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# Theoretical and experimental study of earth heat exchanger Air / Soil: Application in the site of Biskra

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***Abstract*— The thermal inertia of the soil allows it to maintain a stable temperature at certain depths, regardless of air temperature at the surface. We exploit this property by using a heat exchanger (air -soil) buried at depths appropriate, where a current of air passes through them for later use in air conditioning or heating.**
**This work aims to study the factors that control the thermal behavior of these exchangers, where we first realized a mathematical model whose goal is to calculate the temperature for the soil any depth and any day of the year. And we made a numerical modeling to simulate the air temperature at the exit of the exchanger, for each day during the summer in the region of Biskra. Finally, we compare the theoretical study to a experimental study realized in the same region.**

***Keywords*— Modeling, Geothermal, cooling, Heat exchange, Exchanger air-ground**

## I. INTRODUCTION

In this study, we are interested in the development of renewable energy in general, and especially the cooling by geothermal energy, a technique that is so far untapped in our country.

We first conducted a theoretical study for the development of a model which better reflects the changes in temperature of the soil, from the surface to an optimal depth.

In the second step, we present the results of a numerical study that we conducted, these results are compared to an experimental study which was conducted at the site of Biskra.

## II. MATHEMATICAL MODEL OF SOIL TEMPERATURE

The propagation of a temperature signal into a semi-infinite solid (here soil, which is treated as a homogeneous semi-infinite solid whose physical properties are constant and independent of the depth z), has an analytic solution when the temperature signal is sinusoidal. So we extracted from the measured temperatures a sinusoidal signal:

$$T_e(t) = \bar{T}_e + A_T sin(\omega_T t - \varphi_T) \quad \textbf{(1)} \ [1]$$

$\bar{T}_e$ : Average temperature of the outside air [k]

$A_T$ : Amplitude of oscillation of the air temperature [K]

$$A_T = \frac{T_{emax}+T_{emin}}{2}$$

$\omega_T$ : Pulse oscillation [rad.s$^{-1}$]

$$\omega_T = \frac{2\pi}{period}$$

$\varphi_T$ : The phase difference [rad]

$$\varphi_T = \omega t_{\bar{T}}$$

$t_{\bar{T}}$ : The time when the average temperature is reached for the first time [s]

The flux values of global solar radiation measured from metrological data base (monthly average measured each month of the year) can also be expressed as sinusoidal shape:

$$G(t) = \bar{G} + A_G sin(\omega_G t - \varphi_G) \quad \textbf{(2)}$$

$\bar{G}$: Average global horizontal solar radiation [W.m$^{-2}$]

The parameters, $A_G$, $\omega_G$ and $\varphi_G$ are calculated by the same type of computation above.

### Determination of the temperature of the ground surface

The determination of this temperature is produced from the power balance, expressed on the surface of the ground as follows:

$$\Phi_{con} = \Phi_{eq} + \Phi_{ra} - \Phi_{lat} \quad \textbf{(3)} \ [1]$$

$$\Phi_{con} = -\lambda_{sol} \left.\frac{dT_{sol}}{dz}\right|_0$$

$$\Phi_{ra} = (1-\alpha)G(t)$$

$$\Phi_{lat} = C_l.f.h_{surf}[(a_l T_{surf-sol} + b_l) - r_a(a_l T_e + b_l)]$$

$$\Phi_{eq} = h_{eq}(\bar{T}_e - T_{sur-sol})$$

$\Phi_{con}$ : Conductive heat flow to the ground [w.m$^{-2}$]

$\Phi_{ra}$ : Heat flux received by sunlight [w.m$^{-2}$]
$\Phi_{lat}$: The latent heat flux transferred to the atmosphere [w.m$^{-2}$]
$\Phi_{eq}$: Includes by correlation: the radiative flux emitted by soil and convective heat exchange caused by wind [w.m$^{-2}$]

$\lambda_{sol}$ : Thermal conductivity of the soil [W.m$^{-1}$.K$^{-1}$]
α: Albedo of the soil surface
$f$: An empirical correction factor (between 0 and 1) depending on the soil type considered and the state of its surface.
$h_{surf}$: Soil's convective heat transfer coefficient, calculated by the formula: $h_{surf} = 0{,}5 + 1{,}2 \cdot \sqrt{v_{\text{wind}}}$ [2]
$v_{\text{wind}}$: The wind velocity at ground level [m.s$^{-1}$]
$a_l, b_l$ and $c_l$ : Empirical constants
$r_a$: Relative humidity of air

$h_{eq}$ : Equivalent exchange coefficient ( =12.6 Wm$^{-2}$ K$^{-1}$ for soil sheltered from the wind, 20 Wm$^{-2}$ K$^{-1}$ for a moderately windy soil and 50 Wm$^{-2}$ K$^{-1}$ for a soil particularly windy) [2]

In addition, the solution's expression of the heat balance **(3)** involves both coefficients following exchange :

$$h_r = c_l . f . h_{surf} . a_l . r_a + h_{eq} \quad [1]$$
$$h_e = c_l . f . h_{surf} . a_l + h_{eq} \quad [1]$$

The temperature at the surface resulting from the balance **(3)** finally has the following form:

$$\boldsymbol{T_s(t) = \bar{T}_s + A_1 \sin(\omega t - \varphi_T) + A_2 \sin(\omega t - \varphi_G)} \quad \textbf{(4)}$$

$$\bar{T}_s = \frac{(h_r + h_e).\frac{b_l}{a_l} + h_r.\bar{T}_e + (1-\alpha)\bar{G}}{h_e}$$

$$A_1 = \frac{h_r . A_T}{h_e}$$

$$A_2 = \frac{(1-\alpha)A_G}{h_e}$$

With the boundary condition:

$$\boldsymbol{T_s(o,t) = \bar{T}_s + A_1 \sin(\omega t - \varphi_T) + A_2 \sin(\omega t - \varphi_G)}$$

The heat equation : $\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial z^2}$ has the following solution : (It gives the temperature of the soil at any depth and at any day of the year) [11]

$$\boldsymbol{T_s(z,t) = \bar{T}_s + A_1 e^{\left(-\frac{z}{\delta}\right)} \sin\left(\omega t - \varphi_T - \frac{z}{\delta}\right) + A_2 e^{\left(-\frac{z}{\delta}\right)} \sin\left(\omega t - \varphi_G - \frac{z}{\delta}\right)} \quad \textbf{(5)}$$

$a = \frac{\lambda_{sol}}{\rho_{sol} c_{psol}}$ : Thermal diffusivity of the soil [m$^2$.s$^{-1}$]

$\delta = \sqrt{\frac{2a}{\omega}}$ : Penetration depth [m]

By adding the warming's term geothermal of the soil, $geo(z)$, this model takes its most complete form as follows:

$$\boldsymbol{T_s(z,t) = \bar{T}_s + A_1 e^{\left(-\frac{z}{\delta}\right)} \sin\left(\omega t - \varphi_T - \frac{z}{\delta}\right) + A_2 e^{\left(-\frac{z}{\delta}\right)} \sin\left(\omega t - \varphi_G - \frac{z}{\delta}\right) + geo(z)} \quad \textbf{(6)} \; [1]$$

TABLE I

Meteorological data for the site of Biskra:

| Months | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Spt. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aver. Tem. ($\bar{T}_e$) (°c) | 11.9 | 13.7 | 16.2 | 20.0 | 25.2 | 29.9 | 33.5 | 32.7 | 27.5 | 22.1 | 16.5 | 12.8 |
| Aver. Rel.Humid. | 0.57 | 0.52 | 0.44 | 0.40 | 0.37 | 0.31 | 0.29 | 0.31 | 0.40 | 0.49 | 0.57 | 0.60 |
| Aver. $v_{\text{wind}}$ (m/s) | 3.70 | 4.18 | 4.59 | 4.82 | 4.78 | 4.34 | 3.70 | 3.82 | 3.58 | 3.82 | 3.60 | 3.65 |
| Aver. Hori.Ra.Solar(wh/m$^2$) | 211,7 | 295,5 | 411,7 | 489,7 | 511,2 | 533,5 | 525,1 | 476 | 398,8 | 304,2 | 219,2 | 177,7 |

TABLE II

Soil physical properties in the region of Biskra (type of soil: Sandy Clay- Limon)

| **Density ($\rho_{sol}$) (kg/m$^3$)** | **Heat capacity ($C_{psol}$) (J /kg K)** | **Thermal conductivity ($\lambda_{sol}$) (w.m/k)** | **Thermal diffusivity ($a$) (m$^2$/s)** | **Penetration depth δ (m)** | **Albédo ($\alpha$)** |
|---|---|---|---|---|---|
| **1800** | **1340** | **1.5** | **6.22x10$^{-7}$** | **2.5** | **0.35** |

An overview of the waveform temperature at different depths is shown in Figure 1, below :

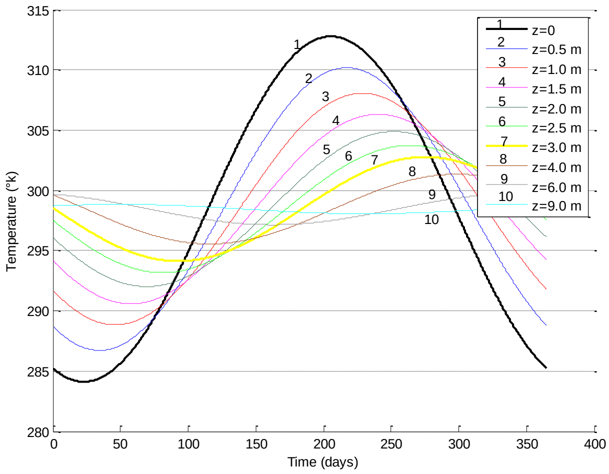


Figure-1

## III. NUMERICAL MODELLING OF AIR TEMPERATURE, IN THE EXCHANGER AIR-GROUND.

**Geometric assumptions:**

The canadian well that will be modelled here, is a horizontal tube of length L = 50 m, arranged horizontally under the ground at the depth z = 2.5 m .

**The mesh:**

The finite difference method is used for the simulation of the heat exchanger. By this method, the system being modelled is divided by volumes (or meshes). Each volume gives rise to the establishment of a thermal balance.

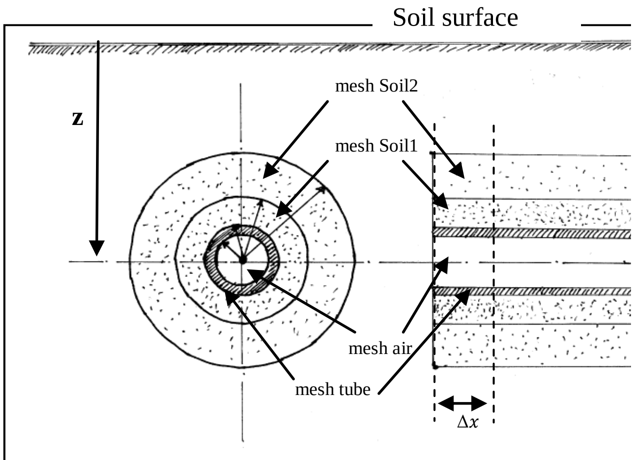


Figure-2

- The time is divided into intervals of fixed duration Δt
- The tube is divided into n fixed-length slots $\Delta x$
- The unknowns of the problem are the temperatures of the different meshes, which must be determined for each time step and for each step space: $T_{air}$, $T_{tub}$, $T_{soil1}$, and $T_{soil2}$.

**Heat balance for each mesh**

Air mesh:

φ(transported) =φ(exchanged with mesh tube)

$$C_{air}\dot{m}\left(T^n_{i-1,air} - T^n_{i,air}\right) = \frac{1}{R_{air-tub}}\left(T^n_{i,air} - T^{n-1}_{i,tub}\right) \quad (7)$$

$c_{air}$ : Specific heat capacity of air [J.kg$^{-1}$.K$^{-1}$]

$\dot{m}$ : Mass flow of the air [kg.s$^{-1}$]

$T^n_{i,air}$: Temperature of the i-th mesh of the air for the n-th time step [k]

$T^n_{i,tub}$ : Temperature of the i-th mesh of the tube for the n-th time step [k]

$R_{air-tub}$ Thermal resistance between i-th mesh of the tube and i-th mesh of the air [k.w$^{-1}$]

Tube mesh:

**φ(store) =φ(exchanged with mesh air) - φ(exchanged with mesh sol1)**

$$C_{i,tub}\frac{dT}{dt} = \frac{1}{R_{air-tub}}\left(T_{i,air} - T_{i,tub}\right) - \frac{1}{R_{tub-soil1}}\left(T_{i,tub} - T_{i,sol1}\right)$$

$$C_{i,tub}\left(T^n_{i,tub} - T^{n-1}_{i,tub}\right) = \frac{\Delta t}{R_{air-tub}}\left(T^n_{i,air} - T^n_{i,tub}\right) - \frac{\Delta t}{R_{tub-soil1}}\left(T^n_{i,tub} - T^n_{i,sol1}\right)$$

**(8)**

Soil1 mesh

**φ(store) =φ(exchanged with mesh tub) - φ(exchanged with mesh sol2)**

$$C_{i,sol1}\frac{dT}{dt} = \frac{1}{R_{tub-sol1}}\left(T_{i,tub} - T_{i,sol1}\right) - \frac{1}{R_{sol1-sol2}}\left(T_{i,sol1} - T_{i,sol2}\right)$$

$$C_{i,sol1}\left(T^n_{i,sol1} - T^{n-1}_{i,sol1}\right) = \frac{\Delta t}{R_{tub-sol1}}\left(T^n_{i,tub} - T^n_{i,sol1}\right) - \frac{\Delta t}{R_{sol1-sol2}}\left(T^n_{i,sol1} - T^n_{i,sol2}\right)$$

**(9)**

Soil2mesh

**φ(store) =φ(exchanged with mesh soil1) - φ(exchanged with mesh soil)**

$$C_{i,sol2}\frac{dT}{dt} = \frac{1}{R_{sol1-sol2}}\left(T_{i,sol1} - T_{i,sol2}\right) - \frac{1}{R_{sol2-sol}}\left(T_{i,sol2} - \overline{T}_{sol}\right)$$

$$C_{i,sol2}\left(T^n_{i,sol2} - T^{n-1}_{i,sol2}\right) = \frac{\Delta t}{R_{sol1-sol2}}\left(T^n_{i,sol1} - T^n_{i,sol2}\right) - \frac{\Delta t}{R_{sol2-sol}}\left(T^n_{i,sol2} - \overline{T}^n_{sol}\right)$$

**(10)**

## IV. EXPERIMENTAL WORK EXECUTED AT THE SITE OF THE UNIVERSITY OF BISKRA

This is a network of four trace a total length of about 50 m. The internal diameter of the tube is 110 mm.The assembly is placed at a depth of 3 m at a slope of 2%. Mounted on site at the University of Biskra. A variable flow air extractor is placed at the inlet of the exchanger. A series of temperature sensors is positioned along the heat exchanger from the inlet to the outlet. The probes are connected to a data logger.

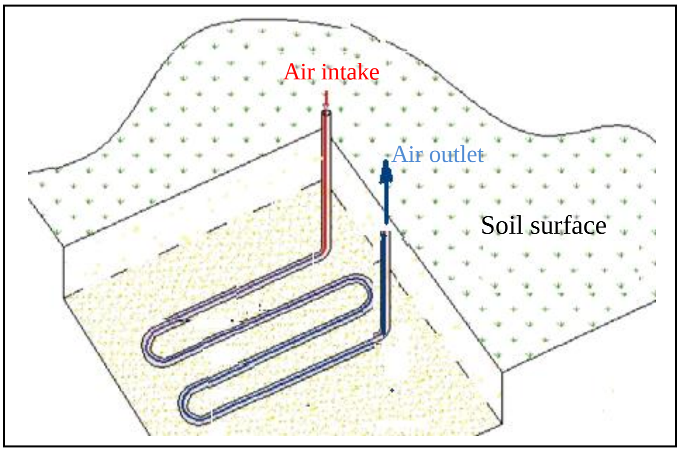


Figure-3

Bench experimental tests [7]

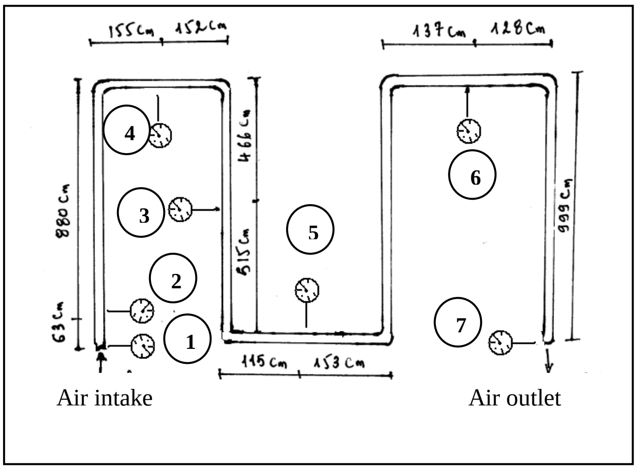


Figure-4
Thermal sensors positions

## V. RESULTS AND DISCUSSION

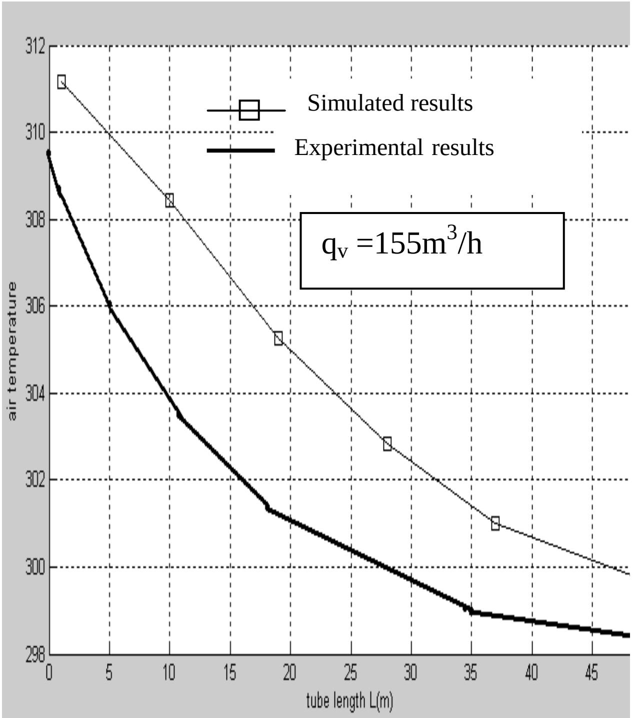


Figure-5

Comparison of the simulated results and the results experimentally measured, of the temperature variation depending on the length of the exchanger

The results show that the two curves have the same shape, which proves that the theoretical study simulates with good precision the exchanger which has been studied.

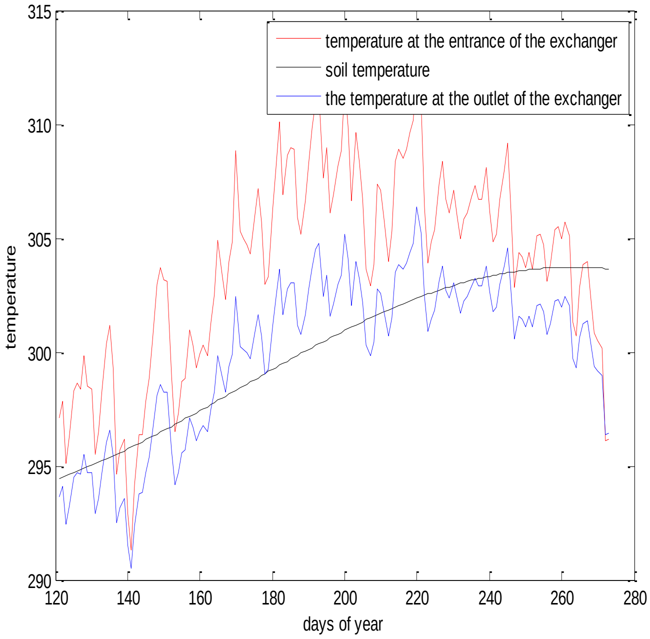


Figure-6

Annual Evolution of the temperature at the outlet of the exchanger air-ground

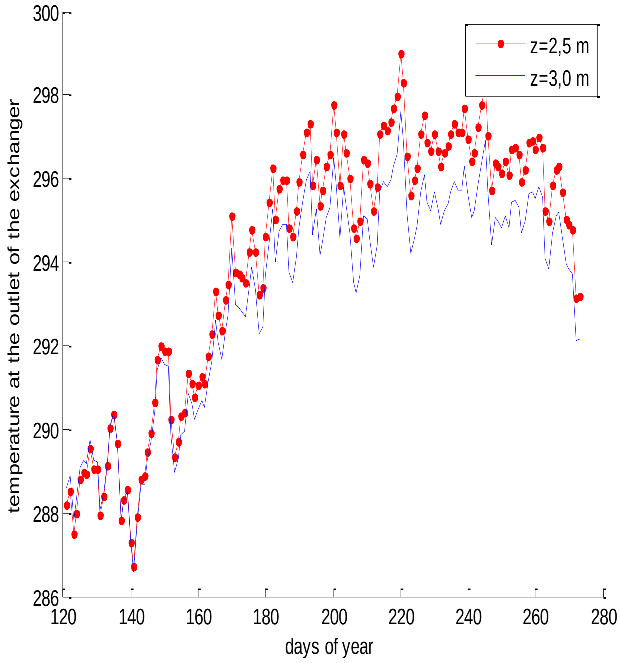


Figure-7

Temperature at the outlet of the exchanger for two different depths

We note that the difference between the input temperature and the output temperature is more important in the middle of the curve, i.e. during the hottest period. However, the two temperatures converge when approaching the cooler periods of the season.

The result shows that during the hottest time of the season, the air temperature at the outlet of the heat exchanger drops when the burial depth increases (from 0.3 to 1 degree per meter), but this fall is negligible during the cooler season, and it is due to the damping of the amplitude of the temperature signal, due to the inertia of the soil .

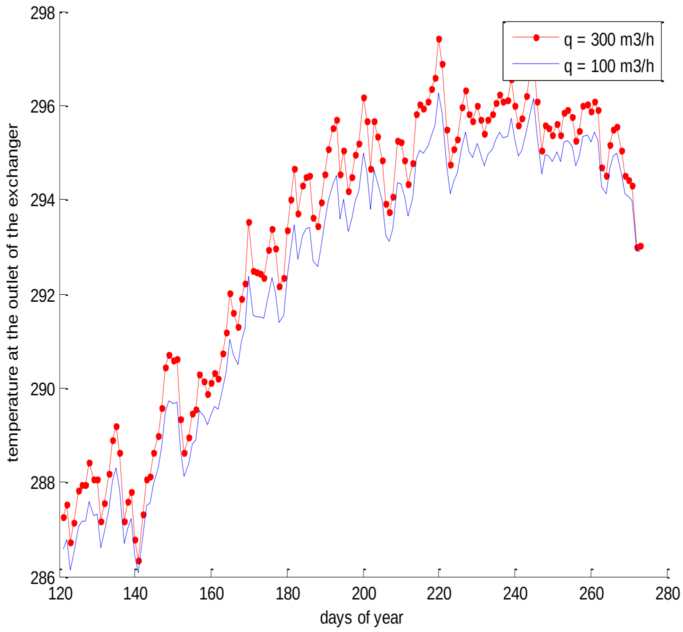


Figure-8

Temperature at the outlet of the exchanger for two different airflows

The results presented show that the effectiveness of the heat exchanger decreases to a higher speed (the air temperature is less then tempered).

So we can conclude that this parameter plays an important role in the flow of air into the system tubes, i.e. the effectiveness of exchange by convection between the air and the tube. By against low flow may be insufficient to ventilate the room to be conditioned.

## VI. Conclusions

At the end of this study and through the results obtained, the exchanger (air / ground), is a promising vector in climatic genius, and as a renewable source of energy must be undoubtedly exploited industrially.

The digital modeling translated changes in the temperature of the air through the exchanger, based on key parameters. The modeling can be used in the absence of the experimental data for sizing the exchanger (air/ground), to other sites and in other conditions.

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