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Numerical study of heat diffusion in three soils under the influence of a hot air flow in the Sahelian zone: Case of air-soil heat exchanger

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Abstract

The thermal inertia of the soil is a very influential parameter in the operation of an air-soil heat exchanger. In this work, we studied the thermal behavior of three different soils (moist sandy, dry silt clay and dry sandy) in order to determine which one has the greatest thermal inertia. For this, we used the conduction analysis of the comsol software. According to our results, the most thermally stable soil is the dry sandy soil. It is this latter which possesses the greatest thermal inertia. Thus, for a possible use of an air-soil heat exchanger in Sahelian zone, it would be preferable to choose a dry sandy soil as a priority.

1. Introduction

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 in injecting 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. In the use of an air-soil heat exchanger, soil is a very important factor. According to [1], for an air-soil exchanger, the soil acts as an insulator and a thermal buffer between the atmosphere and the buried pipes.

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. 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 [2-5]. 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 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, 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 Misra et al. [6] is devoted to evaluate thermal performance of an earth air tunnel heat exchanger. Benhammou et al. show in their/his work [7] that the soil depth temperature is characterized by two parameters: the amplitude and the phase shift with respect to the surface thermal signal. The work of Hollmuller [8] is one of the main references for the thermal efficiency of air-soil heat 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 Thiers [1]. 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. carried out an experimental study of the evolution of soil temperature in the case of an air-soil exchanger [9]. They showed that at a depth of 1.5 m, the soil temperature was approximately 30.4 °C. The object of this present work is to determine the soil which has the greatest thermal inertia among moist sandy soils, dry silt clay and dry sandy soils. The retained soil will be used later in the implementation of an air-soil heat exchanger for the air conditioning of a habitat in the Sahelian zone. We use the conduction analysis of the comsol software (version 3.5). The numerical resolution of the problem will determine the surfaces and temperature curves, the heat flux surfaces and the thermal diffusion time.

2. Description of the problem and mathematical modeling

2.1. Description of the problem

We represent in Figure 1 the geometry of the three soils in 2D. The soil is considered circular with a radius of 4.25 m. In the center, there is a tube (concentric circle) of diameter 0.25m. The problem is to circulate hot air inside the tube, and then study the diffusion of heat by air into the soil.

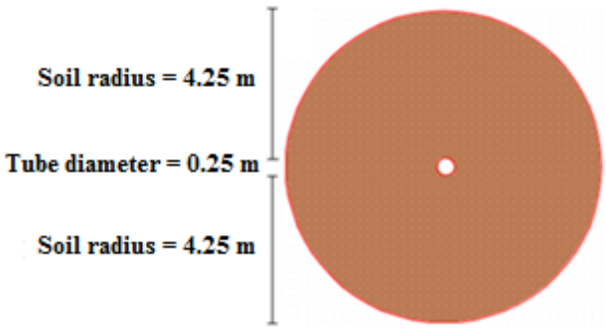

Figure 1: Geometry of soils studied on comsol

2.2. Mathematical model

Equation governing:

The general equation expressing thermal transfer phenomena within the system is expressed by:

$$\rho C_p \frac{\partial T_s}{\partial t} - \nabla.(\lambda \nabla T_s) = Q + h(T_a - T_s) + C(T_a^4 - T_s^{\,4}) \quad (1)$$

This equation contains respectively: the term of temporal evolution of the temperature and the accumulation / restitution of the heat; the diffusion term; the term of heat sources, the term of convection and the term of radiation. With: h, the convective heat transfer coefficient; C, a user-defined constant; T_s, the soil temperature; T_a, the air temperature.

Simplifying assumptions:

For the model, we establish the following assumptions:

- The soil has a circular geometry;
- The soil can be considered as a porous medium;
- The thickness of the tube is negligible;
- The thermal conductivity and the calorific capacity of the different soils are homogeneous and constant;
- The soils are thermally isolated from the outside;
- There is no heat source in the different soils;
- Convection and radiation phenomena are negligible in the presence of conduction in the soil.

Taking all these assumptions into account, Equation (1) becomes:

$$\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} = \frac{\rho C_p}{\lambda} \frac{\partial T_s}{\partial t} \quad (2)$$

Boundary conditions:
The boundary conditions of the problem are given by Figure 2.

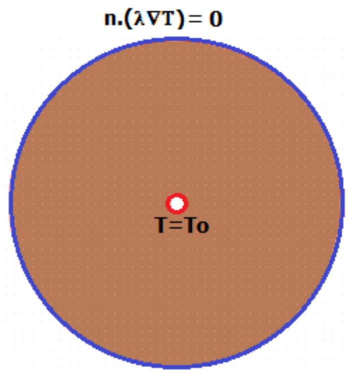

Figure 2: Boundary conditions

Initial conditions:
The initial conditions are shown in Figure 3.

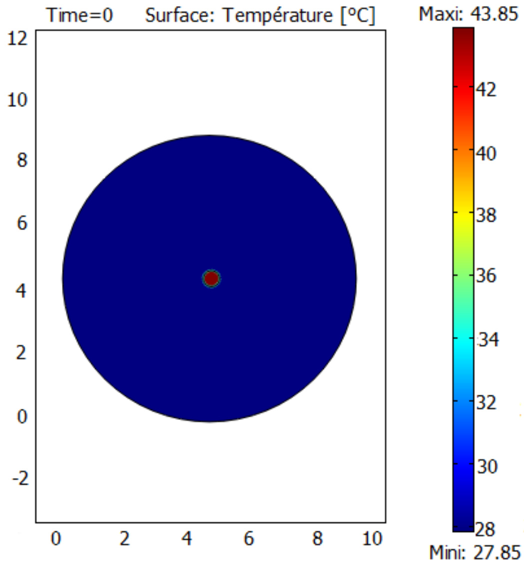

Figure 3: Initial Conditions

Physical properties and input parameters:
The properties of the three soils and those of the air are given in Table 1.

Table 1: Physical properties of soil and air [10, 11]

Properties	Soils			Air
	Moist sandy	**Dry silt clay**	**Dry sandy**	
Thermal conductivity λ (W/K/m)	2.4	0.5	0.4	0.023
Specific heat C_p (J/kg/K)	1500	912	853	1000
Density ρ (kg/m^3)	1700	1700	1700	1.250
Thermal diffusivity $a.10^7$(m^2/s)	9.412	3.225	2.758	184

The input parameters are given in the following Table 2.

Table 2: The Input parameters for simulation

Parameters	Values
Soil radius (m)	4.25
Tube diameter (m)	0.25
Air temperature (°C)	44
Soil temperature (°C)	28

2.3. Numerical simulation

For numerical simulation with comsol software (version 3.5), the system is subdivided into two sub domains (soil and air). We use the conduction heat transfer model. The analysis is temporal and the resolution time is 30 days (10 minutes for time step). The relative tolerance is 0.01 for all parameters. The discretization scheme used is of Lagrange-linear type. Concerning stabilization, heat transfer is isotropic and is done along the current lines.

For all equations, the convergence criterion is of the order of 10^{-6}. To solve the problem, we choose the mesh "normal" described in Figure 4. The mesh possesses 1292 elements (triangular) and 671 nodes.

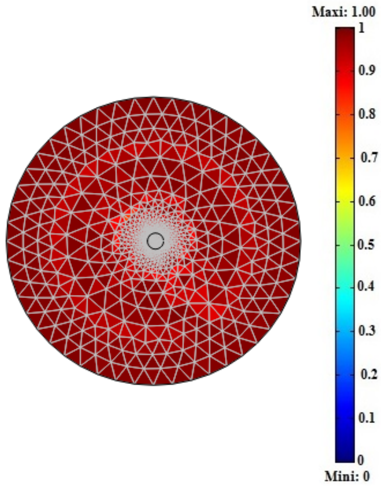

Figure 4: Normal mesh chosen for the simulation

Figure 5 shows the size of the mesh element. We note that the sizes are smaller near the tube. They are on the order of 0.1 m. The sizes of the elements remote from the tube are large and are of the order of 0.6 m.

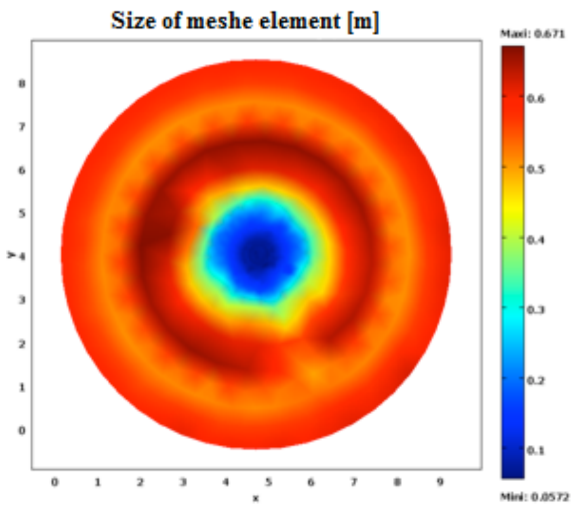

Figure 5: Size of the soil meshing element

By comparing Figure 4 and Figure 5, we note that when an element has a large size, its mesh has good quality.

3. Results and discussion

3.1. Evolution of temperature in each soil

Temperature surfaces:

An isothermal surface represents the geometrical locus of the material points having the same temperature. The isothermal surfaces cannot crisscross because no point can have at the same time two different temperatures [11]. These surfaces are shown in the Figure 6 (a, b and c).

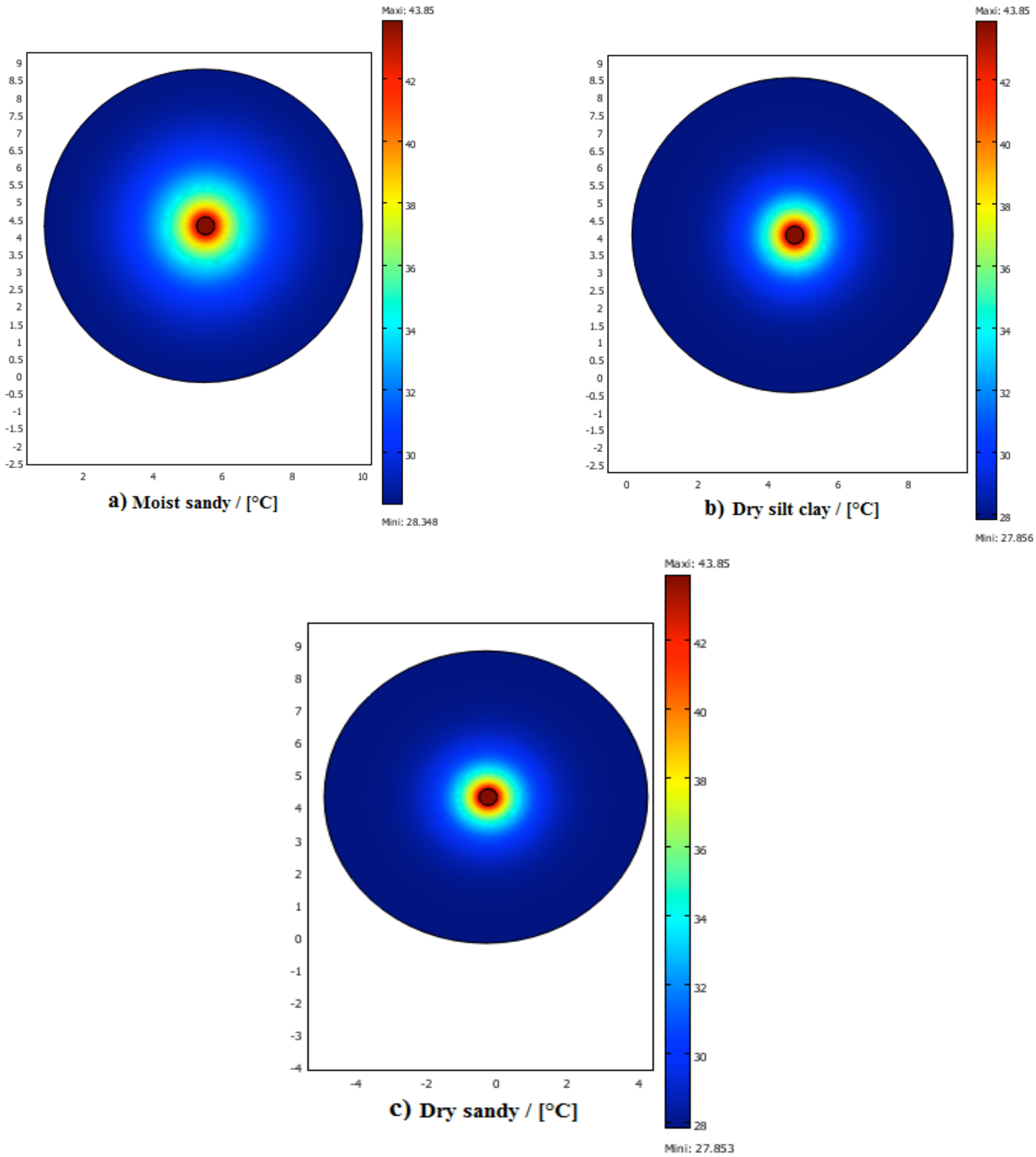

Figure 6: Temperature surfaces in each soil

We observe in Figure 6 (a, b and c) that there are temperature variations around the tube in each of the three soils. In general, the variations are rapid in the soil near the tube. This part of the soil is much more thermally disturbed than the rest of the soil. These variations are more remarkable in the moist sandy soil than in the dry sandy soil and the dry silt clay soil. Thus, the dry sandy soil and the dry silt clay soil are the least disturbed. The thermal inertia of these soils would be the reason.

Isothermal curves:

The intersection of the isothermal surfaces with a plane determines a family of isothermal curve [11]. The isothermal curves are represented in the Figure 7 (a, b and c).

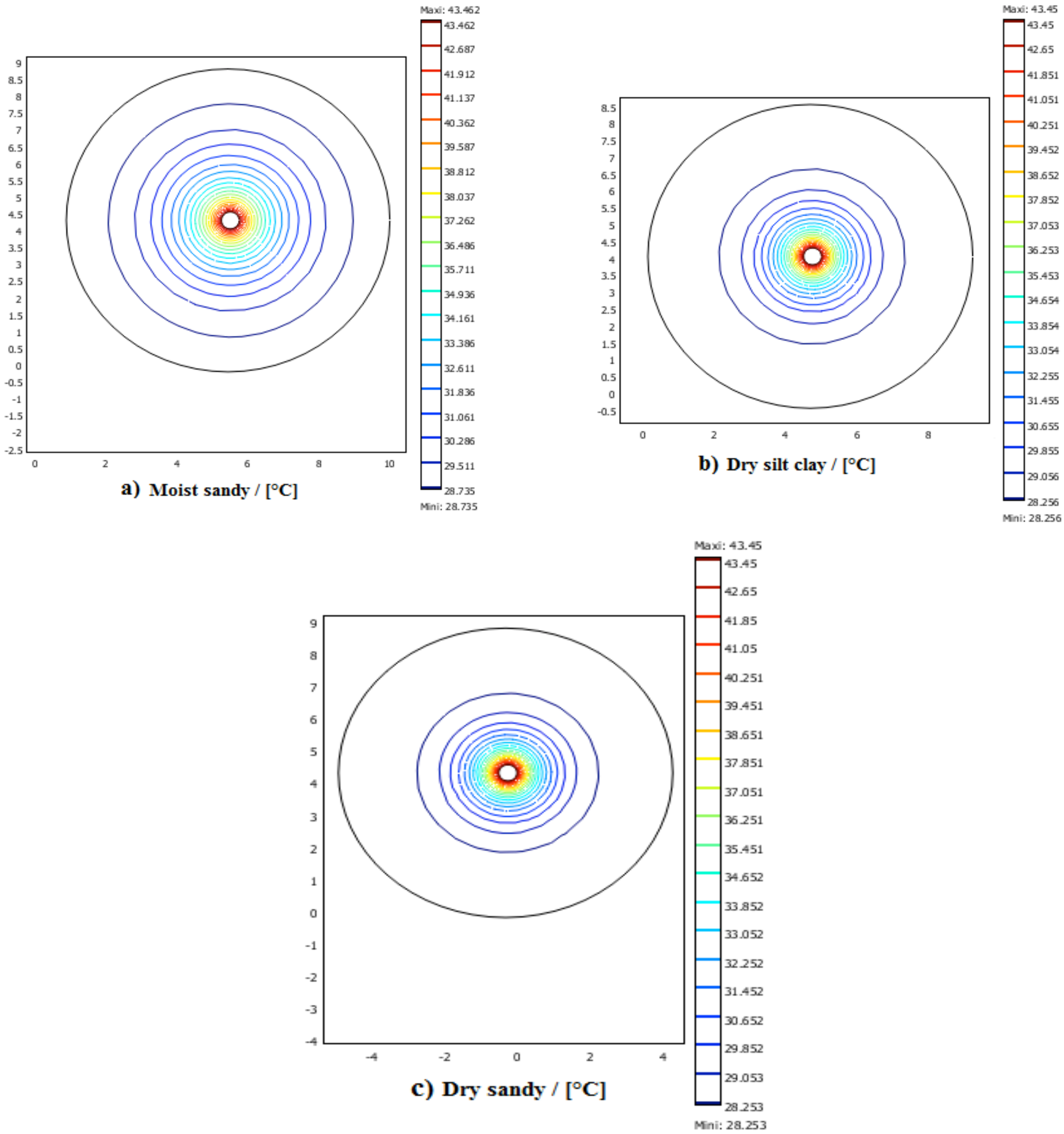

Figure 7: Isothermal curves in each soil

We observe in Figure 7 (a, b and c) that the isothermal curves extend much more in the moist sandy soil and much less in the other two soils. This means that there is more temperature variation in the moist sandy soil and less temperature variation in the dry sandy soil and the dry silt clay soil. Thus, the thermal diffusion length is greater in the moist sandy soil than in the other two soils. This length will be determined later on.

Temperature gradients:
The temperature gradients shown in Figure 8 (a, b and c) result from the thermal exchanges between the air and the soil. We observe in Figure 8 (a, b and c) that in the three soils the temperature gradients are very high around the tube. However, it is much higher in the dry sandy soil (30 K/m, maximum value) and in dry silt clay soil (29 K/m, maximum value). The further one moves away from the tube, the gradient decreases until it vanishes. This indicates the end of the thermal diffusion in the soil.

3.2. Evolution of heat fluxes in each soil
Heat Flow Arrows:
It is a set of arrows indicating the directions and directions of propagation of the convective heat flux (in the tube) and the conduction heat flux (in the ground). The following Figure 9 (a, b and c) describes the different arrows of heat flux in each soil.

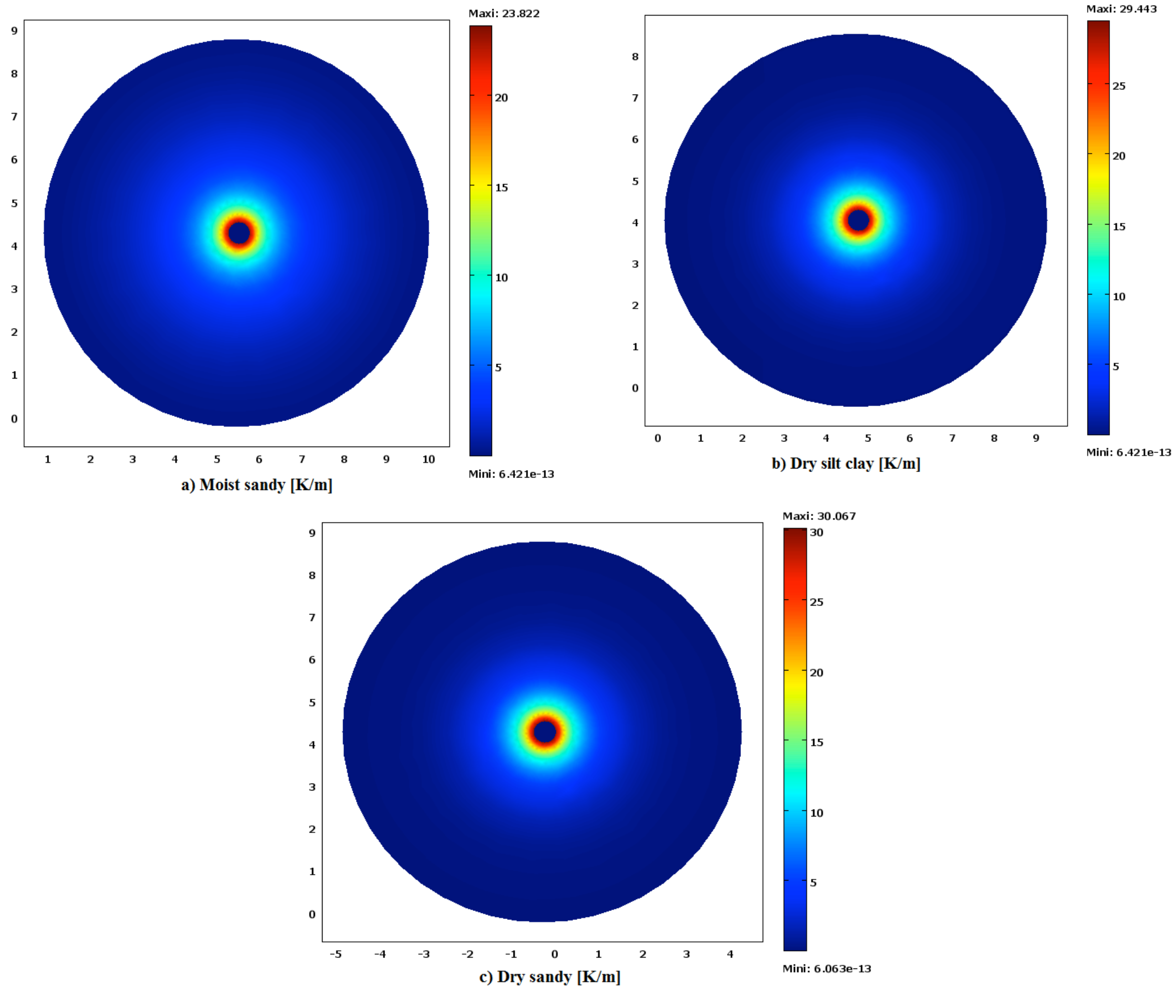

Figure 8: Surfaces of temperature gradients in each soil

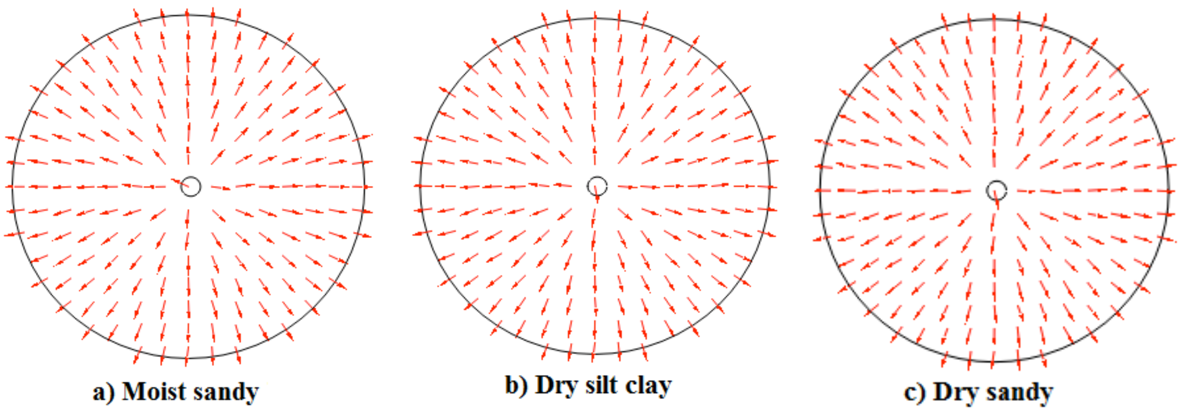

Figure 9: Arrows of heat flux diffused in each soil

We observe in Figure 9 (a, b and c) that the heat flow arrows are radial in all three soils. At the level of the three soils, despite the adiabatic conditions, the heat flow crosses the boundary surface.

Streamline or lines of heat flow:

These are lines indicating the directions of propagation of the heat flux by conduction in the soil. The heat flow lines are shown in the Figure 10 ((a, b and c).

We observe in Figure 10 (a, b and c) that the heat flow lines are straight and radial as in the case of the arrows. The diffusion of heat in the three soils is done in the same way. Thus, the flow direction does not depend on the nature of the soil.

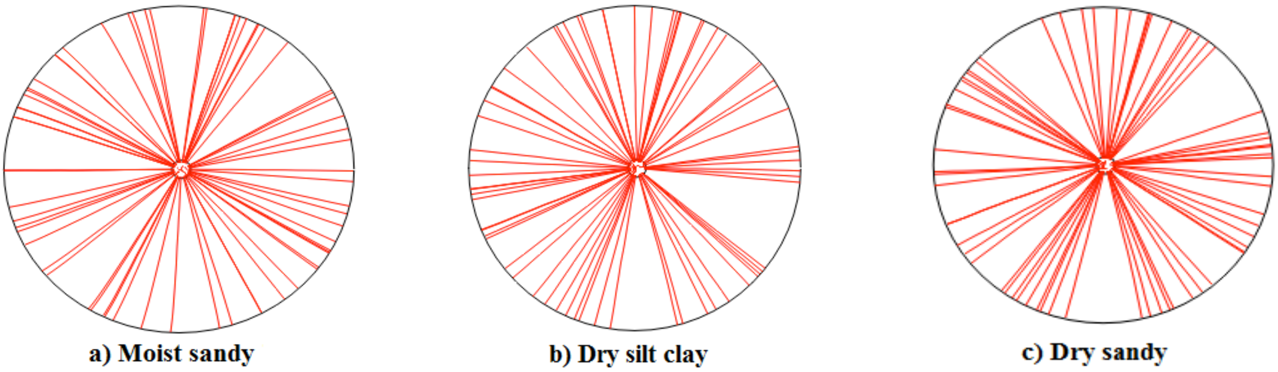

Figure 10: Heat flow diffused in each soil

Heat flow surfaces:
Figure 11 (a, b and c) shows the heat flow diffused in each soil.

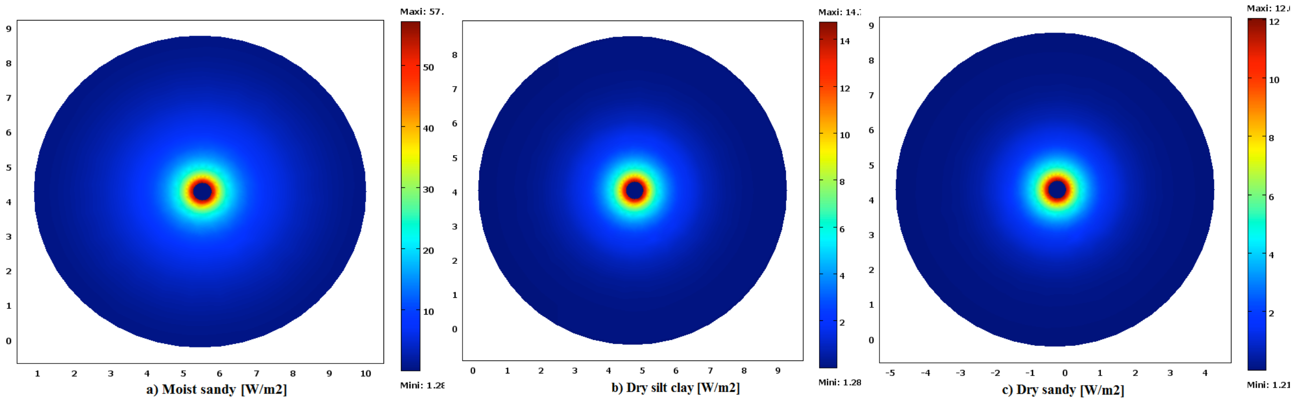

Figure 11: Surfaces of heat flow diffused in each soil

We observe in Figure 11(a, b and c) that the heat flow diffused in the moist sandy soil is much more intense (maximum 57 W/m²) than those diffused in the dry sandy soil (maximum 12 W/m²) and in dry silt clay soil (maximum 14 W/m²). This is due to the high diffusivity of the moist sandy soil and therefore to its low thermal inertia.

Superposition of temperature and heat flow:
In order to better perceive the thermal diffusion in the soil, we superimpose the temperature surfaces, the heat flow arrows and the heat flow lines. We obtain the Figure 12 (a, b and c).

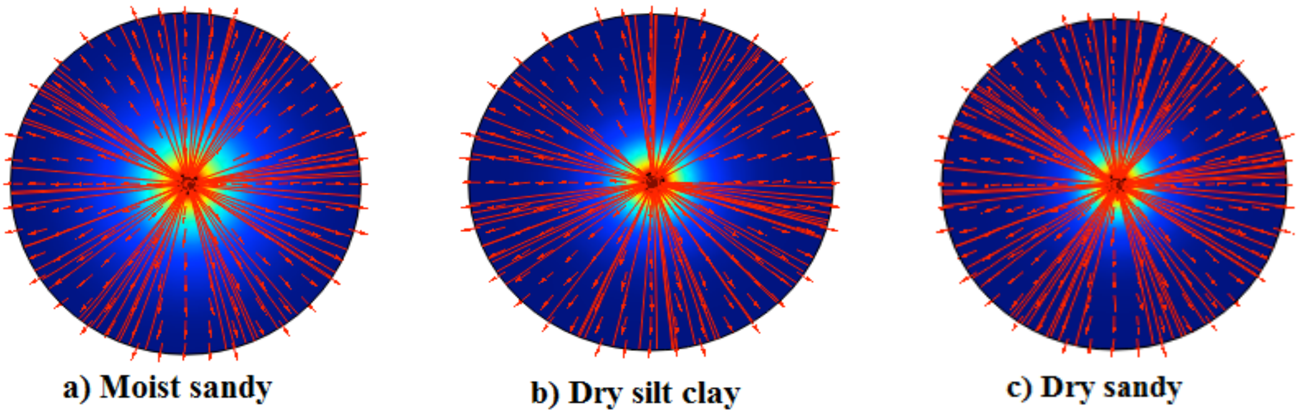

Figure 12: Superposition of temperature and heat flow

3.3. Determination of the thermal diffusion time in each soil

The thermal diffusion time is given by the Equation 3 [11]:

$$t_d = \frac{\rho C_p L^2}{\lambda} = \frac{L^2}{a} \qquad (3)$$

The parameter L represents the characteristic length of thermal diffusion in the soil. For this study, this length is 4.25 m. Table 3 shows the length and time of thermal diffusion in each soil.

Table 3: Length and time of thermal diffusion in each soil

Properties	Soils		
	Moist sandy	**Dry silt clay**	**Dry sandy**
Thermal diffusivity $a.10^7(m^2/s)$	9.412	3.225	2.758
Time of thermal diffusion (months)	7	21	25

The diffusion time is longer in the dry sandy soil than in the other two soils. So the dry sandy soil slowly diffuses heat. This means that the dry sandy soil has a very high thermal inertia than the other two soils. Similarly, dry silt clay soil has a high thermal inertia as the moist sandy soil. According to [12], the Earth-Air Heat Exchangers (EAHE) take advantage of this thermal inertia.

3.4. Curves of temperature evolution of the three soils

In the Figure 13, the curves show the evolution of the temperature of each soil, further to the thermal disturbance which takes place around the tube.

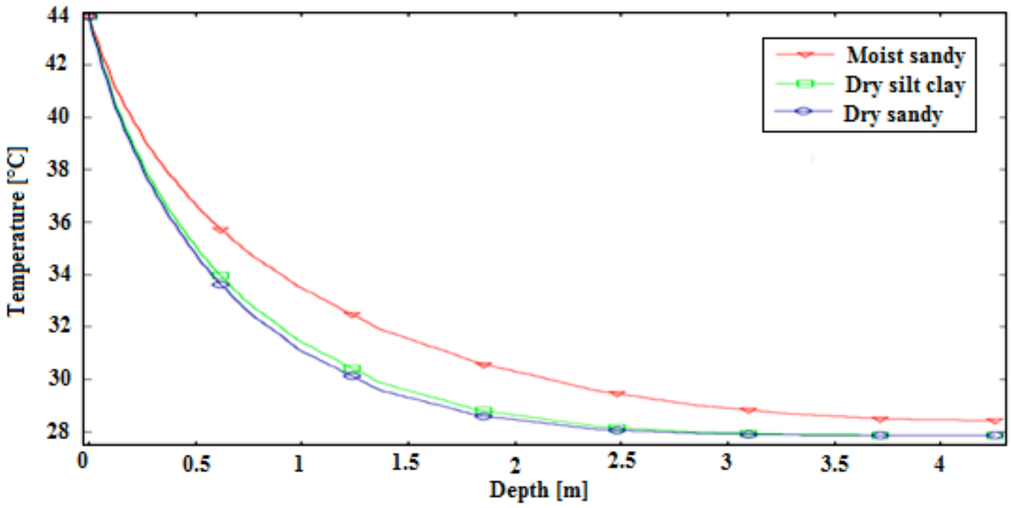

Figure 13: Evolution of the temperature of three different soils

We observe in Figure 13 that the moist sandy soil cools slowly than the other two soils. This soil loses practically its initial temperature of 28°C. This is justified by its low thermal inertia. On the other hand at 2.5 m from the tube, the dry sandy soil and dry silt clay soil regain their initial temperature (28°C). The analysis that we make of this is that the two soils (dry sand and dry silt clay) are no longer disturbed thermally beyond 2.5 m depth. This suggests that they have greater thermal inertia compared to moist sandy soil. According to [13], the temperature of ground becomes constant at the depth of 4 m for annual variation under both bare and greenhouse surfaces. This constant temperature is called undisturbed temperature of earth [14].

According to [15], a sandy soil will be more inert than other types of simulated soils and therefore much more efficient in terms of heat exchange, because it allows reaching soil temperature. Our result (Figure 13) shows that dry sandy soil temperature is nearly constant at 3 m of depth. According to [16], the cost of excavation of trench to increase its depth from 2 m to 3m increased by about 50%while decrease in outlet air temperature achieved is only 4.13%. [17] show that to reach a soil temperature of 300 K, additional technical and economic means are required. We have to dig the soil much deeper [17]. In general case, with the help of earth-air-tube heat exchanger heating in winter season or cooling in summer can be done by the air, depending upon weather session [18].

Conclusion

We have studied the thermal behavior of three different soils, with the object to identify the one which has the greatest thermal inertia. To do this, we assumed that each soil has a circular geometry. At the center of the soil there is a tube containing hot air with an initial temperature of 44°C. Heat diffusion occurs in the soil mantle surrounding the tube. We obtained with comsol software (version 3.5) the following results for 01 month study:

- The diffusion of the heat is radial whatever the soil considered.
- Dry sandy soil, dry silt clay soil and moist sandy soil diffuse heat respectively during 25 months, 21 months, and 07 months.
- The temperature gradient is higher in the dry sandy soil (maximum 30 K/m) than in the dry silt clay soil (maximum 29 K/m) and the moist sandy soil (maximum 23 K/m).
- The temperature of the dry sandy soil stabilizes after 3 m of depth. The moist sandy soil is the most thermally disturbed.

In view of these results, we note that the most thermally stable soil is the dry sandy soil. Thus, for a possible use of an air-soil heat exchanger intended for the air conditioning of a habitat, it would be preferable to choose a dry sandy soil as a priority.

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