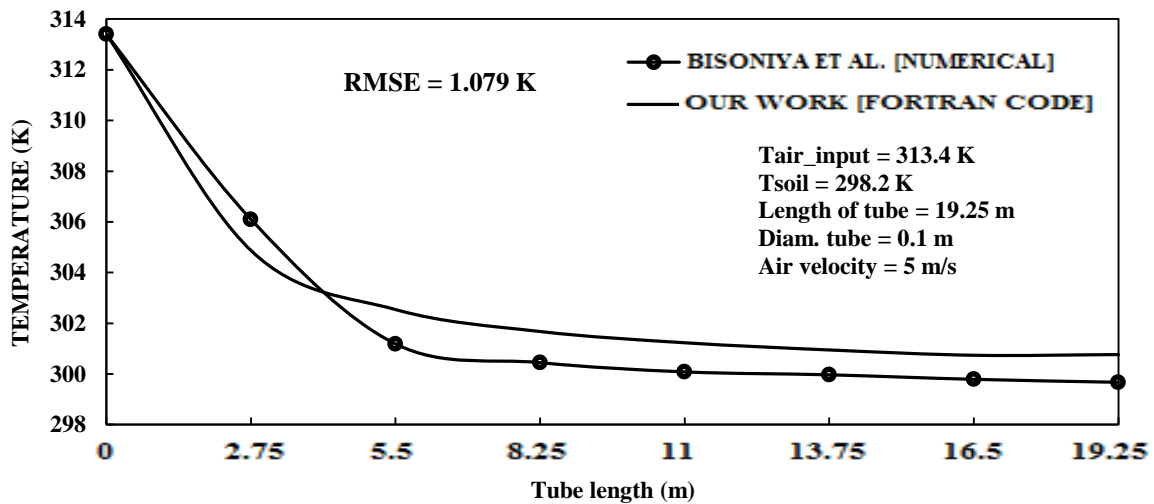Fig. 8 describes evolution of air temperature along the exchanger in our model and the one of [16].

Fig. 8: Validation of our results with the one of [16]

The air-soil heat exchanger model developed by [16] is a 3D numerical model that uses the CFD (Computational Fluid Dynamics) method. It consists of a single tube buried in the soil. Based on the value of the calculated error, we note an acceptable agreement between our numerical results and those of [16].

4.4. Validation with numerical model of [17]

Fig. 9 describes evolution of air temperature along the exchanger in our model and the one of [17].
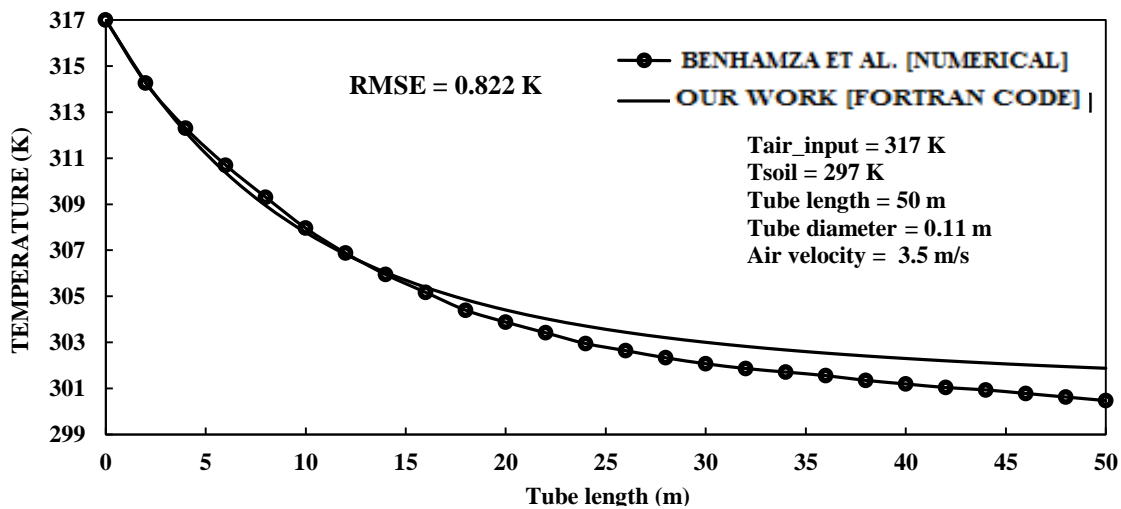

Fig. 9: Validation of our results with the one of [17]

The model of [17] is a numerical model based also on the CFD method. This model consists of one tube buried in the soil. In Fig. 9, there is good agreement between our numerical results and those of [17].

5.5. Validation with our experimental results

Figs. 10 and 11 present evolution of air temperature along of horizontal part of air-soil heat exchanger in the case of our numerical model and our experimental results of June and August 2016.
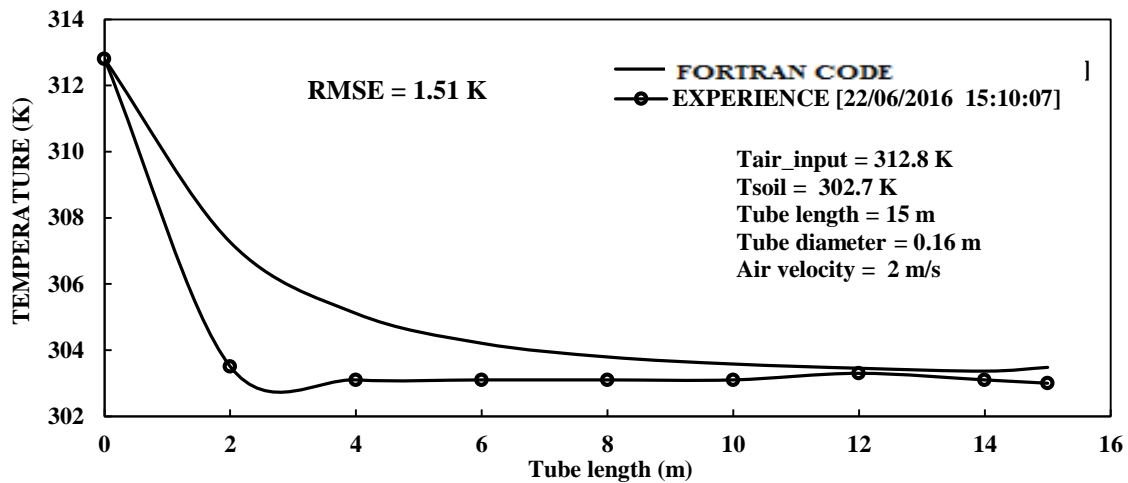
Fig. 10: Validation of our numerical results with our experimental results of juin 2016
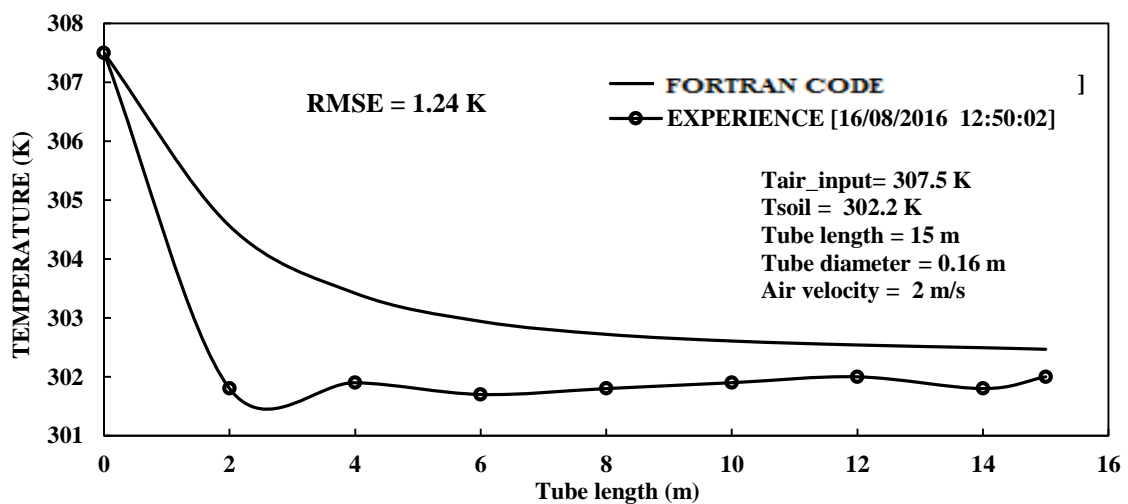

Fig. 11: Validation of our numerical results with our experimental results of August 2016

In Figs. 10 and 11, we observe that the air temperature evolution curves have the same profile, but they include deviations at certain levels. In the case of the experiment, the air temperature stabilizes above 4 to 6 m of length. On the other hand, at the level of the numerical model, the stabilization takes place starting at about 8 m. In addition, the cooling of the air is more important at the level of the experiment than in the simulation. This is partly due to the presence of a source of water in the soil of the experimental site. Indeed, during the implementation of our system, we encountered moisture at 1.5 m depth in the soil. This water contributes favorably to the cooling of the air along the exchanger, whatever the input temperature or even the period. According to [9], water has higher thermal capacity and conductivity than other soil constituents. Thus, moist soil stores heat better than dry soil and transmits it more easily to the air in the exchanger ducts. For simplification reasons, we did not integrate this parameter (presence of a source) in our numerical model. This justifies the temperature differences observed between the curves. However, given

the margins of error, we can say that our numerical results clearly reflect the physical phenomenon studied.

V.   CONCLUSION

In this paper, we have shown that a nodal approach is efficient for the study of air-soil heat exchangers. This method leads to acceptable results from the literature and from the experimental measurements.

This study allowed us to show that in the Sahelian zone, with an exchanger about 15 m long and buried at a depth of 1.5 m in the soil, we can cool the air during hot periods. The experimental exchanger makes it possible to stabilize the air temperature above 4 m to 6 m of length in the tube, regardless of the input temperature 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. Given the margins of error between our numerical results and those of the literature, we are convinced that our numerical work can serve as reliable

support for future study or possible improvement of the design of our experimental setup.

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