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The Earth to Air Heat Exchanger for Reducing Energy Consumption in South Algeria

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ABSTRACT

In Algeria, the construction sector accounts for 30% of the country's final energy consumption. The integration of passive or semi-passive cooling/heating systems in construction is now essential for the reduction of energy consumption while improving thermal comfort. Amongst the systems used is the air-to-ground exchanger. It consists of tubes buried at a depth of 2 to 4 m in which the ambient air is pushed in order to be cooled/heated in contact with the ground whose temperature is almost constant throughout the year. This temperature, which is highly dependent on weather conditions, is about 24℃ in Bechar, a region located in south- west of Algeria. The cooled/heated air was blown into the building. The objective of the present study is to highlight the possibility of installing and using this system in arid regions. The mathematical model established to calculate the temperature at the outlet of the exchanger, based on the k-ε turbulence equations and the energy equation, discretized by the finite volume method. For the temperature distribution in the soil, a simple analytical solution is developed. The parameters of (1) the length diameter ratio (alpha), (2) the Reynolds number, and (3) the depth of burial was studied. The results obtained are validated with the experimental device installed at the University of Biskra, a region in the south- east of Algeria. Sand, as a soil type, gives a constant annual temperature of 21℃ at a depth of 3m. For Reynolds equals 7500 and the ratio, alpha=250 gives a temperature at the outlet of the ground air exchanger equal to 24℃. An optimal solution was chosen for the installation of the ground air exchanger in south-western Algeria.

1. INTRODUCTION

Currently, the construction sector is positioning itself as a key player in solving the worrying environmental challenges we face. Indeed, the context is global, and it is a question of global warming. As a result, this sector may well be the only one with sufficiently strong opportunities for progress to meet multiple national commitments to reduce greenhouse gas emissions.

Climate change and rising temperatures in habitable zones have a direct impact on the quality of indoor environments in buildings, especially during heat waves. Thus, the deterioration of summer comfort and the quality of life inside the atmospheres are pushing more and more populations to use air conditioning, which has become almost essential. Sometimes, the latter is even vital when it comes to elderly people living in such arid regions.

The objective of the present paper is mainly to evaluate the benefits of using the air-to-ground exchanger in Béchar, which is located in the south- west of Algeria, where the climate is arid and temperature rate exceeds; sometimes, 46℃. The present manuscript was divided into four sections.

The first section is devoted to the principle of operation of the ground air exchanger, their installation and the parameters used.

In the second section, we presented a literature review of previous studies. A variation between the analytical and numerical models was presented and it was concluded that the numerical, analytical and experimental results were almost identical.

The third section deals with the modelling of air-to-ground exchangers. The objective is to present the mathematical model of the simulation tool, to calculate the temperature of the air traversing the air-to-ground exchanger. For this we chose the method of finite volumes to discretize the differential equations.

The fourth section is devoted to the presentation of the results obtained. Once the validation of the simulation tool used was acquired, we carried out a parametric study on the most influential parameters of the air-to-ground exchanger whose objective is to show the effect of each parameter, or the combination of several parameters, on the sensitive energy lost by the air passing through the exchanger. The temperature distribution in the soil (assumed homogeneous) for different soil type was analysed using an analytical solution and conclude with an aeraulic study.

As a conclusion, the use of the ground air exchanger in arid areas is possible. Following the reflections and discussions revolving around numerical simulation, perspectives for this work are proposed.

1.1 Principle of the air-to-ground exchanger

Depending on the atmospheric conditions, the time, the day and the season, the outside air undergoes strong variations in temperature and humidity. On the other hand, the ground, a few meters below its surface, has a little variable temperature due to its high thermal inertia. The air-to-ground exchanger, Canadian well or a Provençal well, takes advantage of this great inertia by putting the outside air in thermal contact with the ground. Firstly, its primary purpose is the thermal and hygrometric pre-conditioning of the ventilation air of buildings. Secondly, it can also avoid winter icing of the exchanger on stale air, when it is associated with it upstream.

Concretely, the air-to-ground exchanger consists of tubes buried a few meters deep under the ground, near or directly under the building to be ventilated. Air from the outside, driven by a fan, travels through the tubes before being blown into the building (Figure 1). While remaining in the tubes, the air exchanges its calories with the ground and can also deposit some of the water it was loaded with in the tubes. The air-to-ground exchanger; therefore, attenuates the thermal and hygrometric variations of the outside air, which corresponds to a pre-conditioning of the air. This system consumes very little electricity; so, it is almost passive.

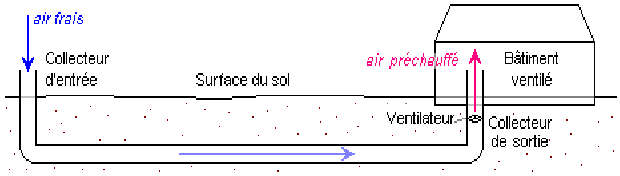

Figure 1. Drawing earth to air heat exchanger

This type of equipment is not suitable for all buildings. Indeed, its construction requires the realization of relatively deep trenches (from one to several meters) and a relatively large ground space is required. It therefore seems more suitable for buildings built in an open area (suburban district, business area) than for those located in dense urban areas. Buildings of all sizes can be equipped with them, from individual houses to collective dwellings and office buildings (several projects in Germany Dibowski [1]). From a technical and economic point of view, it is preferable to install the interchange at the time of the realization of the structural work, rather than after the commissioning of the building.

2. BIBLIOGRAPHIC SYNTHESIS

Research on air-to-ground exchangers appears to have started after peak oil in 1979 and stopped temporarily after the counter-shock of 1985 Tzaferis et al. [2].

It is only since 1995 that some researchers have resumed studies on the issues of the performance of air-to-ground exchangers, their thermal behavior and their integration into the building as an air pre-conditioning system. An analysis of the different approaches encountered in the literature makes it possible to identify the different hypotheses and simplifications, as well as the mathematical representation tools used that depend on the objectives of the model. This analysis provides an interesting basis for work prior to the design of a model.

2.1 State of the art of air-to-ground exchanger models

A plethora of literature is available in the models of air-to-ground exchangers that have been developed for applications either in the field of buildings or in that of horticultural greenhouses.

2.2 Analytical models

Among the analytical models, there are large numbers of models that consider the temperature of the ground not being influenced by the presence of the exchanger.

The simplest model of air-to-ground exchanger is the one proposed by Badescu et al. [3], which assumes that at a sufficient depth, the soil temperature is constant throughout the year. It assumes that the tube is very long and that the air outlet temperature can be considered equal to the ground temperature. We therefore have a constant outlet temperature of the exchanger all year round equal to the temperature of the surface of the tube.

Without using such a simplistic hypothesis, several authors Tzaferis et al. [2]; Serres et al. [4]; De Paepe [5] and Jones et al. [6]; Al-Ajmi et al. [7]; Ghosal and Tiwari [8]; Tiwari et al. [9] consider that the surface temperature of the tube does not vary along it and can therefore evaluate the Temperature of the air at the outlet of the tube as a function of its inlet temperature analytically. Tzaferis et al. [2] compared eight models (four analytical and four numerical) that differ in the way of calculating the outlet temperature as a function of the inlet temperature, with the surface temperature of the tube fixed. It is found that all these models give about the same results, which is not surprising because all use the same type of approach, the way of writing the problem being the only difference.

2.3 Elaborate models

Among the most elaborate models, for studying the behavior of an air-to-ground exchanger is the semi-analytical analysis of Soontornchainacksaeng, [10] in which the soil is broken down into slices in which the solution of the thermal problem is carried out analytically.

The model is based on the decomposition of the thermal problem of a tube in the ground considered as a semi-infinite 2D medium into two elementary problems solved separately.

The solution of the problem is done in a classic way no influence of the tube while that of other problem uses the method of the mirror source line, that is to say that we consider a fictitious source line (tube) symmetrical to the first with respect to the ground and of opposite intensity. The answer to this problem is given analytically for a slot surface stress and the complete dynamic regime is obtained by superimposing responses to slots of different intensity, which gives rise to a numerical calculation of series. We can then at any time know the temperature field everywhere in the slice considered. This model has the advantage of being able to be transposed to the study of multi-tube exchangers; however, it does not take into account radiation at ground level. Moreover, the decomposition into these two elementary sub-problems is not exact and remains valid only if we consider that the exchanges at the tube level have no effect on what happens on the surface. The model is therefore only valid for deep tubes and stresses of not too large periods (the response to an annual period signal is poorly taken into account). In addition to all these analytical models, we also find in the literature a large number of numerical models.

2.4 Numerical models

Several models consider the problem of the single-tube exchanger by considering that only the exchanger

Mihalakakou et al. [11]; Giardina [12]; Kumar et al. [13] disturbs a ground cylinder around the tube.

The model of Mihalakakou et al. [11] is based on a discretization of the soil into concentric cylinders and axial meshes. The author as a mix of the finite difference method and the finite element method describes the numerical method used. The re-bonding with the undisturbed soil is not precisely described (diameter considered, type of boundary...).

The model proposed by Giardina [12] was originally developed for water-to-ground exchangers, but it is the method of resolving conduction in the soil that interests us here. Compared to the previous model, each cylinder was cut into angular portions and the finite difference method is used for discretization. On the boundary of the mesh was considered that the temperature is equal to the temperature of the undisturbed ground.

The model of Kumar et al. [13] uses the same principle as that of Mihalakakou et al. [11] but by coupling the phenomena of mass and moisture transfer. In the same way, the regluing with the undisturbed soil was very little explained.

The model proposed by Thiers and Peuportier [14] makes it possible to take into account the interaction between several tubes in parallel on the same tablecloth. A finite volume mesh with a limited number of meshes is used, which allows for very fast calculation. For each tube, two concentric cylindrical meshes are used plus a third if the different tubes are far enough apart from each other. If the tubes are too close, the third mesh encompasses them all to take into account their interactions. On the outer surface of this third mesh is imposed a temperature equal to the average of the temperatures of the undisturbed soil at the high and low levels of the mesh. This model can take into account the influence of the building on the exchanger by involving an additional term in the balance to calculate the ground temperature.

The model of Bojic et al. [15] proposes a 1D discretization of the heat equation with horizontal meshes. He studies an exchanger with several parallel and coplanar tubes by not considering the cylindrical geometry of the system. This model takes into account in the balance equation at the ground surface radiation as well as convective exchanges by a global exchange coefficient. The connection between the soil model and the tube slick is done via a source flow in a mesh that is calculated from the temperature difference between the ground and the air circulating in the tubes.

The other models encountered in the literature take into account in more detail the exchanges by carrying out studies in 2D or 3D.

The model of Badescu [16] proposes a cutting into slices perpendicular to the tubes. On each of these units, the resolution of the heat equation is carried out by the method of formulation in control volume. The regluing between the different slices is done at the level of the air circulating in the tube (no axial flow is considered in the ground).

Two models of exchangers can take into account multiple aquifers Boulard et al. [17]; Gauthier et al. [18] these are 3D models of soils comprising tubes of square sections of the same exchange surface as the actual tubes in which the conductive problem is solved by the finite volume method by considering adiabatic conditions at the boundaries of the control volume.

The model of Gauthier et al. [18] allows the consideration of non-homogeneous soils.

2.5 Hollmuller model

Hollmuller's doctoral thesis is now one of the main references for the thermal of air-to-ground exchangers Hollmuller [19]. Based on in-depth analytical theoretical modelling but also on numerous in-situ measurements, the author establishes simple rules for the sizing of air-to-ground exchangers.

Several authors [20-23] have published revisions on the different types of ground air exchangers, their installation in the different regions and the methods used to study this phenomenon.

3. GENERAL CONSERVATION EQUATION

$$\frac{\partial}{\partial x_j}(\rho U \phi) = \frac{\partial}{\partial x_j}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_j}\right) + S_\phi \qquad (1)$$

where, ϕ: represents a general dependent variable which can be the velocity U, the kinetic energy of turbulence, K, and its dissipation rate, ε; Γ_ϕ: is the diffusion coefficient of the φ property; S_ϕ: is the source term (See Table 1).

Table 1. Terms of the generalized equation

Equation	**φ**	$\boldsymbol{\Gamma_\phi}$	$\boldsymbol{s_\phi}$
Continuity	1	0	0
Momentumt	U	$\frac{\alpha}{Re} + \upsilon_T$	$\frac{\partial P}{\partial X}$
Energy	θ	$\frac{\alpha}{RePr} + \frac{\upsilon_T}{Pr_t}$	
Kinetic energy	K	$\frac{\alpha}{Re} + \frac{\upsilon_T}{\sigma_k}$	$\upsilon_T \left(\frac{\partial U}{\partial X}\right)^2 - E$
Energy dissipation	E	$\frac{\alpha}{Re} + \frac{\upsilon_T}{\sigma_k}$	$C_{\varepsilon 1} f_1 \frac{E}{K} \upsilon_T \left(\frac{\partial U}{\partial Y}\right)^2 - C_{\varepsilon 2} f_2 \frac{E^2}{K}$

3.1 Boundary conditions

The boundary conditions specific to the cases treated are:
At the entrance to the canal (X=0),
(a) U=1, V=0, θ=0, K=0.003 Et $E = \frac{K^{3/2}}{0.06}$
Solid wall of the duct,
(b) U=0, V=0, θ=1
At the exit of the channel (X=1),
U=V=0, $\frac{\partial \theta}{\partial Y} = 0, \frac{\partial K}{\partial Y} = 0, \frac{\partial E}{\partial Y} = 0.$

3.2 Computational details

The governing equations were iteratively solved by the finite-volume method using Patankar’s SIMPLE algorithm [24]. A two-dimensional uniformly 80_80 spaced staggered grid system was used. The QUICK scheme was utilized for the convective terms, whereas the central difference scheme was used for the diffusive terms. The under-relaxation factors for the velocity components, pressure correction, thermal energy, turbulent kinetic energy, and its dissipation rate are all set to 0.15.

Tolerance of the normalized residuals upon convergence is set to 10^{-5} at each time step for all cases investigated.

4. RESULTS AND DISCUSSION

4.1 The parameters used

The Table 2 below shows the parameters used for our numerical simulation.

Table 2. The parameters used for our numerical simulation

Nom	Expression	Valeur	Description
alpha	L/D	250-1000	Length-to-diameter ratio
Re		2500-10000	Nombre de Reynold
Pr		0.71	Prandt number
Tin		28-48°C	Input temperature
Twall		3-23°C	Surface temperature

4.2 Validation of numerical results

The results obtained were validated by taking as a reference certain experimental studies available in the literature. In particular, Hatraf et al. [25] who experimentally studied this problem at the University of Biskra. The data used for experimental site and the properties of the fluid were mentioned in the Table 3. Their results were used as a reference to test our numerical results for driving (D=0.11m, L=60m, ie: alpha=545).

Table 3. Data for validation

Length of the pipe	60 m
Pipe diameter	0.21m
Input velocity	3.79 m/s
Kinematic viscosity	16.96x10^{-6} m$^{2/s}$
Inlet temperature	37°C
Soil temperature (z=4m)	24°C

This comparison (Figure 2) shows that there is a qualitative agreement between the results we obtained and those of Hatraf et al. [25], which comforts us in the choice of our mathematical and numerical models, thus allowing us to validate our numerical simulation procedure.

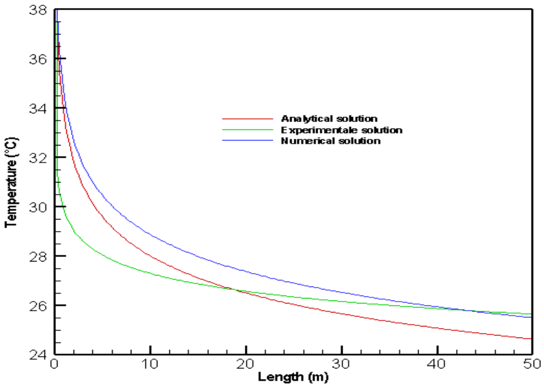

Figure 2. The temperature at the driving output as a function of length

4.3 Temperature distribution in the soil

Variations throughout the year in soil temperature at different depths and for different soil types can be easily obtained using Eq. (2), if the value of the soil diffusivity and the variation in the ambient temperature of the locality are known as follows:

- ➢ Heat transfer due to moisture gradient in the soil is neglected in front of the temperature gradient.
- ➢ The temperature of the soil at a certain depth is constant during the year.
- ➢ The soil around the pipe is isotropic with homogeneous thermal conductivity.
- ➢ Soil surface temperature is approximately equal to the ambient air temperature.

$$T(z,t) = T_m + T_0.\exp\left(-\frac{z}{\gamma}\right).\cos\left(\omega t - \frac{z}{\gamma}\right) \qquad (2)$$

These variations in ground temperatures allow the evaluation of the potential of the use of surface geothermal energy and appropriate technology for its exploitation. Particular attention will be paid to the feasibility of the ground air exchanger technique, given its simplicity and its infirm energy consumption.

In Béchar (south-west Algeria), the set temperatures inside the premises, commonly used are 24°C for the air conditioning season and 20°C during the heating period Mebarki et al. [26]. These periods extend from June to September and from December to February respectively. We can therefore examine the possibility of air conditioning and/or heating in Béchar, by direct exchange between the air and the ground, by comparing the set temperatures with those of the ground. This is to check that the ground temperature is above 20°C during the heating period and below 24°C during the air conditioning period. However, another important parameter in the application of the technique is the thermal potential, defined by ΔT=T soil (t,z) – T amb (t).

The difference between ambient and soil temperatures is a measure of how much energy can potentially be extracted from the soil. In the case, of the feasibility of the technique, the thermal potential makes it possible to judge the ease with which the heat exchange can be done which influences the size of the installation for example. Otherwise, the thermal potential makes it possible to determine the importance of the preheating or pre-cooling of the air that geothermal energy can provide.

Soil temperature was calculated at different depths for three soil types see (Figure 3) for gravel sand matrix - (Figure 4) for sand soil - (Figure 5) for fin sand soil.

According to the distributions obtained, the most suitable depth for the installation of the ground air exchanger is 3 m, since there is no change in temperature plus this depth. The soil temperature for given depth will be conditional on the limit (Temperature imposed) for the exchanger.

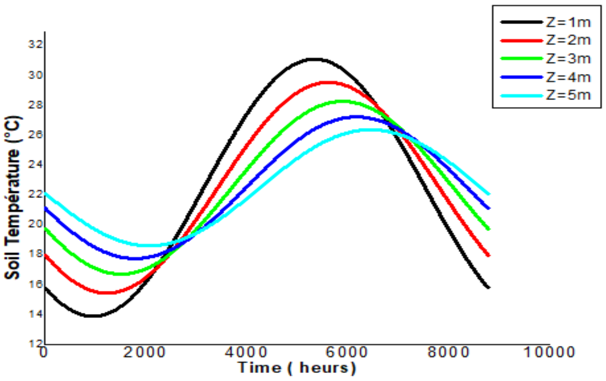

Figure 3. Gravel sand matrix soil at different depths

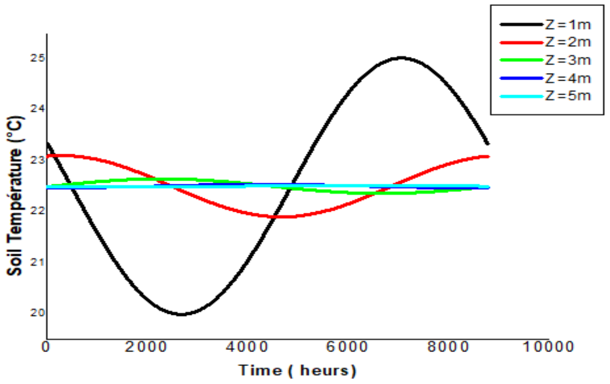

Figure 4. Sand soil at different depths

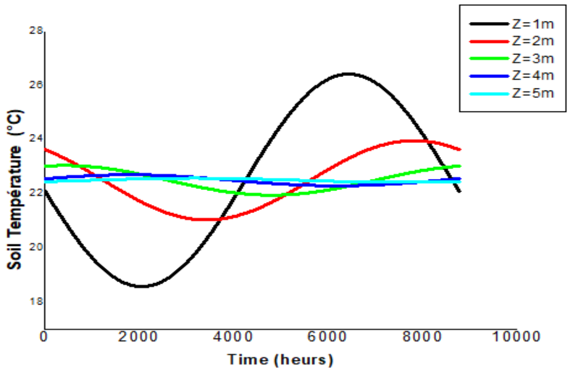

Figure 5. Fin sand soil at different depths

4.4 Ground air exchanger

4.4.1 Temperature at the outlet of the exchanger

The sizing of a ground air exchanger is quite delicate because of the number of parameters to be optimized: form factor (length / diameter), depth of burial, Reynolds number (ventilation flow).

The results obtained do not present any particular difficulties or originality. It is a simple application of heat exchange calculation by convection forced to a buried pipe.

We calculate the outlet temperature for each depth, varying the Reynolds number for different alpha (Figures 6-9).

For each depth the alpha=1000 form factor records temperature drops at the outlet of the exchanger for different Reynolds number compared to the other factors of the form. We notice for depth Z=4 m, the temperature at the outlet of the exchanger is less than 26°C for Re=15000. It is still observed that the growth of Reynolds number influences the outlet temperature.

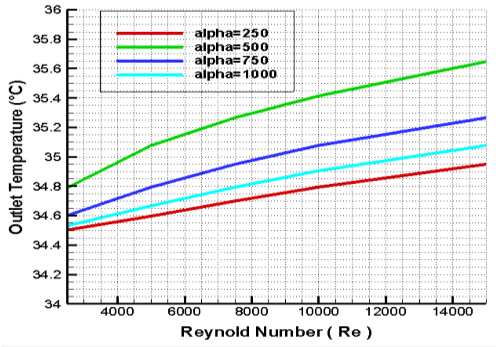

Figure 6. Z=1m

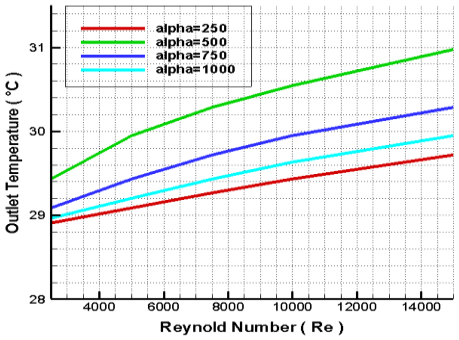

Figure 7. Z=2m

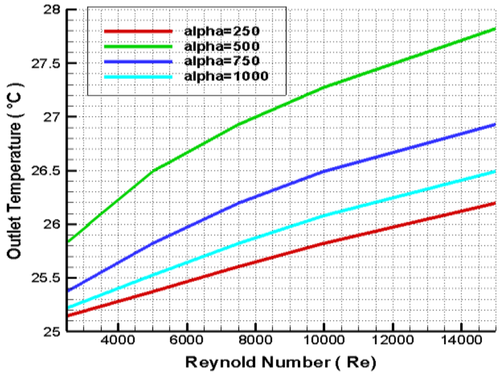

Figure 8. Z=3m

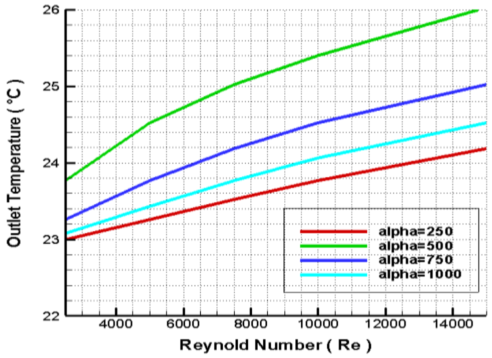

Figure 9. Z=4m

In (Figure 10), we plotted the isotherms for Re=7500 and alpha=250.

The temperature decreases from 40°C to 24°C in the middle of the channel (Y=0.5), the outlet temperature at the outlet of the exchanger tends towards the temperature imposed on the upper wall.

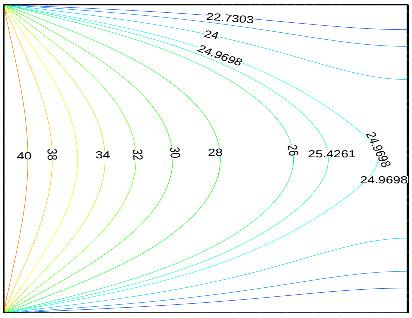

Figure 10. Isotherms at Z=4m

5. CONCLUSIONS

The results obtained in this study, some can be synthesized as follows:

- The performance of a soil thermal energy recovery system is exploited using a HDPE pipe of L/D=250.

- The particularity of the ground air exchanger lies in the fact that the difference in temperature between the incoming air and the ground is variable during the year and depends on the depth of burial of the pipe.

- Air conditioning and heating by surface geothermal using this technique is possible for the locality of Béchar.

In the future, it seems interesting to us to conduct studies in 3D and in an unsteady turbulent regime in order to have numerical results that had better reflect physical reality. For this, it will then be necessary to take into account the variation of the physical properties of the fluid as a function of the temperature when establishing the mathematical model. So, to have an experimental facility to better validate our results.

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NOMENCLATURE

D	Pipe diameter m
K	Kinetic energy m^2/s^2
L	Length of the pipe m
P	Pressure Pa
Δp	Pressure drop Pa
T(z,t)	Temperature at depth z and instant t °C
Tm	Average annual soil surface temperature °C
To	Amplitude of soil surface temperature oscillations °C
z	Depth in the soil m
ω	Pulsation of surface temperature oscillations rad/s
γ	Depth of penetration of a signal m
ν	Kinematic viscosity m^2 /s
ε	Dissipation rate of turbulent kinetic energy m^2 /s^3
μt	Turbulent viscosity Pa .s

Dimensionless

S_ϕ	The term source
U,V	Dimensionless components of the velocity vector
X	Dimensional Cartesian coordinates
α	Length to diameter ratio
θ	Dimensionless components of temperature
$\Gamma\phi$	Diffusion coefficient for the general variable
ϕ	Dependent variables u,v,k,T et ε
Pr	Prandtl number
Re	Reynolds