THE PARAMETERS OPTIMIZING OF THE EARTH-TO-AIR HEAT EXCHANGER

Clin RAHARIVELO[1], Adolphe RATIARISON [2], J. Eugène RANDRIANANTENAINA [3], Andrianantenaina RAFIDISON [4]

[1] *Student, Department of physics, Faculty of Sciences, Toliara, Madagascar*
[2] *Emeritus Professor, Department of physics, DYACO laboratory, Antananarivo, Madagascar*
[3] *Master of conferences, Department of physics, Faculty of Sciences, Toliara, Madagascar*
[4] *Student, Department of physics, Faculty of Sciences, Toliara, Madagascar*

ABSTRACT

The main objective of this work is the exploitation of geothermal energy contained in the soil. It is therefore a study related to an air / ground heat exchanger. Thus, we have established an analytical model that allows us to describe the behavior of the air temperature along the interchange, assumed to be located in Toliara and in a region that has weather data and soil characteristics similar of our soil in Toliara, in the south western region of Madagascar. The calculation, related to the temperature leaving the exchanger, is based on the Bessel function and the periodic resolution of the signal. As in the majority of the practical cases, we resorted to empirical relations which are based on the simplifying hypotheses such as the admission of a constant average value of this parameter for the whole surface of transfer. For the simulation of the parameters determining the functioning, we have written computer programs under MATLAB, which comprise two main programs. The first program was used to estimate the soil temperature in order to know the variation of the soil temperature at several levels of depth as a function of time. The soil temperature mainly affects the performance of such a phenomenon because the soil, at a certain depth, becomes the primary factor for heat exchange between the air circulating inside the exchanger and the environment. which surrounds it.The second program concerns the calculation of the air temperature while varying the thermal design parameters of the exchanger. These sizing parameters concerning the characteristic quantities of the earth-to-air heat exchanger are: length, diameter and the velocity of air flow in the buried tube.

Keyword : - *earth-to-air heat exchanger , soil, amplitud*

---

1. Introduction

An earth-to-air heat exchanger system consists of one or more tubes (possibly a single tube), buried horizontally under the building (or next to it), and integrated into the ventilation system. Thus, we will examine successively, in this work, the depth of penetration of the heat in the soil by resorting to the equation of heat in conductive mode for an ideal burying of the tube. Then, we will propose an analytical correlation to find the temperature in every point, along the buried horizontal tube. Finally, simulation results are presented to illustrate the development of theoretical equations. But above all, we will see the ambient temperature model using the Fast Fourier Transform method (FFT).

2. The ambient temperature

It will be noted that the studied signal is not continuously known, but only by discrete values. On the other hand, the algorithm of the Fourier Transformation assumes a sample of given length T , sampled regularly with a period Te , the number of points considered N being a power of 2:

$$T = N\,Te \qquad \text{and} \qquad N = 2^M \tag{1}$$

The raw signal to be processed is sampled at a variable frequency. For the processing of all signals, the following criteria are chosen:

- length of a sample *T=365* days (so, one year)
- number of points *N=64* (so 2^6)
- sampling period $T_e = T/64$ (so 5.7 days).

From the previous calculation, we can then generalize the relation resulting from this analytical approach to the case of a surface excitation of any form. The input signal being of the form:

$$T_{amb}(t) = T_0 + \sum A_n \cos(\omega_n t - \varphi_n) \tag{2}$$

The calculation carried out over a period of one year with 64 equal time steps, allows to obtain for each signal. A sample already discretized for the use of Fourier Transform.

3. Operating principle of the earth-to-air heat exchanger

The principle of an earth-to-air heat exchanger is simple. The air of renewal is passed before it enters the house into a buried tube. Depending on atmospheric conditions, time, day and season, the outside air undergoes strong temperature variations. In contrast, the soil, a few meters below its surface, has a variable temperature because of its high thermal inertia. The earth-to-air heat exchanger therefore attenuates the thermal and hygrometric variations of the outside air, which corresponds to a pre-conditioning of the air.

3.1 Burial depth

In the rest of the study, we will look for the depth of burial. Air entering the pipe, we seek for a more stable temperature to solve the unidimensional heat equation unsteady [2]:

$$\frac{\partial T_{sol}(z\,,t)}{\partial t} = -a_{sol}\,\frac{\partial^2 T_{sol}(z\,,t)}{\partial z^2} \tag{3}$$

a_{sol} is the thermal diffusivity of the soil in m^2/s

z is the depth in meters.

The evolution of soil temperature as a function of depth is calculated by considering the response over time to changes in surface temperature. This requires a transient calculation.

Solving the transient heat equation for a semi-infinite medium whose surface excitation is a sinusoidal shape temperature next [3] :

$$T_{sur}(t) = \overline{T}_{sur} + A_1.\sin(\omega.t - \varphi_{amb}) + A_2.\sin(\omega.t - \varphi_{\Phi_g}) \tag{4}$$

knowing that :

$$\overline{T}_{sur} = \frac{(1 - Albedo)\cdot \Phi_g + h_r \cdot T_{amb} + (h_r - h_e)\cdot \dfrac{b_{lat}}{a_{lat}}}{h_e} \tag{5}$$

$$A_1 = \frac{h_r.A_{amb}}{h_e} \quad \textbf{(6)}$$

A_{amb} and φ_{amb} are the amplitude and the phase of the ambient air temperature which can be obtained respectively using formula (2) above.

$$A_2 = \frac{(1-albedo).A_{\Phi}}{h_e} \quad \textbf{(7)}$$

$$h_r = c_{lat}.f.h_{sur}.a_{lat}.H_r + h_{eq} \quad \textbf{(8)}$$

$$h_e = c_{lat}.f.h_{sur}.a_{lat} + h_{eq} \quad \textbf{(9)}$$

h_{eq} : Equivalent exchange coefficient

h_r : Intermediate variable of calculation

H_r : Relative air humidity

h_{sur} : Coefficient of convective exchange at the soil surface

a_{lat} : Empirical constant

b_{lar} : Empirical constant

c_{lat} : Empirical constant

Φ_g : Global flux of horizontal solar radiation

3.2 Experimental description of the earth-to-air heat exchanger

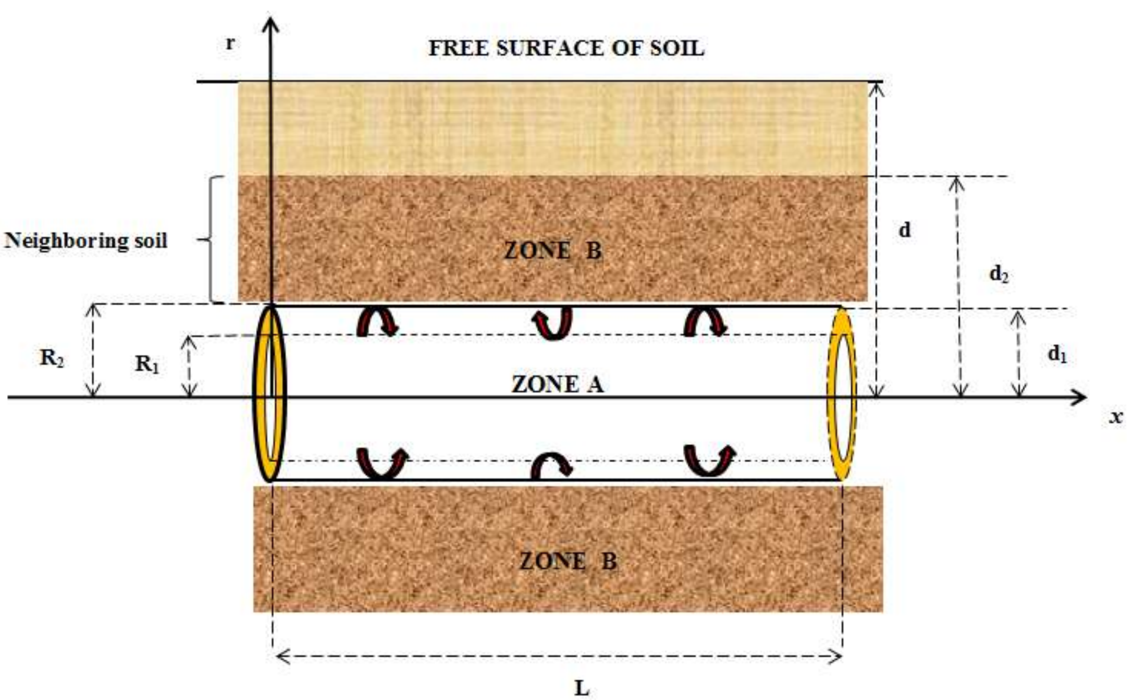

Fig -1: Experimental description

ZONE A : liquid area

ZONE B : neighboring soil area

 : Convection between the inner surface of the tube and the indoor air

4. Mathematical formulation of the problem

Given the complexity of the problem described above, its analytical resolution is almost impossible. In this type of situation, we used simplifying assumptions to make the problem affordable. The hypotheses that we have retained are: the fluid used is incompressible and the monophasic flow (temperature below that of boiling); the thermo-physical properties of the solid and the solid are constant; the terms viscous dissipation and natural convection are negligible; the problem is assumed to be two-dimensional (no edge effect); the system has no source of internal heat; the velocity profile is uniform in any straight section of the duct; the solid medium is considered homogeneous and isotropic. The flow of air in the well is governed by basic equations expressing in cylindrical coordinates, which are respectively the continuity equation, the Navier-Stokes equations and the energy equation [4].

- Continuity equation

$$\frac{d\rho}{dt} + \rho\, div \cdot \vec{U} = 0 \tag{10}$$

- Movement equation

$$\rho\left(\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \overrightarrow{grad} U\right) = -\overrightarrow{grad} P + \mu \Delta U + \rho \vec{g} \tag{11}$$

- Heat equation

$$\frac{\partial T}{\partial t} + \vec{U} \cdot \overrightarrow{grad} T = \frac{k}{\rho C_P} \nabla^2 T \tag{12}$$

knowing that:

ρ : Density of the fluid

μ : Fluid dynamic viscosity

k : Thermal conductivity

C_P : Specific heat of the fluid at constant pressure

U : Fluid velocity

$\vec{g}$: Gravity acceleration

Taking into account the raised simplifying hypotheses and the drawn objective, we are only interested in the equation of heat, there remain:

$$\frac{\partial T}{\partial t} + U_x \frac{\partial T}{\partial x} = \frac{k}{\rho C_P}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{13}$$

Thermal diffusivity is defined by $a = \frac{k}{\rho C_P}$, the equation (13) becomes:

$$\frac{\partial T}{\partial t}+U_x\frac{\partial T}{\partial x}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad \textbf{(14)}$$

and because, the following thermal diffusion is much higher than that following x, we can neglect the term $\frac{\partial^2 T}{\partial x^2}$ with $\frac{\partial^2 T}{\partial y^2}$, it remains of the heat equation:

$$\frac{\partial T}{\partial t}+U_x\frac{\partial T}{\partial x}=a\frac{\partial^2 T}{\partial y^2} \quad \textbf{(15)}$$

In cylindrical coordinates [5]:

$$\frac{\partial T(x,r,t)}{\partial t}+u(r)\frac{\partial T(x,r,t)}{\partial x}=a\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(x,r,t)}{\partial r}\right) \quad \textbf{(16)}$$

It splits into two parts, the fluid part and the solid part:

- Fluid area (zone A):

$$\frac{\partial T_{air}(x,r,t)}{\partial t}+u(r)\frac{\partial T_{air}(x,r,t)}{\partial x}=a_{air}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_{air}(x,r,t)}{\partial r}\right) \quad \textbf{(17)}$$

$$T_0(0,r,t)=T_0\cos(\omega t) \quad \textbf{(18)}$$

- Neighboring soil area (zone B)**:**

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_{sol}(x,r,t)}{\partial r}\right)=\frac{1}{a_{sol}}\frac{\partial T_{sol}(x,r,t)}{\partial t} \qquad x>0 \quad , \quad t>0 \quad \textbf{(19)}$$

- Neighboring soil and outer-wall **interface** [6]:

$$k_{sol}\left.\frac{\partial T_{sol}(x,r,t)}{\partial r}\right|_{r=R_2}=k_{paroi}\left.\frac{\partial T_w(x,r,t)}{\partial r}\right|_{r=R_2} \quad \textbf{(20)}$$

$$T_{sol}(x,R_2,t)=T_{paroi}(x,R_2,t) \quad \textbf{(21)}$$

4.1 Periodic solutions

In this study, we focus on the established periodic regime. So, temperatures in the fluid and in the soil are foud in complex notation in the form [7]:

$$T_{air}(x,r,t)=\tilde{\theta}_{air}(x,r)\exp(i\,\omega t) \quad \textbf{(22)}$$

$$T_{sol}(x,r,t)=\tilde{\theta}_{sol}(x,r)\exp(i\,\omega t) \quad \textbf{(23)}$$

By the use of Euler's expansion of the exponential function:

(24)

$$\exp(i\,\omega t) = \cos(\omega t) + i\sin(\omega t)$$

After introducing the equation (23) in the equation (19), and taking into account the development of Euler (equation 24), the relationship (19) becomes:

$$\tilde{\theta}_{sol}(x,r) = C_1\, I_0\left((1+i)\sqrt{\frac{\omega}{2\,a_{sol}}}\,r\right) + C_2\, K_0\left((1+i)\sqrt{\frac{\omega}{2\,a_{sol}}}\,r\right) \quad \textbf{(25)}$$

C_1 and C_2 are constants determined by the boundary conditions and the conditions at the walls, from which the particular solution can be written [8]. :

$$\tilde{\theta}_{sol}(x,r) = \tilde{\theta}_{air}(x)\tilde{\Gamma}_{sol}(r) \quad \textbf{(26)}$$

$\tilde{\Gamma}_{sol}$ is called the amplitude of the soil temperature or radial modulation.

Taking into account the relationships (25) and (26), and noting respectively by $\tilde{\Gamma}_{réel}$ and $\tilde{\Gamma}_{im}$ respectively the real part and the imaginary part of $\tilde{\Gamma}_{sol}(r)$ in the expression (26) and for $r = d_1$:

The amplitude A_{air} :

$$A_{air} = T_0 \exp\left[-\frac{\pi\, h_{tot}\; R_1\, x}{c_a \dot{m}_a}\left(1-\tilde{\Gamma}_{réel}(d_1)\right)\right] \quad \textbf{(27)}$$

The phase shift φ_{air} :

$$\varphi_{air} = \omega t_0 + \frac{\pi\, h_{tot}\; R_1\, x}{c_a \dot{m}_a}\tilde{\Gamma}_{im}(d_1) \quad \textbf{(28)}$$

4.2 Temperature of the air at the outlet of the exchanger

Thus, the temperature of the air at the outlet of the exchanger is given by the following expression:

$$T_{air}(x,t) = T_0 \exp\left[-\frac{\pi\, h_{tot}\; R_1\, x}{c_a \dot{m}_a}\left(1-\tilde{\Gamma}_{réel}(d_1)\right)\right]\cos\left(\omega(t-t_0) - \frac{\pi\, h_{tot}\; R_1\, x}{c_a \dot{m}_a}\tilde{\Gamma}_{im}(d_1)\right) \quad \textbf{(29)}$$

knowing that [9]:

$$h_{tot} = \frac{2\pi}{\dfrac{1}{k_{sol}}Ln\left(\dfrac{d}{R_2}\right) + \dfrac{1}{k_{tube}}Ln\left(\dfrac{R_2}{R_1}\right) + \dfrac{1}{R_1\, h}} \quad \textbf{(30)}$$

h : is the convective air / tube exchange coefficient.

5. Results and discussion

5.1 The depth of the tube burying

We have established a programming code, according to equations (3) and (4) to have different temperatures in depth. The depths considered vary from 0 m to 7 m in steps of 1m.

The different curves corresponding to each depth are indeed sinusoidal, of the same period but of different amplitudes. Table 1 below gives the different maximum temperature values and soil temperature amplitudes at depth from Figure 2.

Table -1: Soil temperatures and amplitudes in depth

Depth	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m
Maxima	28.54	26.80	25.95	25.52	25.32	25.21	25.16	25.16
Amplitude	3.43	1.69	0.83	0.41	0.20	0.10	0.05	0.05

Table 1 allows to find a temperature almost constant in depth. We can also note a soil inertia, as regards the attenuated penetration of the surface temperatures: in addition to reducing the temperature with the depth, the soil also causes in time the differences between the surface temperature and the deep temperature. Thus, we can see that the average air temperatures outside Toliara (corresponding to z = 0 m) can vary from 21.5 ° C to 28.5 ° C (Fig 2), while those from the soil vary less, and remain in the vicinity of 25.16 ° C for a depth of 7 m. It should be noted that this range of temperature is even lower than the depth of the pipes which is high. When the soil thickness exceeds the depth of penetration, indicating that beyond the active layer, the airflow no longer sees the surface temperature (constant, but equal to the average of the input oscillation).

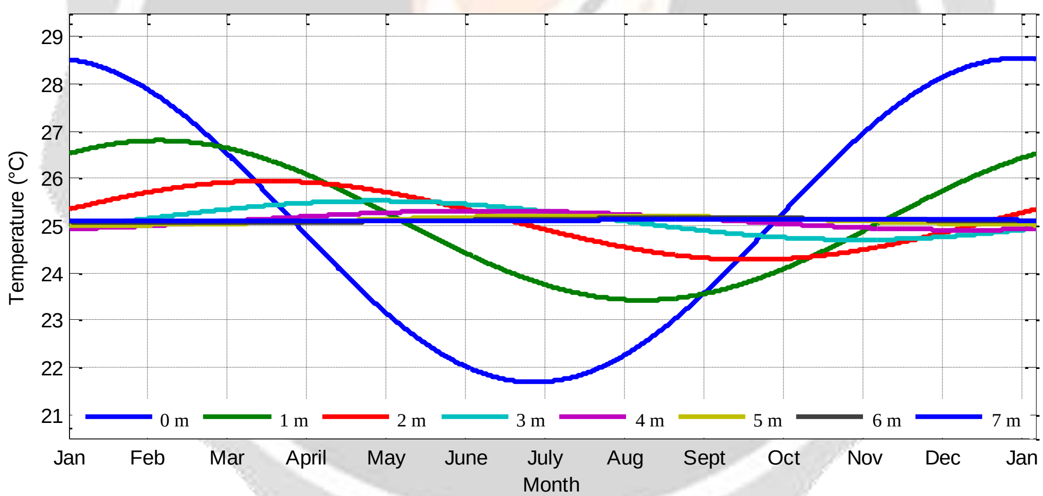

Fig. 2 : Soil temperature evolution in depth

5.2 Optimization of tube length

To verify the effectiveness of the system, we performed a simulation under the conditions of sandy soil (Toliara Region), the exchanger is PVC (polyvinyl chloride) with a wall of 2 mm thick, buried at a depth of 7 m . From Figure (3), the optimal depth for burying the pipe is beyond 5 meters, but we set the burial depth at 7 m for the simulation.

By fixing the diameter of the buried tube at 50 mm, by varying the lengths of the tube from 10 m to 50 m, for the different velocity values, these results are presented in Figures (3), (4) and (5). By analyzing these different figures, we have found that for a length of 10 m of the tube, depending on the air flow velocity in the tube, the maximum temperatures vary between 27.24 ° C and 28.30 ° C with amplitudes which are between 2.1 ° C and 3.19 ° C.

But as soon as we increased this length to 50 m, the maximum temperature variation became less than 26.67 ° C, with an amplitude that does not exceed 1.54 ° C. The length of the tube determines the exchange surface and the residence time of the air in the tubes. These figures (3), (4) and (5) also illustrate the influence of velocity. As air velocity increases, fluid will not have enough time to transfer heat to the ground.

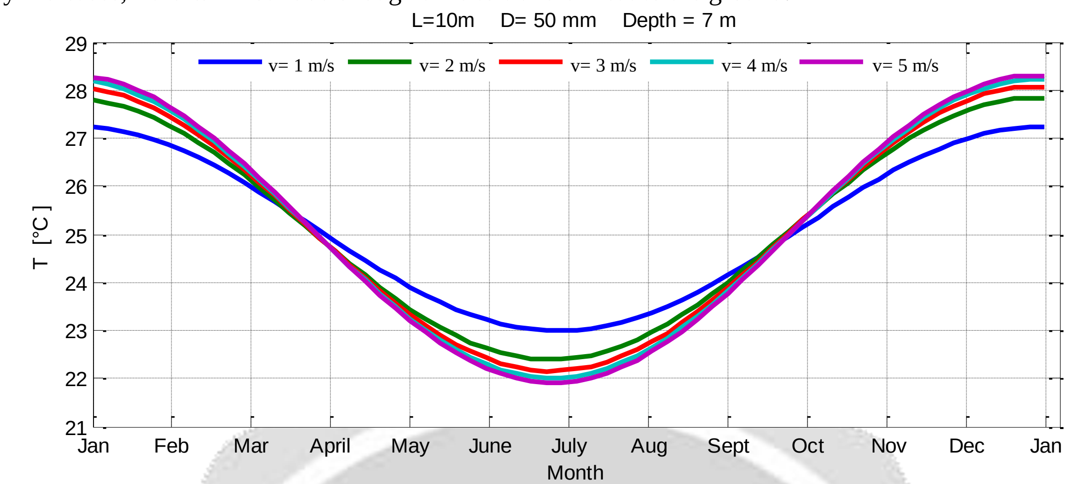

Fig. 3 : Evolution of the air temperature for L= 10 m

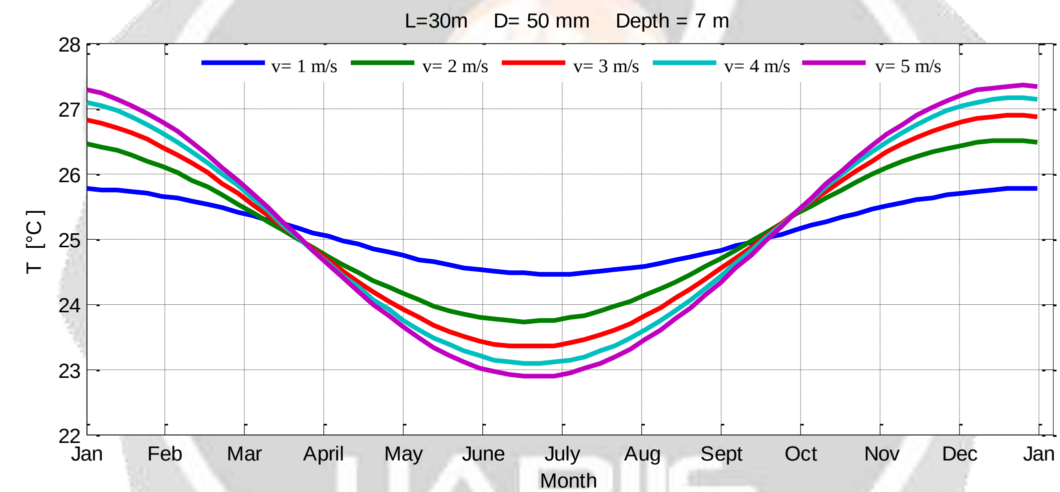

Fig. 4 : Evolution of the air temperature for L = 30 m

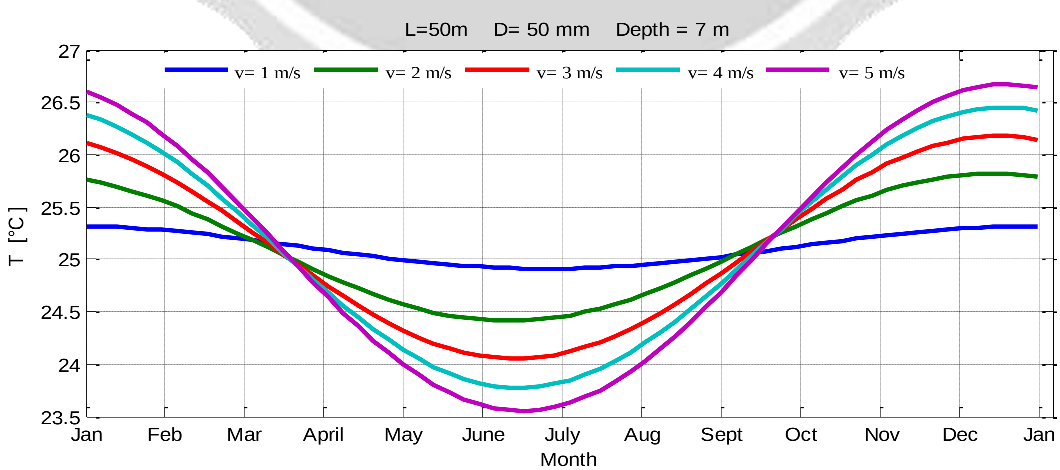

Fig. 5 : Evolution of the air temperature for L= 50 m

5.3 Optimization of the diameter of the tube

Now fixing the length of the tube at 50 m, varying the diameter of the tube for different velocity values, we have the curves going from (Fig.6) to (Fig.8), which show us that for small values and for diameters between 100 and 150 mm, we have amplitudes around 25.78 ° C at an amplitude of 0.67 ° C.

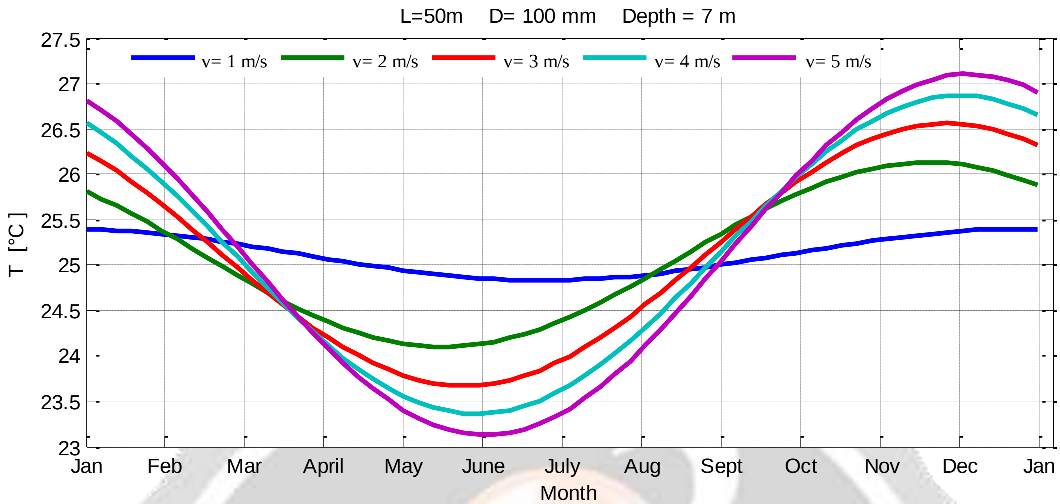

Fig. 6 : Evolution of the air temperature for L = 50 m and D = 100 mm

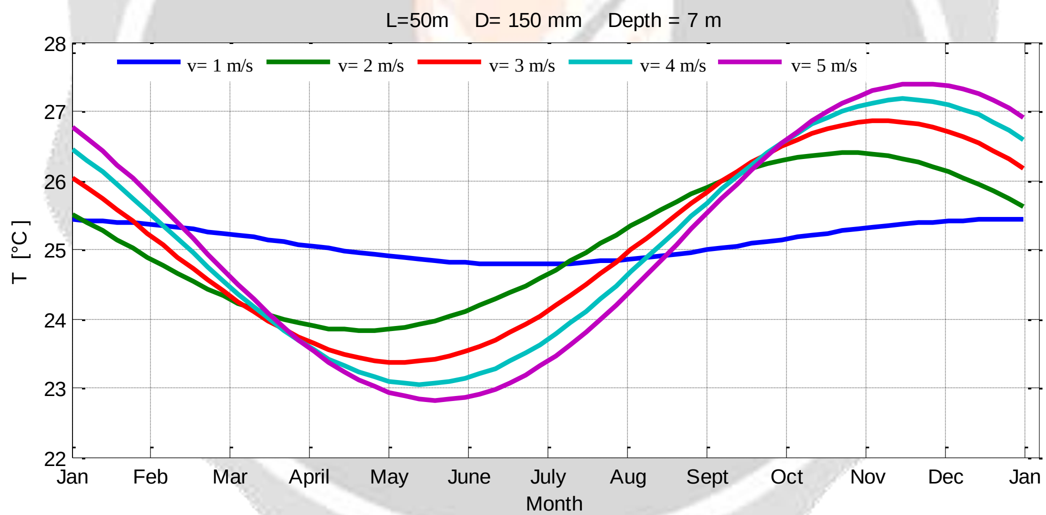

Fig. 7 : Evolution of the air temperature for L = 50 m and D = 150 mm

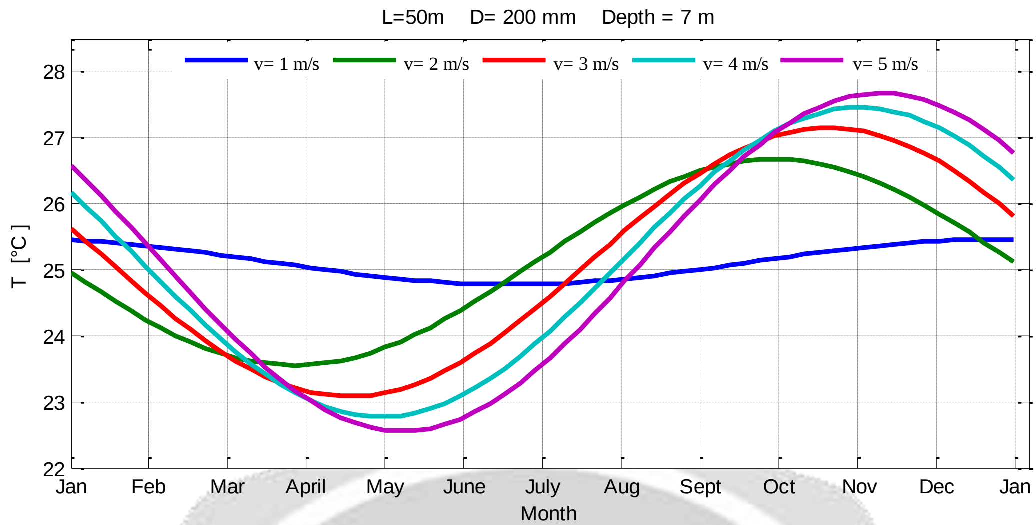

Fig. 8 : Evolution of the air temperature for L = 50 m and D = 200 mm

5.4 Optimization of the air velocity inside the exchanger

The figure 9 to 12 shown below represents the numerical resolution of equation (2), (4) and equation (29). These figures shows the comparison between three curves: the curve in red color is ambient air, that is to say, the temperature of the air at the inlet of the exchanger, the curve in green is the temperature of the air at the outlet of the exchanger and the temperature in blue color is the temperature of the ground.

By fixing the optimum parameters retained above, that is to say, for a length of 50 m and of diameter 100 mm, for a small value of velocity, v = 1 m / s for example (Fig. 9), the temperature of the air leaving the well tends to reach the temperature of the ground.

Air velocity is not an independent parameter since it stems directly from the choice of length and diameter of the tube.

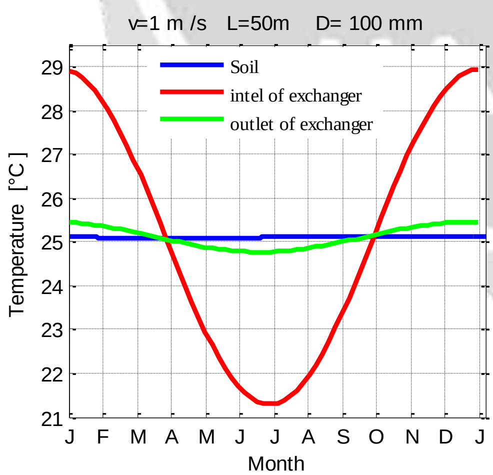

Fig. 9 : The temperatures, for v=1 m/s

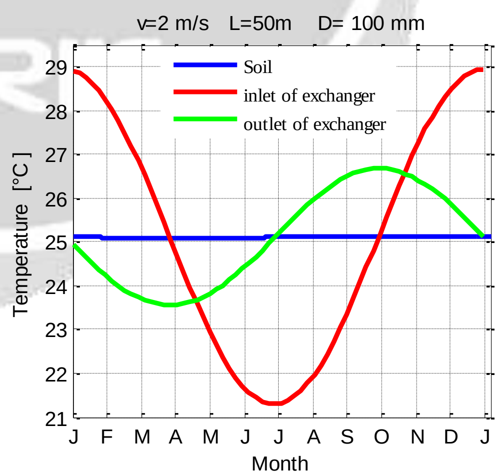

Fig. 10 : The temperatures, for v=2 m/s

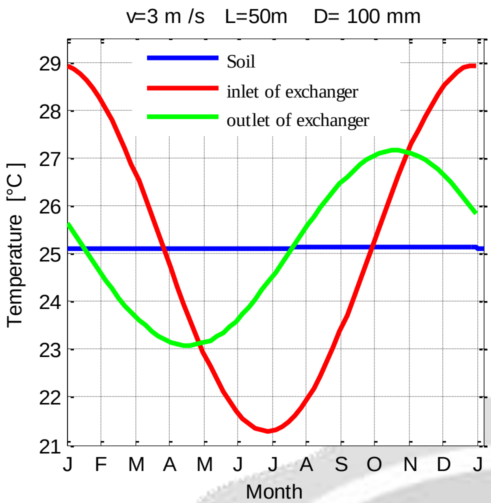

Fig. 11 : The temperatures, for v=3 m/s

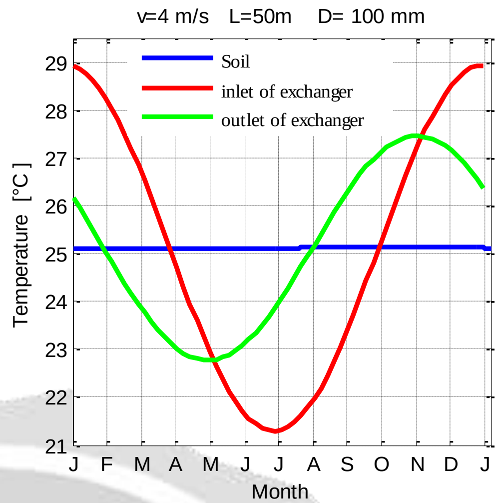

Fig. 12 : The temperatures, for v=4 m/s

6. CONCLUSIONS

To sum, our goal is to install an underground pipe (heat exchanger) that allows you to exchange heat with the ground and collect fresh air at the exit. We presented the technical procedures of the installation which bring the calculations and the necessary results to show essentially: the optimal depth of burying of the pipe (d = 7m), the optimal length and the diameter of the tube (L = 50m, D = 100mm) as well as the velocity of air flow required in the pipe (v = 1m / s).

7. ACKNOWLEDGEMENT

Our deep gratitude to Mr. RATIARISON Adolphe Andriamanga, Emeritus Professor at the Faculty of Sciences of the University of Antananarivo, Madagascar and his team, for allowing us to conduct our investigations in their DYACO laboratory.

8. REFERENCES

[1]. Shubha Kadambe et G.Faye Boudreaux-Bartels, (1992). Application de la transformée en ondelettes (TO) pour la détection de la fréquence fondamentale (JD) des signaux de la parole de IEEE.
[2]. HOLLMULLER, P. (2002). Utilisation des échangeurs air-sol pour le chauffage et le rafraîchissement des bâtiments. Thèse de doctorat. Faculté des sciences de l'Université de Genève. 125 p.
[3]. Naimi, R. Devienne et M. Lebouche, “Etude dynamique et thermique de Couette-Taylor-Poiseuille ; cas d’un fluide présentant un seuil d’écoulement ”, Int. J. Heat and mass transfer, Vol. 33, N°2, pp. 381-391 (1990).
[4]. S. Thiers, B. Peuportier: Modélisation thermique d’un échangeur air-sol pour le rafraichissement de bâtiments. École Nationale Supérieure des Mines de Paris, France 2007.
[5]. SALHI Toufik et ROUAHNA Salah, Etude d’un échangeur air/sol cylindrique à input Périodique, Mémoire d’ingénieur d’état, Université du Biskra (2010).
[6]. R. O. C. Guèdes et R. M. Cotta, Periodic laminar forced convection within ducts including wall heat conduction effects. Int. J. Engng. Sci, Vol. 29, N° 5, pp. 535-547, (1991).
[7]. R F. W. Schmidt et J. Szego, Transient response of a solid sensible heat thermal storage units single fluid, J. Heat Transfer, Vol. 98, pp. 471-477, (1976)
[8]. K. Mansouri, Etude théorique et expérimentale du transfert de chaleur en régime périodique pour un écoulement forcé à plan directeur. Thèse de Doctorat. Science pour l’ingénieur université de Nantes, Nantes, France, (1995)
[9]. RAZAFIMANDIMBY H.A., « Énergétique Appliquée », Cours de 3ème cycle de Physique, Fac.Sciences de l’Université, Toliara(Madagascar), 2007.