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Numerical Study of An Air-soil Heat Exchanger Related to a Habitat Air Conditioning in Sahelian Zone: Determination of Temperature Surfaces and Heat Flows

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Since 1995, researchers conducted studies about the performance issues of air-soil heat exchangers also called Canadian well. In this paper, we used Comsol software to study heat exchanges that take place in an air-soil heat exchanger intended for the air conditioning of a Sahelian zone house. The modeling was made with a complete 2D geometry. This study allowed us to determine the temperature surfaces, heat flow surfaces and values of the Peclet number. The results show that this system can contribute to the air conditioning in a Sahelian zone.

Keywords: Heat exchanger; Canadian well; comsol; cooling; Sahelian zone.

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1. INTRODUCTION

An Air-Soil Heat Exchanger (ASHE) is a geothermal system that uses the thermal inertia of the soil to heat or cool a part of the air renewing a habitat. The principle of the system consists of injecting into a habitat a flow of air coming from the outside that is previously forced beforehand to circulate in a pipe buried at a certain depth in the soil [1].

Air-soil heat exchangers have been the subject of numerous numerical and experimental works. Hollmuller paper [2] represents nowadays one of the main standard commodity in the field of air-soil exchangers. Based on extensive theoretical modeling but also on many in-situ measurements, the author sets out simple rules for the design of air-soil exchangers. Stéphane Thiers [3] did also an interesting related work. The author has produced an advanced mathematical model that gives the soil temperature according to the time and at any depth, taking into account the thermal behavior of the soil. In Burkina Faso, [4] carried out an experimental study of the soil temperature evolution with regard to 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 [5], the author proposed objective criteria for the choice of parameters based on numerical simulations of heat exchange by forced convection in a buried tube. Kaboré et al. [6] have also presented an experimental prototype implemented in Ouagadougou. This study has allowed determining the evolution of air temperature along the exchanger and also validating our numerical results with those of the literature and the experiment. In 2016, [7] also conducted an experimental study of the thermal performance of an air-soil heat exchanger used to improve the efficiency of heating, ventilation and air conditioning in a building . The soil temperature is considered constant and the soil is used as a cold source or as a hot source for cooling or heating the building.

Our work deals with the numerical study of an air-soil heat exchanger intended for the air cooling in habitat in Sahelian zone. We use the convection and conduction analysis of the comsol software. To control the temperature evolution along the exchanger tube, we draw the geometry of the exchanger on the software. We respect the dimensions (length, diameter, depth and bending) for both geometries (a complete shape and a symmetrical shape). The numerical solution will allow us to determine the temperature surfaces, the heat flow surfaces and the number of Peclet meshes.

2. DESCRIPTION OF AIR-SOIL HEAT EXCHANGER

2.1 Geometry of Air-soil Heat Exchanger

In this part, we represent the geometry of the air-soil exchanger in 2D. The tube diameter is 200 mm. The soil depth is 4 m. The horizontal tube length is 20 m and there are two elbows of 90°.

In Fig. 1, we represent the air channel as a long rectangular channel. It is because, we used 2D model.

2.2 Solver Parameter

For numerical simulation, the system is subdivided into two sub domains (soil and air). The necessary data are communicated and we define the boundary conditions in Fig. 2. We use the (forced) convection heat transfer model and conduction in turbulent regime. The analysis is

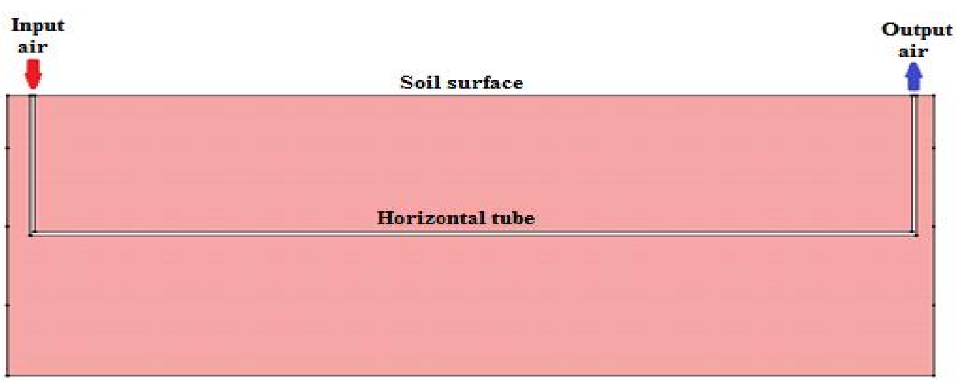

Fig. 1. Diagram of air-soil heat exchanger in 2D

temporal and the resolution time is 30 days (time step is 600 seconds). The relative tolerance is 0.01 for all parameters. The discretization scheme used is of Lagrange-linear (Finite Element Method). Concerning stabilization, the heat transfer is isotropic and moves along current lines. For all equations, the convergence criterion is of the order of 10^{-6}.

3. MATHEMATICAL MODELING

3.1 Equation Governing

The general equation reflecting the heat transfer phenomena within the system is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-\lambda \nabla T) = Q - \rho C_p u.\nabla T \quad (1)$$

This equation contains respectively: the temporal term evolution of the temperature and the accumulation of the heat; the diffusion term; the term of heat sources and the term of convection field by the movement of the air.

Equation (1) is named transport equation. This means that variations in temperature result from a balance between convection, diffusion and internal heat sources [8]. The parameter u [m/s] represents the velocity of the air inside the tube and Q represents heat source term.

The convective coefficients between the air and the soil depend on air velocity. Air velocity u is given by user in comsol software.

3.2 Basic Assumption

For our model, we establish the following assumptions:

- The air flow inside the tube is the same;
- The tube thickness is negligible;
- The thermal conductivity and the heat capacity of the soil are homogeneous and constants;
- A constant heat flux is imposed on the soil surface;
- Any latent exchanges are not taken into account, which means that there is no infiltration in the tube;
- The relative humidity of the air is constant along the tube;
- The heat transfer by friction is neglected;
- There is no heat source in the soil.

Taking into account the previous assumptions, equation (1) becomes:

In soil: $$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{\rho C_p}{\lambda} \frac{\partial T}{\partial t} \quad (2)$$

In air: $$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{\rho C_p}{\lambda} \left(\frac{\partial T}{\partial t} + u. \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \right) \quad (3)$$

The coefficient of forced convection h_a of the air in the tube is given by equation (4) [6]:

$$h_a = \frac{Nu \times \lambda_a}{L} = \frac{(0.023 \, \mathrm{Re}^{0.8} \times \mathrm{Pr}^n) \times \lambda_a}{L} \quad (4)$$

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

$$\mu_a = \nu_a \times \rho_a .$$

For cooling n = 0.3 and for heating n = 0.4.

The characteristic length *L* is equal to the inside diameter D_I of the tube; 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^{-1} is the kinematic viscosity of the air; ρ_a is the density of the air [6].

3.3 Boundary Conditions

Fig. 2 presents the boundary conditions during daytime. In Sahelian zone, it is hot period.

At soil surface, boundary condition is given by equation (5):

$$q_0 = \lambda \nabla T \quad (5)$$

At the entrance of tube, boundary condition is given by equation (6):

$$T = T_0 \quad (6)$$

At the exit of tube, boundary condition is given by equation (7):

$$-\lambda \nabla T = 0 \quad (7)$$

T is air temperature, λ is air thermal conductivity.

The boundary conditions related to Fig. 2 are of two types: Dirichlet and Neumann. We represent an imposed fixed temperature at the exchanger entrance. At the surface of the soil, we imposed a constant heat flow. At the exit we assume that the flow is convective because we do not know the temperature. On the border, the temperatures are considered constants and are value of non disturbed soil temperature. Indeed, this condition allows the model to approach the physical reality.

3.4 Initial Conditions

The initial conditions are shown in the following Fig. 3. These are obtained by using all parameters indicated above.

3.5 Physical Properties and Input Parameters

The soil in question is dry sandy and its properties, as well as those of the air, are given in the following Table 1. According to the weather data of the city of Ouagadougou from 1983 to 2012, the average annual relative humidity of the air is worth 51% [9].

The input parameters are given in following Table 2.

3.6 Mesh of Simulation

A mesh is the spatial discretization of a continuous medium, or also, a geometric modeling of a domain by finite and well defined proportioned elements. The objective of a mesh is to simplify a system by a model representing this system and possibly its environment, in the context of simulations of calculations or graphical representations. To solve the problem, we choose the "normal" mesh. Fig. 4 shows the elements quality.

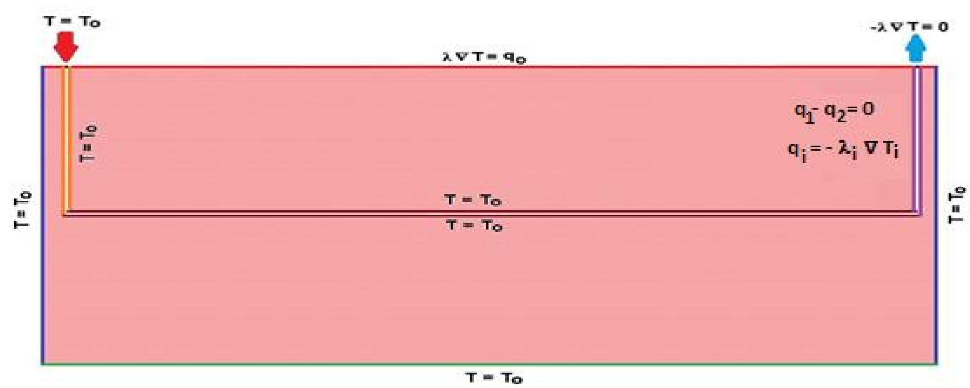

Fig. 2. Boundary conditions

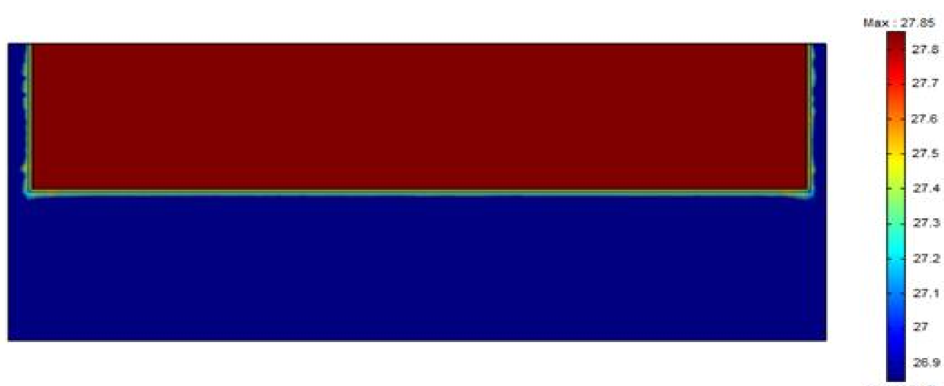

Fig. 3. Initial conditions

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

Properties	Soil	Air
Thermal conductivity λ (W/K/m)	0.4	0.023
Thermal capacity C_p (J/kg/K)	853	1000
Density ρ (kg/m^3)	1700	1.250
Thermal diffusivity a .10^7(m^2/s)	2.758	184

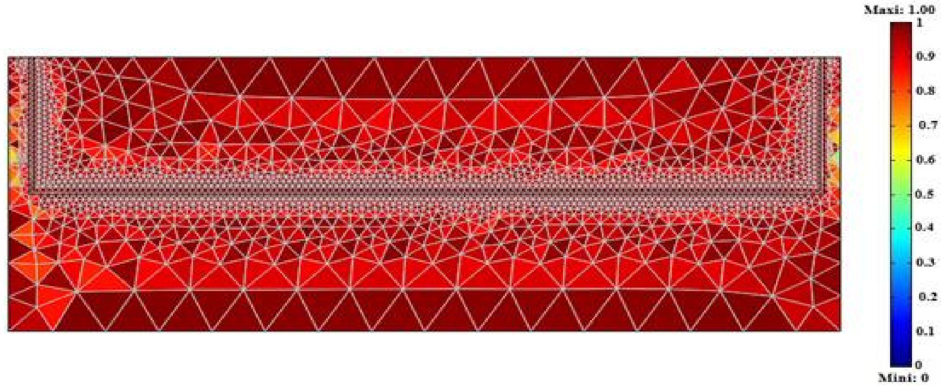

Fig. 4. « Normal » mesh for simulation

Table 2. Input parameters

Parameters	Values
Horizontal tube length (m)	20
Tube diameter (m)	0.2
Soil depth (m)	4
Air velocity (m/s)	0.88
Input air temperature (°C)	44
Soil temperature (°C)	27 - 28

The mesh consists of 3626 elements (triangular) and 1855 nodes.

The Fig. 5 shows the size of each element of the previous mesh.

We note that the sizes are getting smaller and smaller close to the tube. They are of the order of 0.1 m. The sizes of the elements distance from the tube are large and are of the order of 1 m. By comparing Figs. 4 and 5, we notice that when an element has large size, its mesh is good quality. Generally, the results are dependent of mesh.

3.7 Convergence and Calculation Time

For the 2D model, the calculation time is 242.8 seconds. After solving the problem, the convergence obtained is 3.86×10^{-6}. The convergence scheme is shown in the Fig. 6.

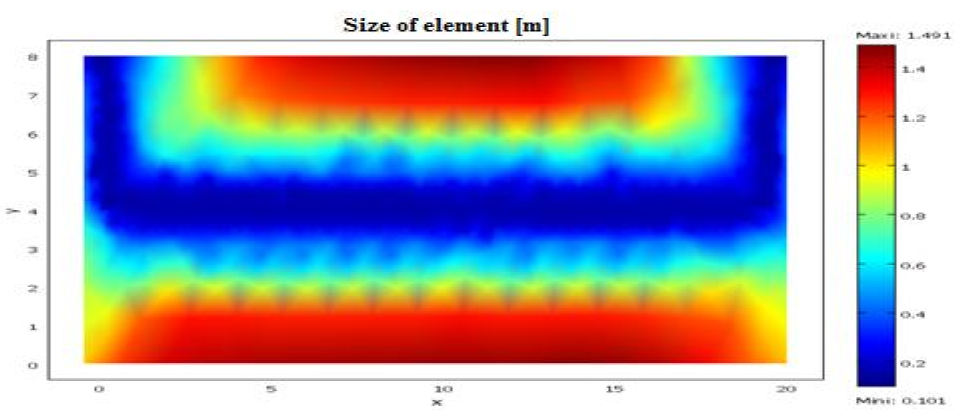

Fig. 5. Size of elements of mesh

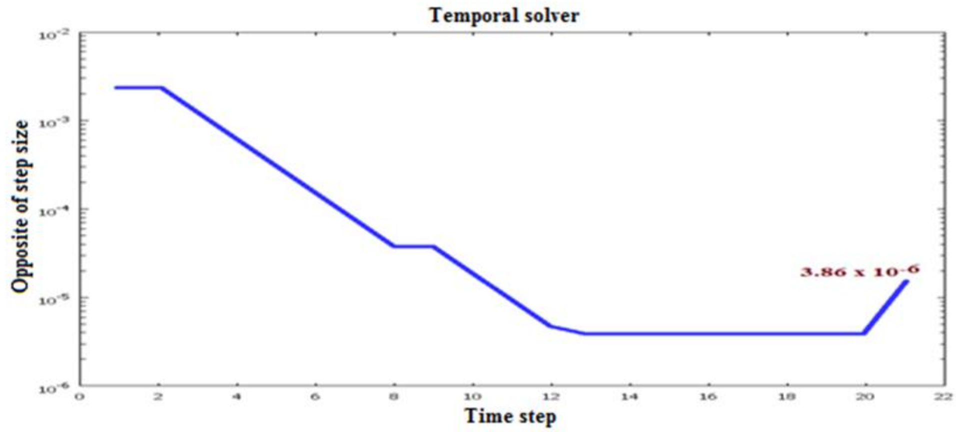

Fig. 6. Convergence scheme

4. RESULTS AND DISCUSSION

We can determine temperature surfaces, isovalues, heat flow arrows, heat flow lines, temperature gradient surfaces, and the Peclet mesh number.

4.1 Evolution of Temperature in the Exchanger

4.1.1 Temperature surfaces

An isothermal surface represents the geometric locus of the material points which have the same temperature. Isothermal surfaces cannot intersect because no point can have at the same time two different temperatures [8]. These surfaces therefore make it possible to determine the temperatures at any point of the exchanger. These surfaces are shown in the following Fig. 7.

We note that the high temperature variations take place at the exchanger entrance. The colors indicate the diffusion of heat in the soil.

This heat is transmitted to air by forced convection. The maximum temperature is obtained at the inlet of the exchanger (43.85°C). There is a significant decrease in air temperature as it passes through the elbow.

Fig. 8 shows evolution of air temperature at the entrance of the tube.

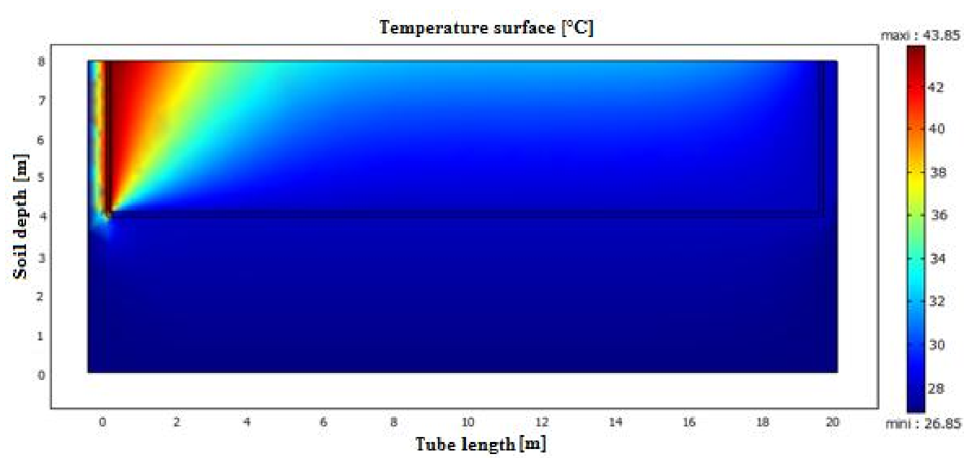

Fig. 7. Temperature surfaces

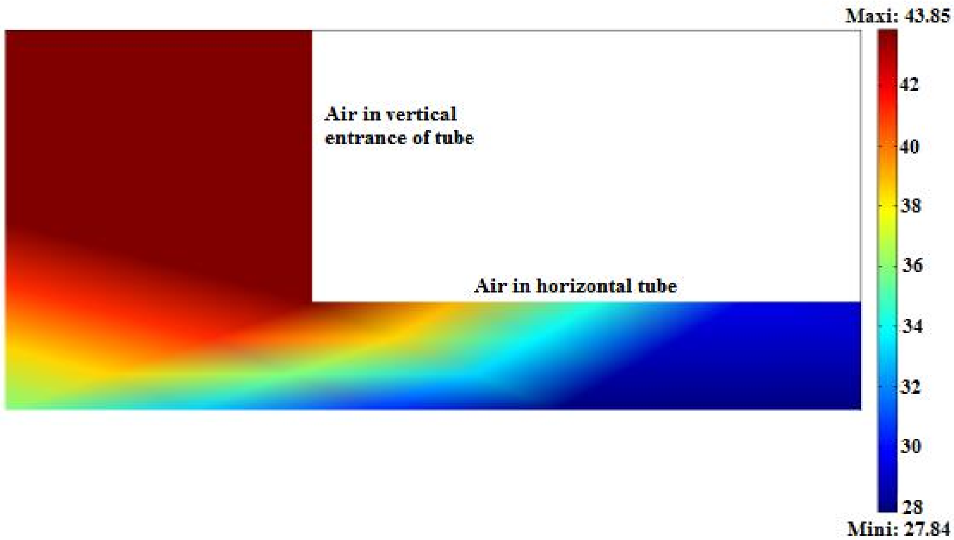

Fig. 8. Air temperature surfaces at the entrance of tube

In Fig. 8, we observe that air temperature decreases along the tube. From the vertical entrance to horizontal, air temperature vary from 44°C to 28°C. The air temperature drop is noted during the passage in left elbow.

4.1.2 Temperature isovalues

The intersection of the isothermal surfaces with a plane determines a family of isothermal curves which, like the surfaces, cannot intersect each other [8]. The isothermal or isovalues curves of temperature are distinguished by their colors and are represented in the following Fig. 9.

We notice that the temperature values are much more concentrated at the inlet of the exchanger. This means that high temperature changes occur at this level. The heat exchange between the air and the soil takes place essentially at the inlet of the exchanger.

4.1.3 Temperature gradient

Temperature gradients result from heat exchanges between air and soil. The following Fig. 10 shows these gradients over the entire surface of the exchanger.

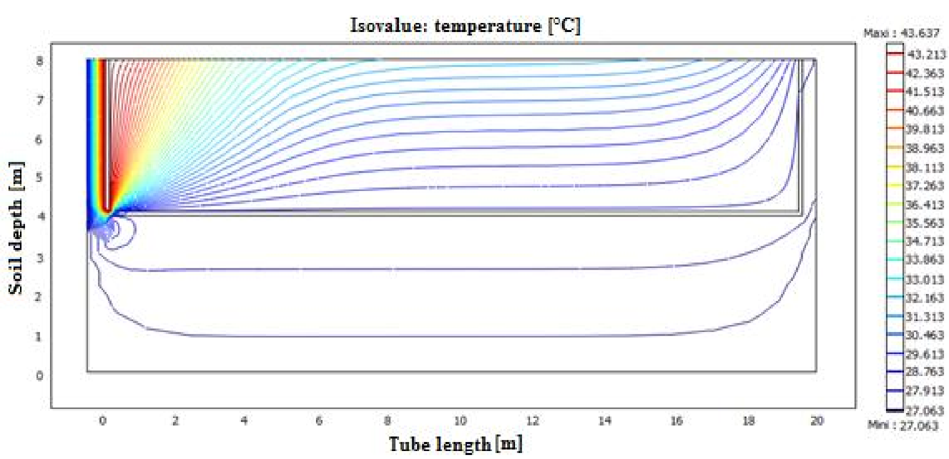

Fig. 9. Temperature isovalues

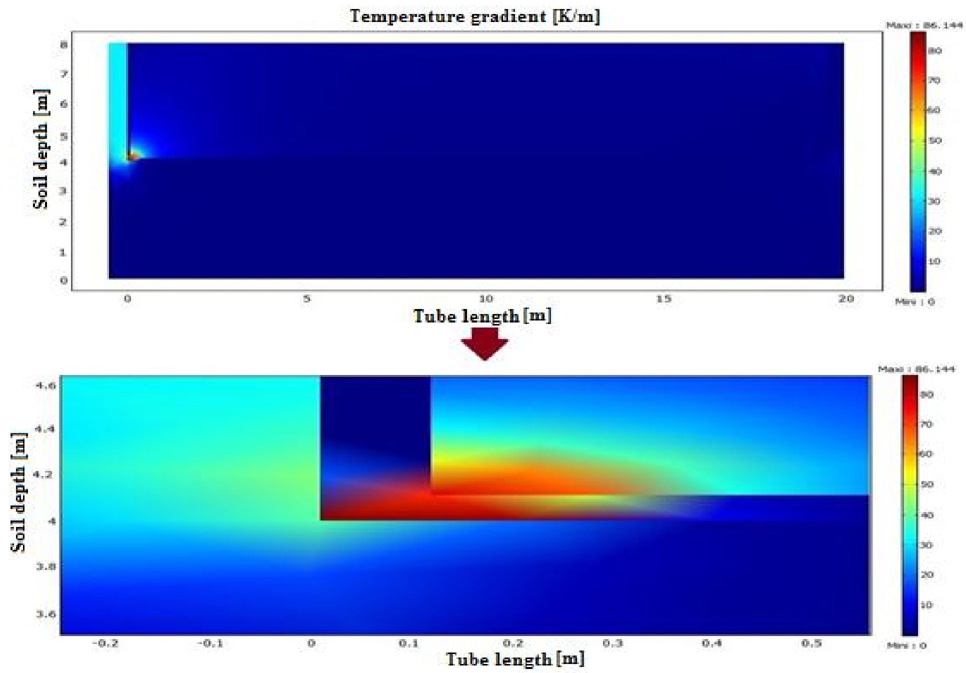

Fig. 10. Temperature gradient surfaces

The temperature gradients are remarkable only at the exchanger inlet. The maximum values are noted at the elbow. This is more noticeable when we zoom in on the surface. The maximum value is of the order of 80K/m. This strong variation of the gradient at the elbow can be explained by the change of direction of the air (from vertical to horizontal). This change of direction creates a shock in the air particles. It is also an area of turbulence and loss of loads.

4.2 Evolution of Heat Flow

During the heat exchanges in the exchanger, there is a transfer of heat between the air and the soil. These heat flows can be represented in various ways.

4.2.1 Heat flow arrows

It is a set of arrows which indicate the directions of propagation of convection heat flow (in the tube) and conduction heat flow (in the soil). The following Fig. 11 shows the various heat flow arrows in the exchanger.

At the well entrance, the arrows indicate that heat exchange takes place between the fluid and the ground. This changes the direction of heat flow by conduction in the soil. From the elbow, there is a crossing between conduction heat flow and convection heat flow (zoom). This shows that the heat exchanges along the exchanger are essentially radial.

4.2.2 Streamline: heat flow lines

These are lines indicating the directions of propagation of the convection heat flow (in the tube) and the conduction heat flow (in the soil). The heat flow lines are shown in the following Fig. 12.

In the absence of heat transfer in the soil, the lines are vertical. But we notice in the Fig. 12 that there are zones where the lines are curved. This is the case at the inlet of the exchanger and at the elbow of the tube. This means that there are thermal disturbances in these areas. The curvatures at the entrance are due to the heat exchange between air and soil. The curvatures at the elbow are caused by the change of direction of the air, which causes a loss of loads. It should be remembered that it is at the elbow that the temperature gradient is very high.

4.2.3 Superposition of temperature and heat flow

In order to better understand the heat exchanges in the exchanger, we superpose the temperature surfaces, the heat flow arrows and the heat flow lines on one and the same Fig. 13.

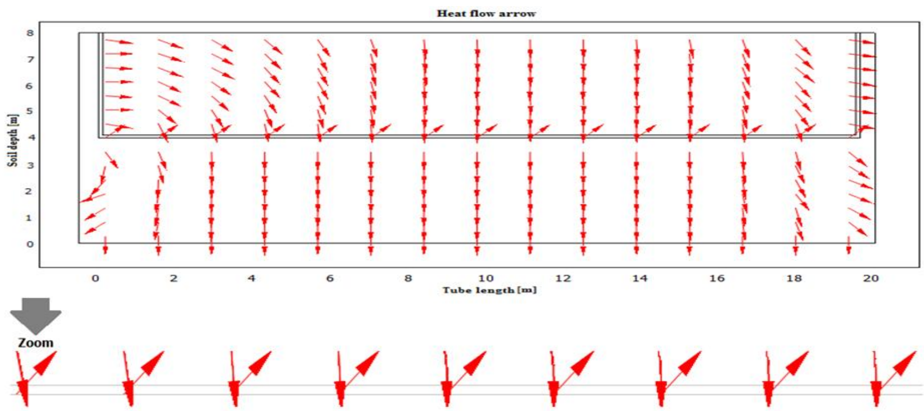

Fig. 11. Heat flow arrows

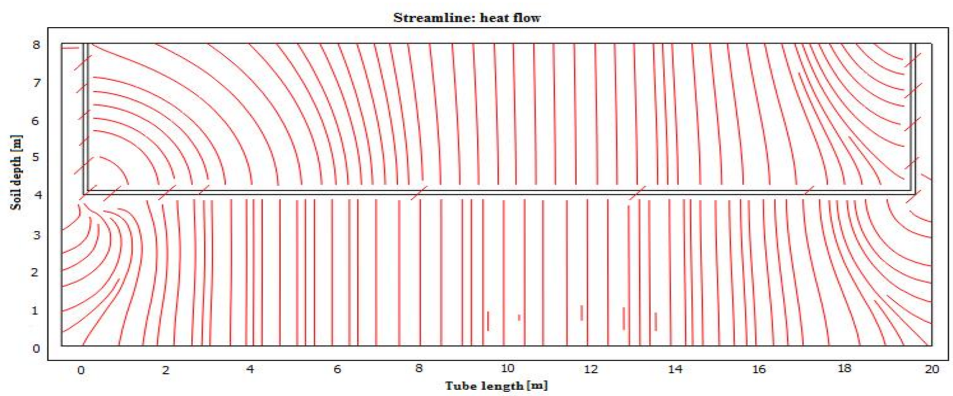

Fig. 12. Heat flow lines

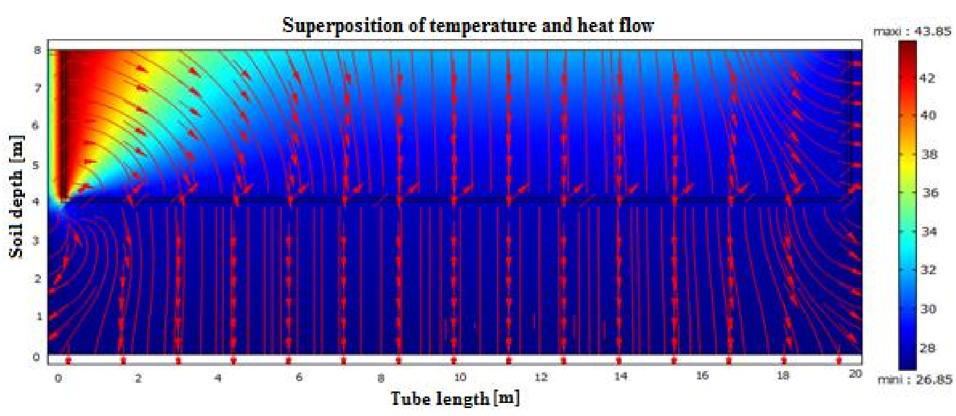

Fig. 13. Superposition of temperature and heat flow

4.3 Evolution of Peclet Mesh Number

The number of Peclet mesh is a dimensionless number defined by the equation (8):

$$Pe = \frac{uL\rho C_p}{\lambda} = \frac{uL}{a} = \mathrm{Re} \times \mathrm{Pr} \qquad (8)$$

The parameter L [m] represents the characteristic length of the tube.

The number of Peclet of mesh (Fig. 14) is, so to speak, the "brother" of Reynolds. It is an intrinsic number which depends only on the fluid under consideration [12]. The Peclet number

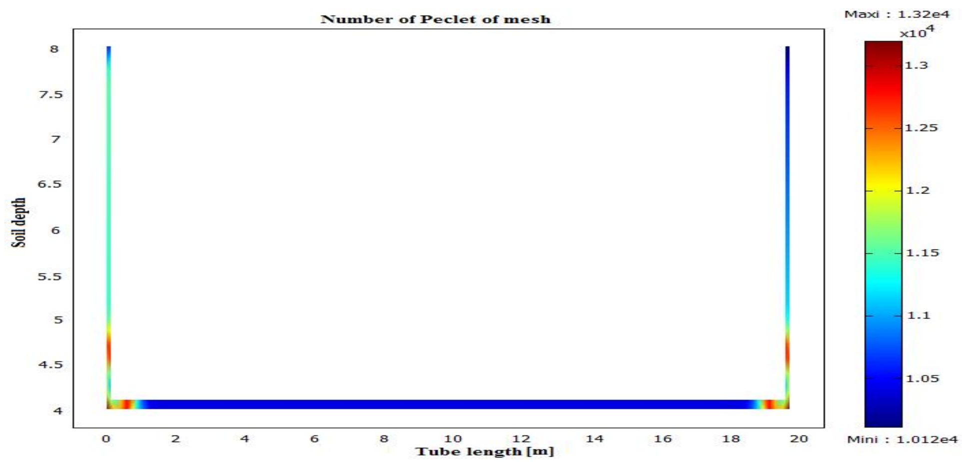

Fig. 14. Evolution of the number of Peclet of mesh

represents the ratio between the convection effects of the temperature field and its conduction. The value of this dimensionless number is related to the appearance of thermal boundary layers, zones where the temperature gradients are located. These boundary layers are often associated with hydrodynamic boundary layers, where the velocity decreases to cancel out partly or totally. The boundary layer exists only if Pe >> 1 [8].

We note that along the exchanger, the Peclet number varies between 1.01×10^4 and 1.32×10^4. This justifies forced convection inside the tube. According to Fig. 14, this dimensionless number is very high at the left elbow. Indeed, the elbow of the tube is zone of strong mechanical disturbances (change of air movement direction) and thermal losses.

5. CONCLUSION

During this work, we have modeled on the comsol software the heat exchanges that take place in an air-soil heat exchanger intended for air cooling in habitat in Sahelian zone. This modeling allowed us to determine the temperature surfaces, the heat flow surfaces and the number of Peclet of meshes.

We obtained the following results:

- The normal mesh and the convergence obtained (3.86×10^{-6}) lead to satisfactory numerical results.
- The elbow of the tube is the zone where the temperature gradients are very high.
- The heat flow arrows show that heat exchanges along the exchanger are essentially radial.
- The values of the Peclet number show that the elbow of the tube is also the zones where forced convection is strongly developed.

These numerical results are proof that the air-soil heat exchanger can cool hot air taken in a Sahelian zone. This will have the positive impact of contributing to air conditioning and saving energy in the building sector.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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