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Numerical and parametric analysis of vertical input and output parts of an air-soil heat exchanger in Sahelian zone

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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 parametric analysis of the vertical parts of an air-soil heat exchanger. This study provided a better understanding of the influence of parameters such as air velocity, soil temperature and air inlet temperature on the operation of the vertical inlet and outlet parts of the system.

Keywords-

Sahelian zone; Air-soil heat exchanger; parametric Analysis; Vertical Parts.

I. INTRODUCTION

In Burkina Faso as in the Sahelian zone, the energy demand for air conditioning is very high, especially during periods of heat. To cope with this reality, several techniques are developed.

These techniques include an air-soil heat exchanger (also known as a Canadian well or a Provencal well). It is a geothermal system that uses the thermal inertia of the soil to heat or cool part of the air renewing 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 soil.

The work of Hollmuller [1] is today one of the main references for the thermal of air-to-ground exchangers. Based on a thorough theoretical modeling but also on numerous in-situ measurements, 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 Stéphane Thiers [2]. 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. [3] 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 [4], the author proposes objective criteria for the choice of parameters based on numerical simulations of thermal exchange by forced convection in a buried tube.

In this article we discuss the numerical and parametric analysis of vertical input and output parts of an air-soil heat exchanger. This study will allow us to better understand the influence of parameters such as air velocity, soil temperature and air input temperature on the operation of the vertical parts of the system.

II. MATHEMATICAL MODELING

The system we are studying is an air-soil heat exchanger consisting of a tube buried in the soil at a given depth. Fig. 1 describes the input and output of the system.

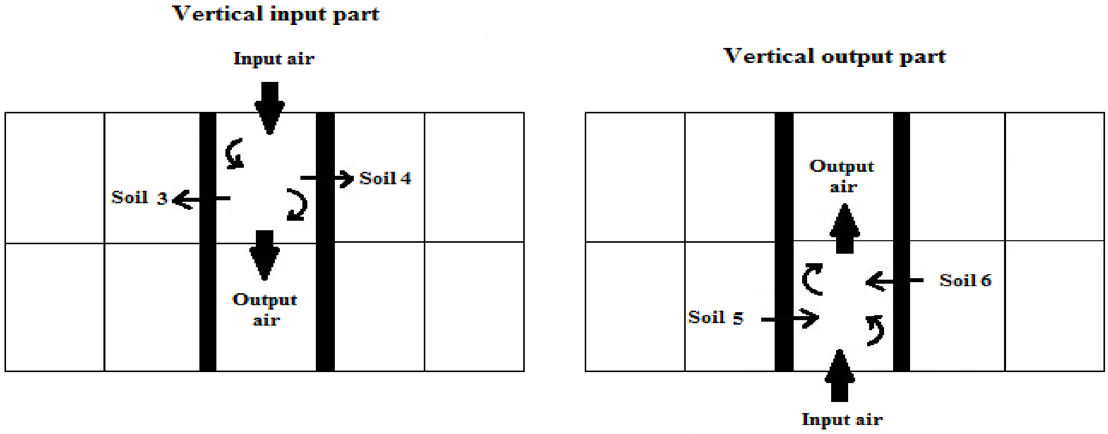

Fig. 1: Diagrams of the vertical parts of the air-soil heat exchanger

These parts are each made of a PVC tube of 1.5 m length. We chose the PVC tube taking into account several considerations that are cost, waterproofing, rigidity and durability. Bojic et al. [5] and Bansal et al. [6] have shown that the nature of the tube has very little influence on the thermal performance of an air-soil heat exchanger. For mathematical modeling, we are interested in the "vertical input part". The principle is the same for the "vertical output part". 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 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).

The basic equation for heat exchanges is therefore [7]:

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

$DFSA_i$: 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. The heat exchanges between the soil and the air inside the tube are radial.

- In Soil 3: Soil 3 is the part of the soil situated to the left of the outer wall of the vertical entrance tube.

$$e_s \rho_s c_{ps} \frac{dT_{sol3}}{dt} = -h_{ds}(T_{sol3} - T_{ss}) - h_{ds}(T_{sol3} - T_{ptGE}) \quad (2)$$

- At the level of the outer left wall of the vertical input tube:

$$e_{pt} \rho_{pt} c_{ppt} \frac{dT_{ptGE}}{dt} = -h_{ds}(T_{ptGE} - T_{sol3}) - h_{dpt}(T_{ptGE} - T_{ptGI}) \quad (3)$$

- At the level of the inner left wall of the vertical input tube:

$$e_{pt} \rho_{pt} c_{ppt} \frac{dT_{ptGI}}{dt} = -h_{dpt}(T_{ptGI} - T_{ptGE}) - h_{cat}(T_{ptGI} - T_{atv}) \quad (4)$$

- At the level of the air in the vertical input tube:

$$\frac{Vol_{at}}{S_{pt}} \rho_{at} c_{pat} \frac{dT_{atv}}{dt} = -h_{cat}(T_{atv} - T_{ptGI}) - h_{cat}(T_{atv} - T_{ptDI}) \quad (5)$$

- At the level of the inner right wall of the vertical entrance tube:

- $$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptDI}}{dt}=$$
$$-h_{cat}(T_{ptDI}-T_{atv})-h_{dpt}(T_{ptDI}-T_{ptDE})$$
(6)

- At the level of the outer right wall of the vertical entrance tube:

$$e_{pt}\rho_{pt}c_{ppt}\frac{dT_{ptDE}}{dt}= \quad (7)$$
$$-h_{dpt}(T_{ptDE}-T_{ptDI})-h_{ds}(T_{ptDE}-T_{sol4})$$

  - In soil 4: Soil 4 is the part of the soil situated to the right of the outer wall of the vertical entrance tube.

$$e_s\rho_s c_{ps}\frac{dT_{sol4}}{dt}= \quad (8)$$
$$-h_{ds}(T_{sol4}-T_{ptDE})-h_{ds}(T_{sol4}-T_{ss})$$

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

- Soil conduction coefficient [7]:

$$h_{ds}=\frac{\lambda_s}{e_s} \quad (9)$$

λ_s is the thermal conductivity of the soil and e_s is the thickness of the soil.

- Tube conduction coefficient [7]:

$$h_{dpt}=\frac{\lambda_{pt}}{D_E\times\frac{e_{pt}}{D_I}} \quad (10)$$

λ_{pt} is the thermal conductivity of the tube ; D_E is the outside 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 [3]:

$$h_{cat}=\frac{Nu\times\lambda_a}{L}=\frac{(0{,}023\,\mathrm{Re}^{0,8}\times\mathrm{Pr}^n)\times\lambda_a}{L} \quad (11)$$

$$\mathrm{Re}=\frac{V_a\times D_i}{\nu_a}\ ;\ \mathrm{Pr}=\frac{\mu_a\times C_{pa}}{\lambda_a}\ ;$$
$$\mu_a=\nu_a\times\rho_a$$

If $T_{atv} > T_{sol}$ (cooling) then n = 0.3

or if $T_{atv} < T_{sol}$ (heating) then n = 0.4.

The characteristic length L is equal to the inside diameter of the tube; T_{atv} 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; ν_a = 15.6. 10^{-6} m²/s is the kinematic viscosity of the air; ρ_a is the density of the air.

III. NUMERICAL SIMULATION

For numerical simulation, we use an implicit finite difference method [8, 9]. 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. The calculation code used for the simulation is Fortran.

• Initial conditions in the vertical input:
At the initial time, we take the 6 unknown temperatures (T_{sol3}, T_{ptGE}, T_{ptGI}, T_{ptDI}, T_{ptDE}, T_{sol4}) equal to the mean soil temperature at 1.5 m depth (T_{sol} = 303 K) and the unknown temperature (T_{atv}) equal to the ambient air temperature (T_{ae} = 313 K).

• Boundary conditions in the vertical part of the input:

- At the air level:
$$T_{atv}(X=0,t)=T_{ae}(t) = 313\text{ K}$$

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– At the wall of the tube: $T_{ptv}(X=0,t)=T_{ae}(t)$ = 313 K

T_{atv} Is the temperature of the air in the vertical tube, T_{ptv} is the temperature of the wall of the vertical tube and $T_{ae}(t)$ designates the temperature of the air at the inlet of the vertical tube.

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

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	Valeurs
Vertical tube length	1.5 m
Tube diameter	0.155 m
Air velocity	2 ; 4 m/s
Soil temperature	301 ; 303 K
Input air temperature	308; 317 K

IV. RESULTS

- **Evolution of the air temperature: Influence of the air velocity**

Figs. 2 and 3 describe the evolution of the temperature of the air respectively along the vertical input tube and the vertical output tube for different values of the air velocity.

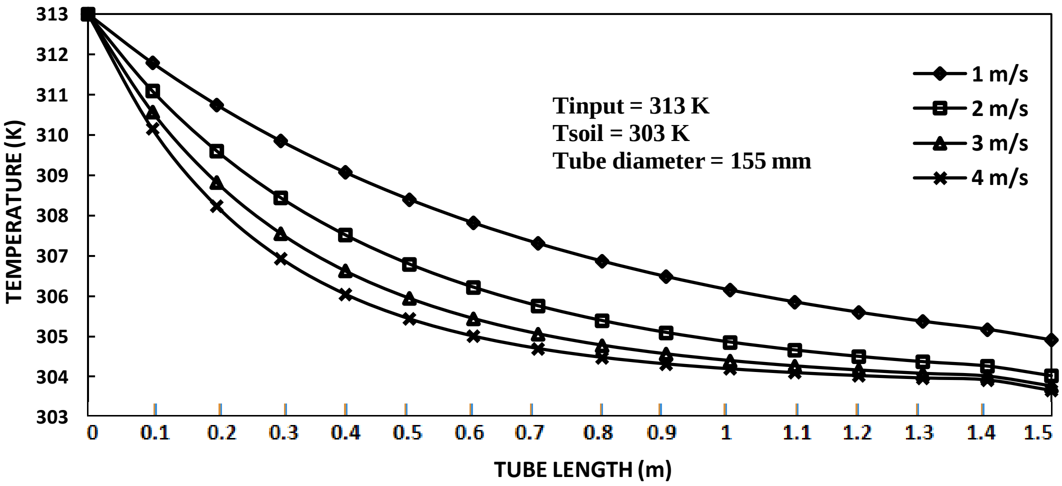

Fig. 2: Evolution of the air temperature along the vertical input tube for different air velocities

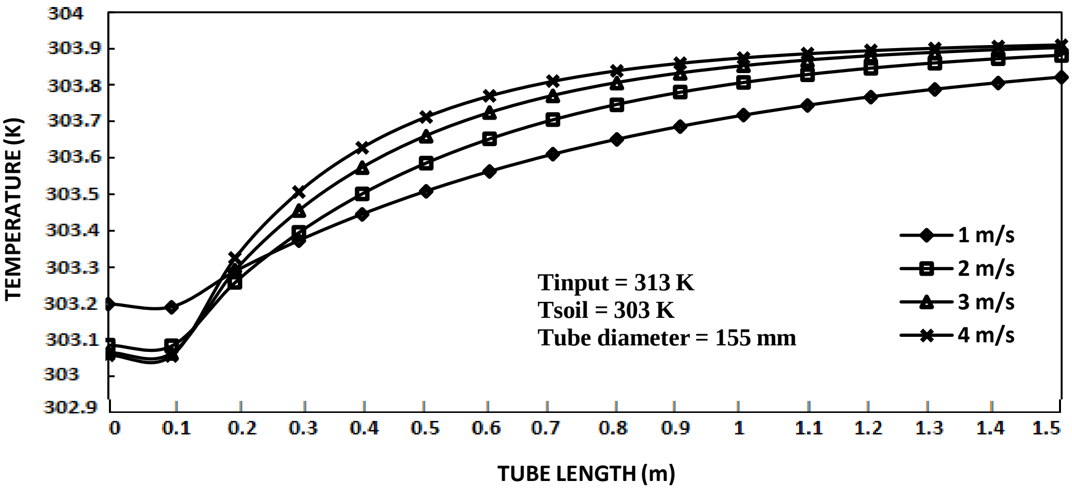

Fig. 3: Evolution of the air temperature along the vertical output tube for different air velocities

In Fig. 2 we notice that whatever the air velocity, the temperature of the air decreases along the vertical input tube. For an input temperature of 313 K, the temperature of the air at 1.5 m length varies between 303.65 K and 304.91 K. We note that when the speed increases from 1 m/s to 3 m/s, the temperature drop is greater (from 8.09 K to 9.24 K). However, above 3 m/s, the temperature drop is very insignificant (ranging from 9.24 K to 9.35 K).

In Fig. 3 we notice that whatever the air velocity, the temperature of the air increases along the vertical output tube. We find that when the speed increases from 1 m/s to 3 m/s, the increase in temperature is greater. But, beyond 3 m/s the temperature increase is very little sensitive. It should be noted that in the vertical outlet tube the temperature variations are small compared to variations in the vertical input tube. This is explained by the fact that the heat exchange between the air and the soil is greater at the inlet of the exchanger than at the output. According to S. Thiers [2], when the speed increases, the convective exchange of air becomes important. But, at fairly high speeds, the air no longer has the time necessary to exchange its heat with the soil to the maximum. According to Ludo Van Caenegem et al. [10], the higher the air velocity, the greater the exchange of heat between the floor mantle and the air. This is due to the thermal resistance of the soil.

- **Evolution of the air temperature: influence of the air inlet temperature**

Figs. 4 and 5 show the evolution of the temperature of the air respectively along the vertical input tube and the vertical output tube for different values of the air input temperature.

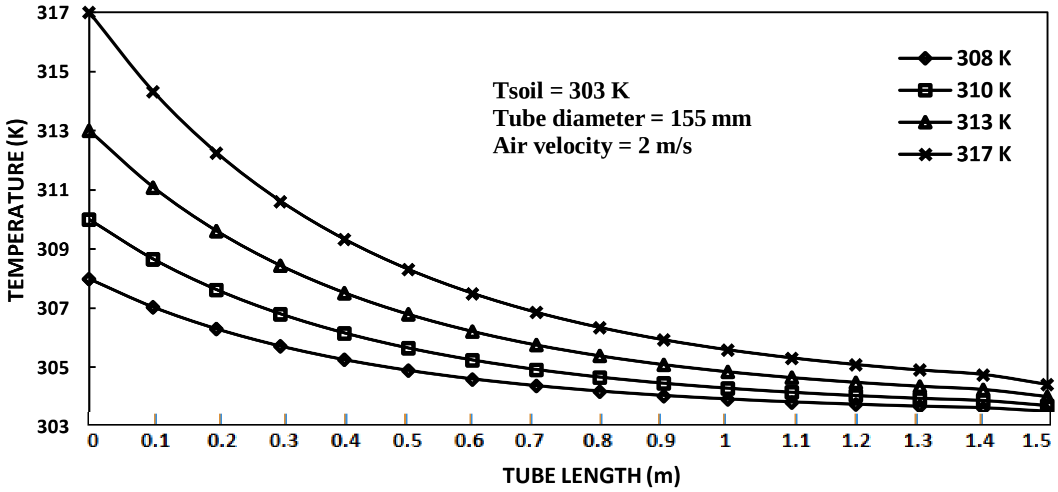

Fig. 4: Evolution of the air temperature along the vertical input tube for different air input temperatures

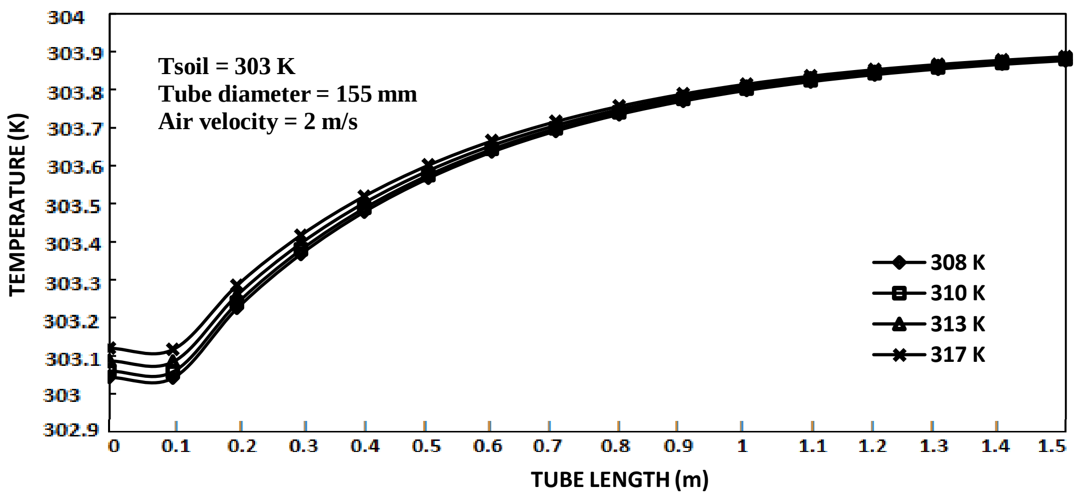

Fig. 5: Evolution of the air temperature along the vertical output tube for different air input temperatures

In Fig. 4 we notice that whatever the inlet temperature is, there is a decrease in the temperature of the air along the vertical inlet portion. The higher the inlet air temperature, the higher the air outlet temperature. For an inlet temperature of 317 K, the outlet temperature is 304.42 K, whereas for an inlet temperature of 308 K, the outlet temperature is 303.51 K. But the temperature drop is all the greater as the inlet temperature is high.

In Fig. 5 we notice that whatever the inlet temperature is, there is an increase in the temperature of the air along the vertical outlet portion. But the temperature variations are not very sensitive. This is explained by the fact that the temperature of the air at the inlet of the vertical outlet tube is close to the ground temperature (303 K). There is thus less heat exchange between the air and the ground.

- **Evolution of the air temperature: influence of the soil temperature**

Figs. 6 and 7 show the evolution of the temperature of the air respectively along the vertical input tube and the vertical output tube for different values of the soil temperatures.

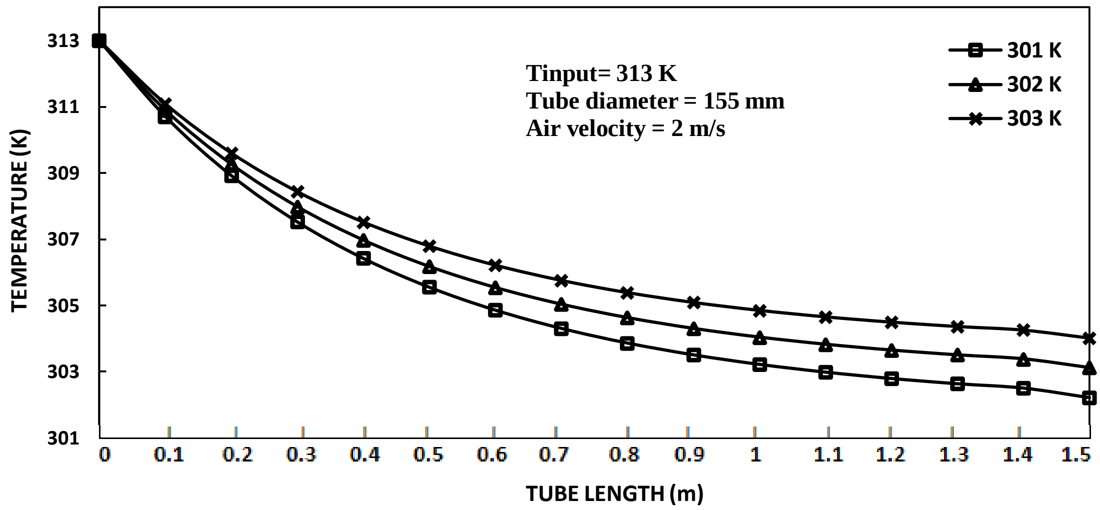

Fig. 6: Evolution of the air temperature along the vertical input pipe for different soil temperatures

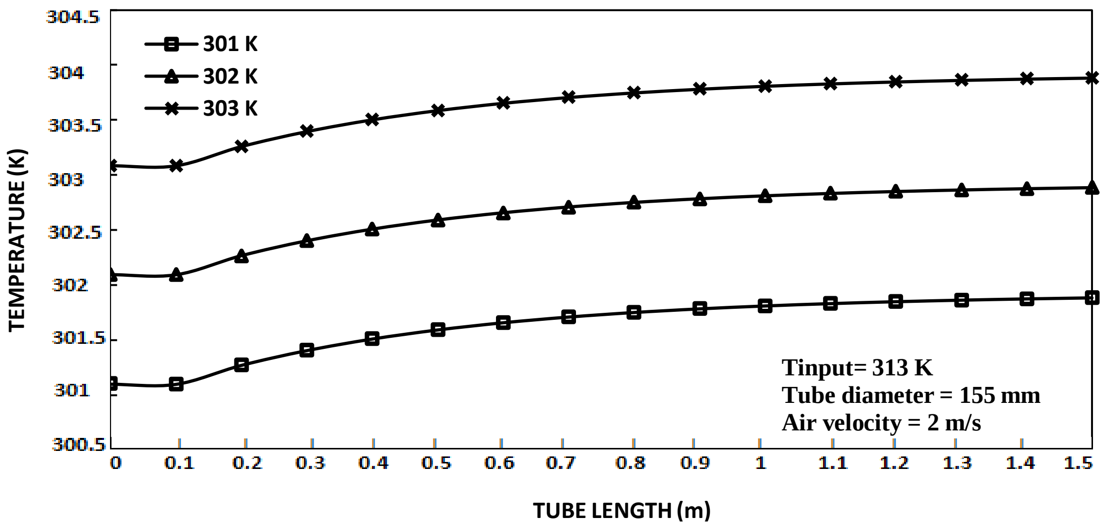

Fig. 7: Evolution of the air temperature along the vertical output tube for different soil temperatures

In Fig. 6, it can be seen that whatever the temperature of the soil, the temperature of the air decreases along the vertical input tube. We also find that as the soil temperature increases, the temperature of the air at the output of the tube increases. In other words, the temperature of the air at the output of the tube is lower, the lower the temperature of the soil. For a soil temperature of 303 K, the temperature of the air at the output is 304.02 K. On the other hand, for a soil temperature of 301 K, the temperature of the output air is 302.22 K.

In Fig. 7 we see that whatever the temperature of the soil, the temperature of the air increases along the vertical output tube. Similarly, when the soil temperature increases, the temperature of the air at the output of the tube increases. We note that the heat exchanges between the air and the soil are less important in the vertical output tube. These results show that the temperature of the soil greatly influences the heat exchange between the air and the soil all along the tube. To reach a soil temperature of 300 K, additional technical and economic means are required. We have to dig the soil much deeper.

- **Evolution of air temperature in vertical tubes over a year**

Figs. 8 and 9 describe the evolution of the air temperature in the vertical tubes over a year. The meteorological data used relate to average hourly ambient air temperatures in the city of Ouagadougou from 1992 to 2001. Each month is represented by its typical day. Thus, for a year there is a total of 288 hours or 24 hours per month.

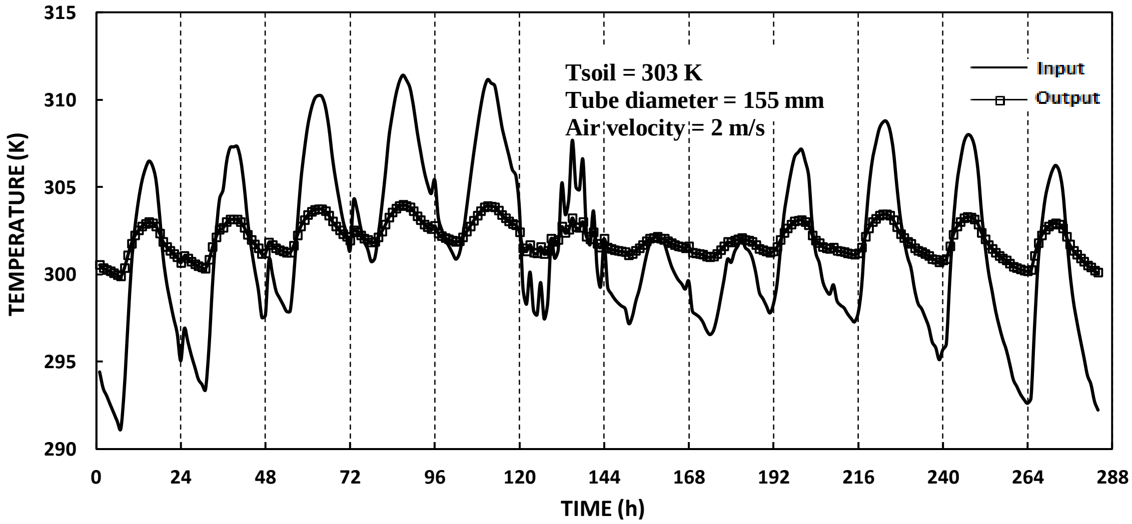

Fig. 8: Evolution of the air temperature in the vertical input tube during one year

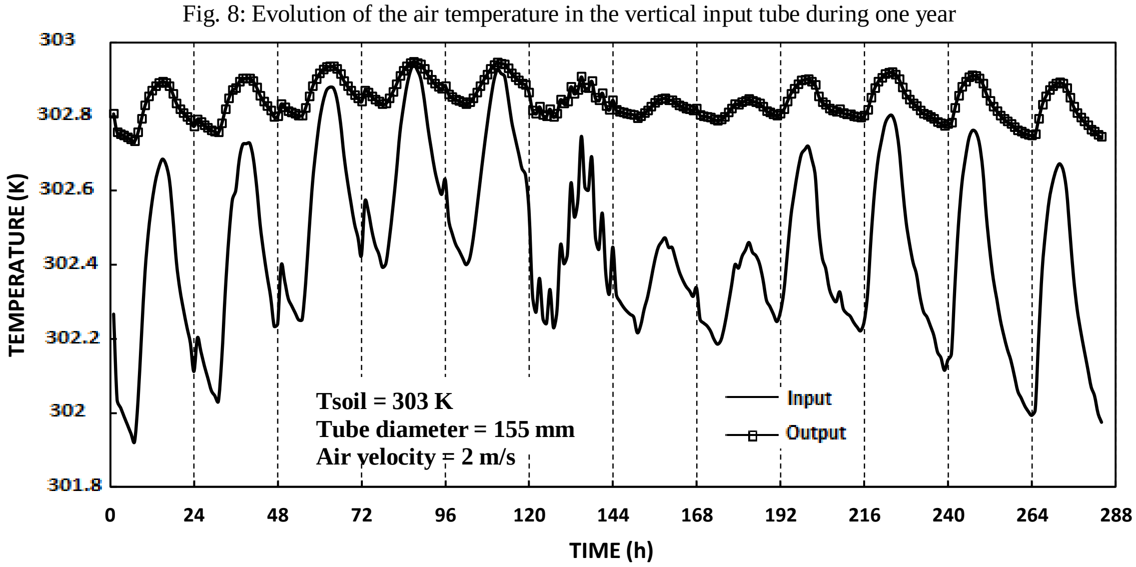

Fig. 9: Evolution of the air temperature in the vertical output tube during one year

In Fig. 8, we note that during the warm periods of the day (between 11h00 and 15h00), the temperature of the air at the output of the vertical input tube is lower than that of the air at the output entrance. For the month of April at 12h00 the temperature of the air at the input is 309.19 K and that of the air at the output is 303.53 K. Thus, the vertical input tube contributes well to the cooling of the air by lowering the temperature by 5.66 K. In general, the vertical input heat exchanger cushions the air temperature during the hot periods of the day and the year (March, April and May). In Fig. 9, we note that whatever the period of the year, the temperature of the air at the exit of the vertical output tube is higher than that of the air at the input. For the month of April at 12h00 the temperature of the input air is 302.82 K and that of the air at the output is 302.92 K. This reflects the fact that the vertical output tube contributes to heating the air by increasing the temperature by 0.10 K. This heating is less important during the hot periods of the day. In general, the vertical output heat exchanger operates in heating mode during the year.

CONCLUSION

In this article, based on a numerical study based on a nodal approach, we carried out a numerical and parametric analysis of the vertical input and output parts of an air-soil heat exchanger.

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We note that the temperature variations are greater in the vertical input tube than in the vertical output tube. There is cooling of the air along the vertical input tube and heating along the vertical output tube. Increasing the speed (1 m/s to 4 m/s) is conducive to cooling the air only in the vertical input tube. On the other hand, the increase in the air inlet temperature (308 K to 317 K) and the soil temperature (301 K to 303 K) is not favorable. Whatever the parameter values (air velocity, input temperature and soil temperature), there is heating of the air along the vertical output tube. But, this heating is relatively low. The simulations with the meteorological data confirm these observations well. Thus, the output vertical portion does not improve the operation of the exchanger on the thermal plane.

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