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Numerical Investigation of Horizontal Ground Coupled Heat Exchanger

A.Benazza[a]*, E. Blanco[b], M.Aichouba[a], José Luis Río[b], S.Laouedj[a]

[a]*Djillali Liabes University of Sidi Bel-Abbès,22000 Algeria – Laboratory of materials and reactive systems*
[2]*Universidad de Oviedo, EDZE (Energía), Campus de Viesques, 33271 Gijón SPAIN*

Abstract
Nowadays, the improvement of the quality of life has contributed to a growing demand for AC systems in buildings. Among the technologies used in AC equipment, the ground-coupled heat exchangers (GCHE) are drawing more and more interest because of its environmental characteristics compared to conventional heat generation or dissipation systems. A typical GCHE consist on a set of pipes buried vertically or horizontally in the ground and coupled to a heat pump (HP). In this paper, the study was focused on a horizontal configuration based on heat exchanger pipes laid out concentrically. An unsteady quasi three-dimensional numerical simulation was carried out for cooling purposes in continuous and cyclic operating mode. The variation of the climatic conditions in transient simulation was taken into account by modeling the air and ground temperature using a simple harmonic function. The influences of thermal conductivities and geometrical parameters on the heat exchanger efficiency have been studied.

Keywords: Horizontal ground-coupled heat exchanger, geothermal energy, numerical simulation

1. Introduction

The recent increase in the cost of the primary non-renewable energy and the new public policies aimed at reducing greenhouse gas emissions, have encouraged the use of renewable energies such as the geothermal energy. The surface geothermal installations or very low-temperature geothermal installations use the thermal inertia of the subsoil, and mainly used for HVAC purposes. Indeed, the temperature at a certain depth in the ground (6m to 45m) remains nearly constant (Chiasson [1]). This constant temperature

* Corresponding author. Tel.: +00213-696-236-010; fax
E-mail address: abdel_benazza@yahoo.fr.

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Nomenclature

T_{ma}	Annual average air temperature
T_{va}	Air annual amplitude temperature
t	Time in days
t_0	The maximum air temperature day
y	Depth
k	Thermal conductivity
α	Thermal diffusivity
ω	annual angular frequency (ω=1.992 10^{-7} rad/s)
Φ_s	Air and soil temperature phase lag (rad)

zone results from a complex interaction of heat brought to the ground surface (sun and atmosphere) and by intrusion into the earth's crust of molten magma originated from great depth. There are several technologies used for the heat exchange between building conditioning equipment and ground.

Among them, we can quote heat pump systems where the heat exchangers are located underground either horizontally (ground source heat pump, GSHP) or vertically (downhole heat exchanger, DHE), and a heat-carrying medium is circulated within the exchanger, transferring the heat from or to the ground via a heat pump. Vertical heat exchangers are relatively well-known and their performance depends mainly on the soil thermal conductivity. However, horizontal heat exchangers are buried at depths ranging between 0.8 and 2 m and their performances are also influenced by weather conditions at the soil surface.

In the literature, numerous studies can be found about the modeling of ground heat transfer. The analytical models are based on the line source theory (Ingersoll [2]) or cylindrical source approximation (Carslaw and Jaeger, [3]). Both models assume an infinitely long heat source or sink in an isotropic medium and do not take into account the temperature variation with depth and the surface effects such as radiation and convection.

Several numerical and experimental studies have specifically addressed the vertical ground heat exchangers. Eskilson [4] developed non-dimensional temperature response factors to estimate the temperature of the multiple borehole ground loop heat exchangers subjected to various conditions. Rottmayer et al. [5] have developed a numerical model based on an explicit finite difference technique to simulate geothermal U-tube heat transfer conditions. Muraya et al. [6] carried out a two-dimensional transitory model in finite elements to study the thermal interference between the U tubes.

About the horizontal exchangers there are much less bibliography, Mei [7] has exploited the finite difference method to study the effects of seasonal ground temperature variation on the heat transfer model for a horizontal ground loop heat exchanger. He compared his work with modified line source and simple line source models. Piechowsky [8] included mass transfer in his model to take into account the effects of the soil moisture. Demir et al. [9] performed a two-dimensional numerical study on horizontal parallel tube performances, using finite difference formulation including all meteorological and surfaces conditions.

In this paper, a new quasi-3D computational model of a horizontal ground-coupled heat exchanger is employed to simulate the heat transfer process to the terrain, including all meteorological and surface conditions. The influence of soil thermal conductivity and geometrical parameters such as tubes spacing and their sizes on the exchanger effectiveness are also investigated.

2. Numerical model

The numerical study focuses on a series of concentric tubes buried 2.5m deep and covering an area of 100m^2. The terrain around the tubes is simulated as a cylinder with a height similar to its radius, big enough so the heat flux remains unchanged and with an axial symmetry. The quasi-3D model has been developed as a 2D domain with an axisymmetric condition (Figure1).The exchanger is assumed to be coupled to a heat pump in summer conditions, cooling a building, and therefore the heat transfer occurs from the tubes to the soil. The heat transfer equation in transitory mode is solved through the finite volume method using a computational fluid dynamics code. The simulation is carried out in a transient way, including the climatic effects of two summer months, July and August. The seasonal variations of air and ground temperatures (T_a, T_s) are approximated by pure harmonic functions ([10] and [11]).

$$T_a = T_{ma} + T_{va} \cos \frac{2\pi}{365}(t - t_0) \tag{1}$$

$$T_s = T_m + T_v \exp(-\sqrt{\frac{\omega}{2\alpha}}\ y) \cos\left(\frac{2\pi}{365}(t - t_0) - \sqrt{\frac{\omega}{2\alpha}}\ y - \Phi_s\right) \tag{2}$$

T_{ma} and T_{va} are obtained by air temperature data smoothing supplied from a meteorological station. The smoothed temperature curve(figure 2) is based on twenty consecutive years of data (1986, 2005) of an Algerian site located at latitude and longitude of 35º00 N, 00°.15 E.

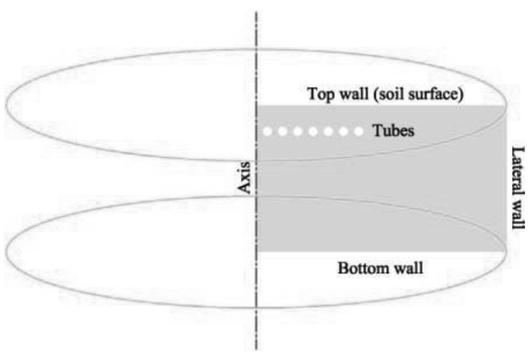

Fig. 1. Axisymmetric 2D configuration.

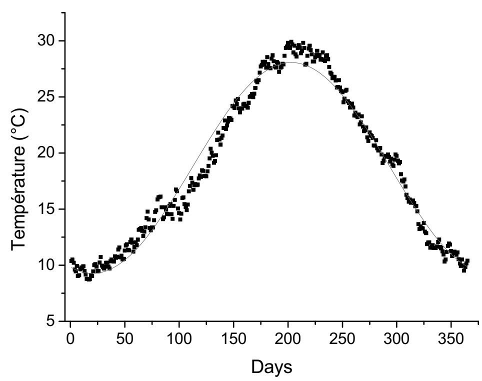

Fig. 2. Air temperature smoothing

The annual average ground temperature T_m, the amplitude of the ground temperature variation T_v and the phase lag Φ_s depend on the air parameters (T_{ma}, T_{va}) and the different energy fluxes in the soil surface. These magnitudes were determined by using an analytical model (Krarti et al. [11]) which integrates various thermal fluxes such as the solar radiation, the ground convection, the long-wave radiation and the evaporation. The values obtained for different soils, are presented in Table 1.

Table 1. T_m , T_v, Φs values and thermo physical tested soils properties

Soil type	**Thermal conductivity** (W/m K)	**Thermal diffusivity α** (10^{-6} m^2/s)	T_m (°C)	T_v (°C)	Φ_s (rad)
dry clay	0.87	0.54	21.34	11.83	0.070
moist clay	1.75	0.6	21.34	11.66	0.084
dry sand	0.4	0.27	21.34	11.93	0.062
moist sand	2.4	0.92	21.34	11.53	0.095
limestone	2.8	1.27	21.34	11.46	0.1

2.1. Computational grid and boundary conditions

The baseline configuration consists on an 8 tubes of 0.03m diameters, with 0.7m spacing over a 5.64m radius representing a horizontal circular heat exchanger area of 100 m^2 (Figure 3). Several configurations were tested varying the number and the diameter of the tubes with the same horizontal area an unstructured triangular meshing type has been employed with 148904 cells concentrated mainly in the vicinities of the tubes surfaces (Figure 4). Finer meshes were tested without performance improvement.

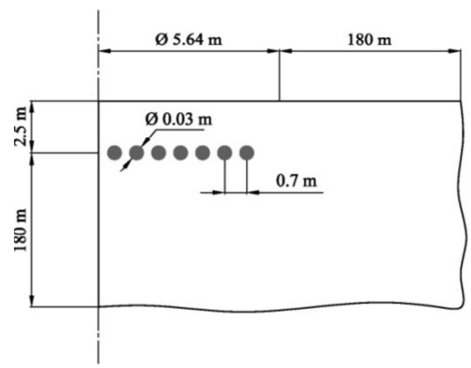

Fig. 3. Horizontal GCHE model and characteristic parameters

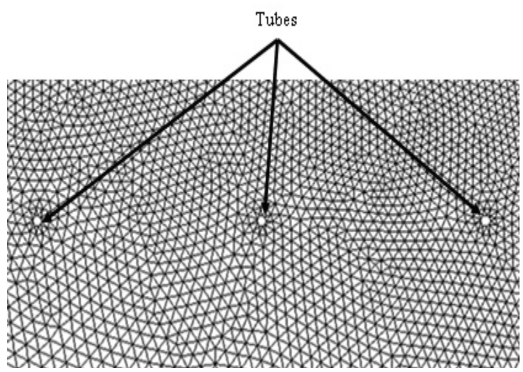

Fig. 4. Detail of the computational grid around the horizontal tubes

The tubes temperature is set to a constant value of T = 29°C. Neither the movement nor the fluid temperature change is modeled, which would require a full 3D model. On the top wall (soil surface), the temperature is imposed by equation (1), the left wall is set as axial symmetry. On the bottom and lateral walls located far enough, the imposed temperatures are dependent on season and depth (equation 2). The ground temperatures initialization at the beginning of the simulation (July 1st) is also realized by means of the equation (2).

3. Results and analysis

3.1 Cyclic and continuous operation

Figure 5 shows the heat flux per m^2 of soil along time under cyclic and continuous operation. Heat flux is referenced to the area (per square meter): total heat flux from the tubes to the terrain divided by the ground area covered by the tubes (100 m^2). In the continuous mode, the amount of exchanged heat has an important decrease in the first operating week, and then it tends asymptotically to a constant value, thus showing a certain soil thermal saturation. For the cyclic mode, the same heat evolution is noticed during the injection phase with an exchanged flux mean value slightly greater than the continuous case. It is clear that the instantaneous heat flux keeps greater values in the cyclic operation than in the continuous one. During the shut-up period, the thermal conditions of the soil recuperate and the heat exchange restarts at superior levels thanks to the thermal regeneration of the soil.

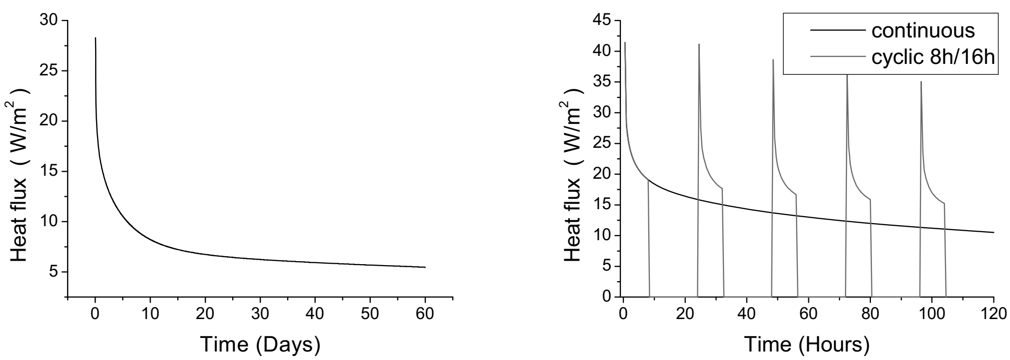

Fig.5. (a) Heat flux variation along 60 operating days; (b) Heat flux evolution under cyclic and continuous operation

3.2. Tube spacing and tube diameter

To study the tube spacing influence, different cases have been simulated under steady state conditions with the 100 m^2 circular area taken as reference, and the tube spacing ranging from 1.4 m to 0.5 m. This is equivalent to use more or less tube length to cover 100 m^2 area: from 71 m to 174 m, or 0.71 to 1.74 meters of tube per square meter of soil. Figure 6 illustrates the relationship between average thermal heat flux and tube length (or spacing). From this figure, it is clear that the heat flux per m^2 increases when the spacing between tubes is reduced. This is because the longer tube provides a longer path over which heat transfer between the tube and the surrounding soil can take place. However, the heat flux increase is not directly proportional to tube length. As a result of the interaction between tubes, the curve has a tendency to stabilize as the spacing tends to zero. Figure 7 illustrates the effect of the tube diameter on the thermal heat flux. The increase in the heat transfer flux to the earth is mainly due to the increase of the tube surface. From the amount of tube material point of view (in other words, tube cost), tube diameters do not affect the results as much as the tube spacing because doubling the diameter is more or less equivalent to four tubes of the inferior diameter but with zero spacing between them.

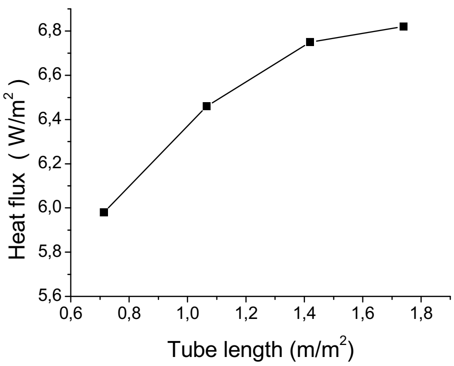

Fig. 6. Relationship between heat flux and tube length.

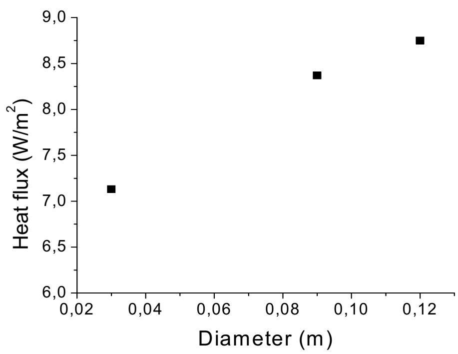

Fig. 7. Variation of heat flux with tube diameter

3.3. Thermal conductivity of the soil

With a respect to the influence of the soil thermal conductivity on the heat flux, five different types of soil has been analyzed (Table 1). The heat flux increase obtained with the thermal conductivity is presented in figure 8. As it can be seen, the relation between them is quite lineal.

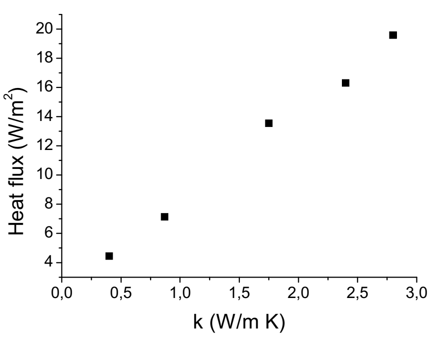

Fig. 8. Relationship between heat flux and soil thermal conductivity

4. Conclusions

A quasi-3D numerical simulation of a horizontal GCHE used for cooling (heat transfer to the ground) was performed under continuous and cyclic operations. Several parametric studies were carried out to investigate the effect of tube spacing, tube diameter, soil conductivity and operating conditions on horizontal buried tubes. It has been found that the continuous operating process produces a certain soil thermal saturation where the heat flux drops to very low values. On the other hand, the cyclic operating process allows a certain thermal discharge during the shut-up period providing an increase of the average heat flux. It has also been found that the soil thermal conductivity has a quasi-lineal effect over the heat transfer, while the effect of the tubes spacing tends towards an asymptotic value. Tubes diameter has an influence equivalent to spacing, although more limited.

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