HORIZONTAL PARALLEL PIPE GROUND HEAT EXCHANGER: ANALYTICAL CONCEPTION AND EXPERIMENTAL STUDY

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ABSTRACT. Due to limited amount of natural resources exploited for heating, and in order to reduce the environmental impact, people should strive to use renewable energy resources. Ambient low-grade energy may be upgraded by the ground heat exchanger (GHE), which exploits the ground thermal inertia for buildings heating and cooling. In this study, analytical performance and experiments analysis of a horizontal ground heat exchanger have been performed. The analytical study, relates to the dimensioning of the heat exchanger, shows that the heat exchanger characteristics are very important for the determination of heat extracted from ground. The experimental results were obtained during the period 30 November to 10 December 2007, in the heating season of the greenhouses. Measurements show that the ground temperature under a certain depth remains relatively constant. To exploit effectively the heat capacity of the ground, a horizontal heat exchanger system has to be constructed and tested in the Center of Research and Technology of Energy, in Tunisia.

KEYWORDS

Horizontal heat exchanger; Ground temperature; Space heating; forced convection; Heat transfer; Thermal analysis

INTRODUCTION

To date, the stake to rigorously save the consumption power by the building sector is often discussed, since the control of the energy consumption for heating and cooling could be the engine of a new economic activity. Since the beginning of the years 1970, the thermal regulation supported the realization of increasingly powerful new residences while being pressed on an able die, by developing a viable industry, to absorb the innovations which became essential. So, it is essential to improve the equipment of generation, distribution and emission of heat by the substitution of the current heating appliances by new technologies whose energy effectiveness is much better.

To extract the heat from the ground, it is preferred to use buried pipes, which can be installed horizontally or vertically. Heating and cooling system with buried pipes system has two primary advantages: high-energy efficiency and little environmental pollution. Before using exchanger we owes first dimensioning it, indeed, the numerical study of Mihalakakou [1996] and al. showed that the effectiveness of an exchanger ground/air increases with its length (range checked 30-70m). Moreover, there is an increase in the effectiveness when the exchanger is buried at larger depths (3m instead of 1, 2 m). In this same context, Florides [2007] and al., in their study, find that the depth of the horizontal exchanger is usually 1,5 with 2m and to minimize the intervention between the various exchangers they must be spaced of 30cm. With an aim of studying the effect of the geometrical properties variation on the dynamic behavior of a tubular exchanger subjected to various temperature conditions, A. Omar and al. [1999] studied three various shapes of tubular exchangers. The experimental study shows that the Heat Transfer Coefficient and the exchanged

thermal power depend on the tubes length and diameter. The effect of the ground exchanger hiding level is treated by Esen et al. [2007], they tested in experiments the performance of an air-conditioning system formed by a ground coupled heat pump with two different depths for ground exchanger: 1m and 2m. Their experiment showed that the ground exchangers performance increases with the depth (2,5 for 1m and 2,8 for 2m). In order to understand the heat transfer performance of saturated soils around coaxial ground coupled heat exchanger (GCHE), experimental investigation is conducted by means of artificial glass micro-balls as porous medium, Zhao and al. [2008] indicate that heat transfer mainly happens near the outer wall of coaxial GCHE and inclines to stabilization at far-field. The inlet temperature, initial temperature of porous medium and the flow rate are major factors affecting heat transfer. An economic comparison of ground-coupled and air-coupled heat pump system was carried out by Petit and Meyer [1997]. The experimental study was made under the South African climatic conditions. The study showed that the ground-coupled heat pump is most profitable. The same result is found by De Swart and Mayer [2001] like Esen et al. [2006] by using a reversible heat pump.The ground exchanger is also treated numerically by several authors, indeed, a finite element numerical model has been developed by Cui and al. [2008] for GHEs simulation in alternative operation modes over a short time period. Comparisons between the numerical and analytical results show that the finite line-source model is not capable of modeling the GHEs within a few hours because of the line-source assumption. This same problem was dealt by Demir et al. [2008], Negiz, Hastaoglu and Heidmann [1993,1995] and Thiers and Peuportier [2007]. Bi et al. [2002] employed a two-dimensional cylindrical coordinate system to model a buried heat exchanger.
This communication aims initially to dimension the Horizontal Ground Heat Exchangers in Cold Climates and in second place to test it under the climate of Tunisia.

ANALYTICAL STUDY

In order to characterize the ground exchanger, an analytical study was developed. It consists in evaluating the effect of the operation parameters (flow coolant, exchanger dimension) on the recovered ground heat flux.

A great number of parameters and soil properties influence the dimensioning of the ground heat exchanger (diameter, length, volumetric flow...). We will make the assumption that the outside temperature of the exchanger is constant, which means that the thermal inertia of the ground is larger than the exchanged quantities of heat. We will thus consider only the heat exchange which is done in stationary regime in which temperatures remain constant in the ground and within the wall of the exchanger. The heat transfer inside a pipe is due to forced convection. Let us consider an infinitesimal element of a tube dx in the flow direction (*Figure.1*).
The heat flux dQ recovered by the heat exchanger is given by the following expression:

$$dQ = \dot{M}\, c_p\, dT_w(x) = h\left(T_g - T_w\right)\, \pi D\, dx \tag{1}$$

Where T_w, Tg and D are respectively the water temperature inside the tube, the ground temperature in the considered level and the exchanger diameter.

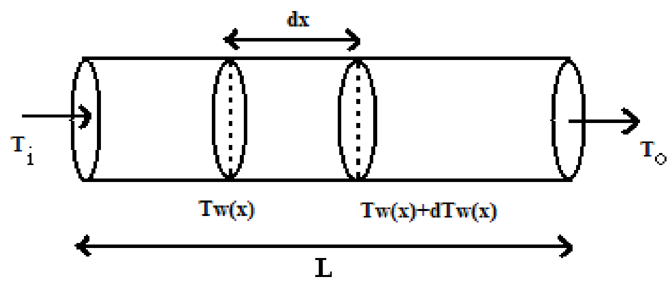

Figure 1. Diagram of an element of a heat exchanger

By admitting that the heat transfer coefficient *h* (x) remains constant all along the exchanger (*h* (x) = *h*), the preceding equation, after integration, gives the water temperature in each pipe section by the following formula:

$$T_w = T_g + (T_i - T_g)\ exp - \left(\frac{h S_x}{\dot{M} c_p}\right) \quad (2)$$

However: $T_o = T_{w(for\ x=L)}$ what gives:

$$T_o = T_g + (T_i - T_g) exp\left(-\frac{h S}{\dot{M} c_p}\right) \quad (3)$$

By replacing T_o by its expression in the relation of the quantity of heat recovered by the ground $Q = \dot{M} c_p (T_o - T_i)$ becomes:

$$Q = \dot{M} c_p \left(1 - exp\left(-\frac{\pi D L h}{\dot{M} c_p}\right)\right)(T_g - T_i) \quad (4)$$

Effect of the flow rate and the exchanger length. The recovered heat from the ground is shown in figure 2 as a function of exchanger length and flow rate. Each curve reaches in an asymptotic way a stage which represents recoverable maximum flow, imposed by the difference in temperature between the water and earth. Figure 2 also shows that the increase in the flow increases the quantity of heat recovered.

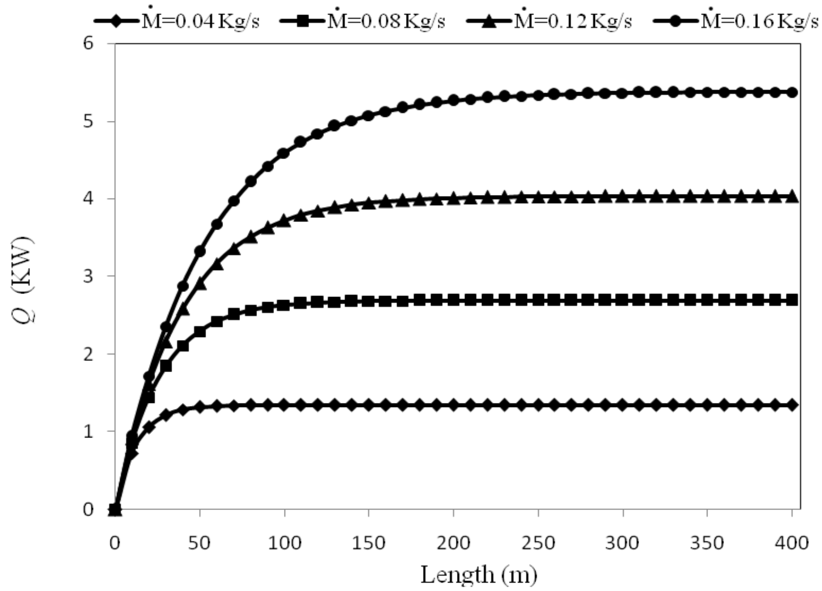

Figure 2. Heat extracted from ground according to the exchanger length and flow rate

To see whether this result is always true, we represented on *Figure* 3 flows per unit of length according to the flow rate of water coolant. The figure shows that the curve reaches in the same way a stage which corresponds to a maximum value of the heat flow gained.

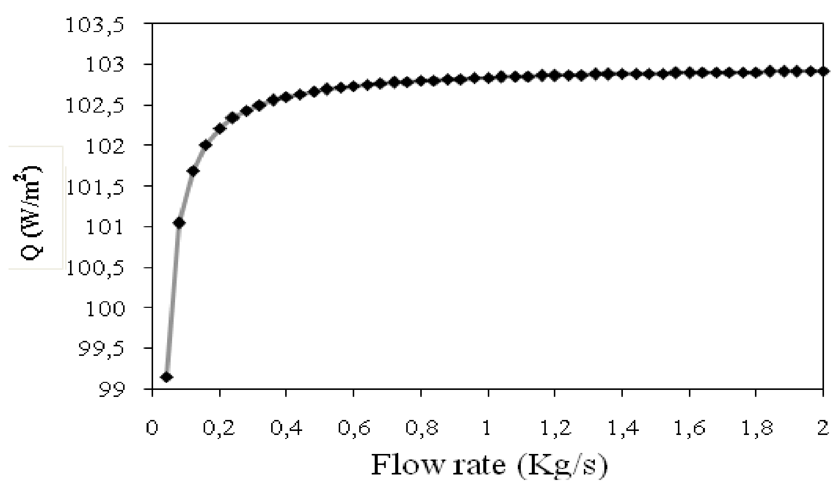

Figure 3. Heat extracted from ground according to the exchanger length and flow rate

<u>*Effect of the exchanger diameter*</u>. Figure 4 shows heat flux as a function of the diameter and the length of the exchanger. As the diameter decreases, more length is needed to have the same heat flux.

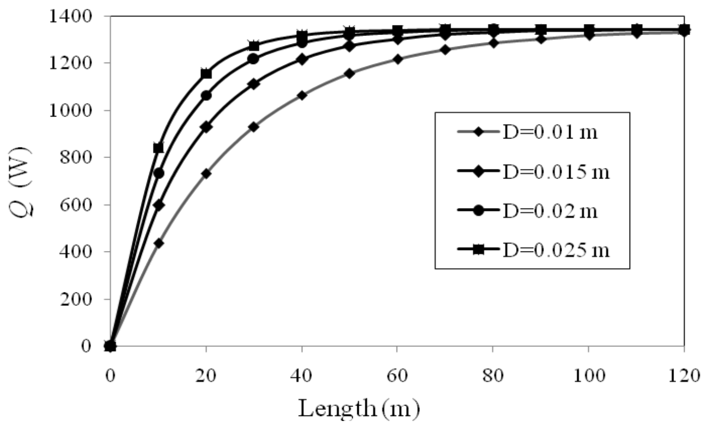

Figure 4. Heat extracted from ground according to exchanger length and diameter

Aeraulic dimensioning. Preceding calculations relate only to the thermal dimensioning of the ground exchanger. The criterion of maximum heat exchange for a length of minimal sheath results in choosing a sheath of low diameter and a high volume throughput. This choice is not inevitably the best in term of pressure loss in the sheath. We thus will give some elements of aeraulic dimensioning in order to allow a choice taking account of these constraints. The pressure losses must be calculated in order to be able to balance the various loops the ones compared to the others. For the calculation of the pressure losses, we must calculate the linear and singular pressure losses (elbows + collecting)

$$\Delta p_{\text{total}} = \Delta p_{\text{linear}} + \Delta p_{\text{singular}} \tag{5}$$

<u>*Linear pressure loss*</u>. The linear pressure loss for a flow in a rectilinear control is determined in the following way:

$$\Delta p = \frac{\Lambda}{D}\frac{\rho u^2}{2} L \tag{6}$$

The calculation of the head loss ratio (Λ) depends on the nature of the flow, laminar or turbulent depending on its Reynolds number:

$$Re = \frac{\rho u D}{\mu} \tag{7}$$

For Re values < 2000, the flow is laminar and the coefficient Λ is given by the relation of Hagen-Poiseuille

$$\Lambda = \frac{64}{Re} \tag{8}$$

Within the limits 2000 < Re < 4000, the mode is regarded as unstable and Λ is determined by the Frenkel's relation (Feyen et al. [1986]):

$$\Lambda = 2,7 / Re^{0,53} \tag{9}$$

For 4000 < Re < 10.000, the mode is considered partially turbulent and Λ is estimated by the relation of Blasius:

$$\Lambda = \frac{0,3164}{Re^{0.25}} \tag{10}$$

For high Re values, the mode is completely turbulent for which Λ is a function of the Reynolds number (Re), the index of the exchanger roughness (χ) and the pipe diameter(D). Von Karman and Prandtl, Nikuradse or Colebrook and White determine Λ by empirical relations (Carlier, [1980]):

* Von Karman et Prandtl :

$$\frac{1}{\sqrt{\lambda}} = -2\,Log_{10}\left[\frac{2,51}{Re\sqrt{\lambda}}\right] \tag{11}$$

* Nikuradse :

$$\lambda = 0,0032 + \frac{0,221}{Re^{0,237}} \tag{12}$$

* Colebrook et White :

$$\frac{1}{\sqrt{\lambda}} = -2\,log\left[\frac{\varepsilon / D}{3,7} + \frac{2,51}{Re\sqrt{\lambda}}\right] \tag{13}$$

Singular pressure loss. The singular pressure loss has as an expression:

$$\Delta p = \xi \rho \frac{u^2}{2} \tag{14}$$

Where ξ is the singular pressure loss factor. This pressure loss is smaller than the linear loss so we will not take it into account.

Calculation of the pressure loss. To choose the empirical formula that we must use, we should know whether the flow is laminar or turbulent. To estimate the type of flow, we calculated in the Table-1 the Reynolds number for various diameters and flow rates:

Table 1. Reynolds number for various flows and diameters of the exchanger

	Pipe diameter			
flow (Kg.s $^{-1}$)	10 (mm)	15 (mm)	20 (mm)	25 (mm)
0,04	5065	3376	2532	2026
0,08	10130	6753	5065	4052
0,12	15195	10130	7597	6078
0,16	20260	13507	10130	8104

We can see that for the considered flow rates and diameters, it is difficult to obtain a laminar flow. We will thus the pressure loss for a turbulent flow. In this case, the head loss ratio is that given by the relation of Blasius:

$$\Lambda = 0{,}3164 / Re^{0,25} \tag{15}$$

The variation of the pressure loss according to the water flow rate and the exchanger diameter are show in figure 4. These results show that the pressure loss increases with the flow rate and, in proportions much more significant, decreases with the diameter of the exchanger.This result is also found by Zella and Smadhi [2008].

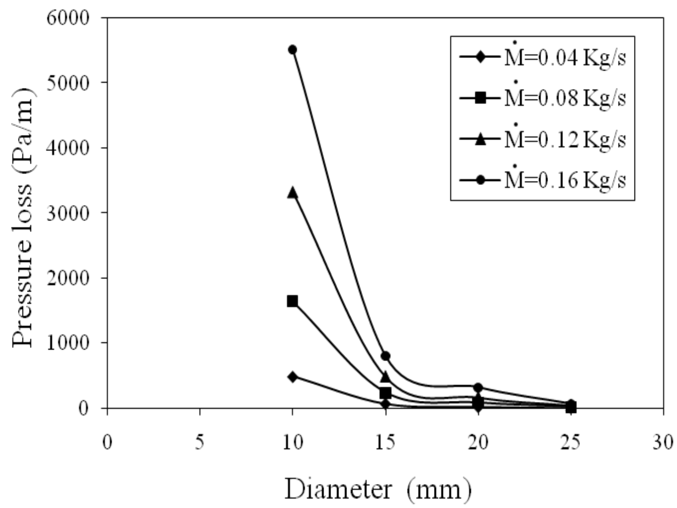

Figure 3. Pressure loss according to the flow rate and Diameter

EXPERIMENTAL STUDY

Ground Temperature Distributions The ground temperature constitutes an essential data to study various projects of construction. In our study, ground temperature distributions are required, for the determination of the depth to which the ground heat exchanger should be installed.

To determine the ground temperature, we installed in different ground levels, thermocouples of type K which are connected to an acquisition system data. The ground temperature pattern at various depths (w) measured in winter (December) is shown in figure 4.

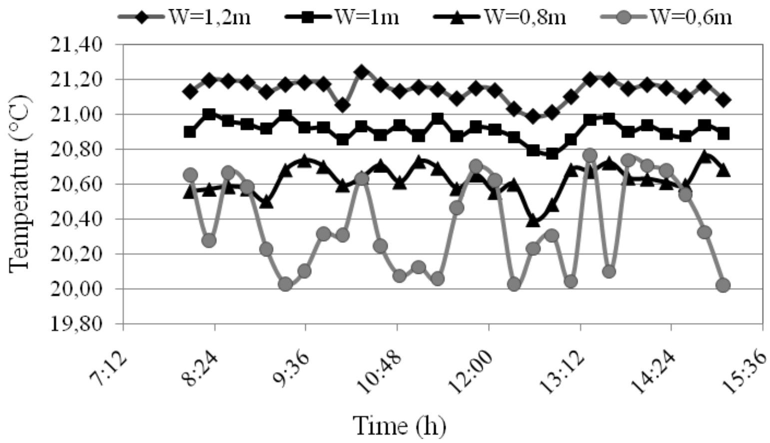

Figure 4. Distribution of the ground temperature (December)

Measurements show that the ground temperature below a certain depth remains relatively constant. This is due to the fact that temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases because of the high thermal inertia of the soil.
As it can be seen, the temperature is nearly constant below a depth of 0.8 m.

Buried Exchanger Test The difference in temperature between the outside air and the ground can be utilized as a preheating means in winter and pre-cooling in summer by operating a ground heat exchanger. Since the temperature increases slightly with the depth from 0.8 m, the exchanger will be installed in 1 m depth. The GHE system consists of a horizontal 10m of pipe length, 0.3 m of pipe distance, 0.02 m of nominal pipe diameter.
The fluid (water) inlet and outlet temperatures are compared in figure 5.

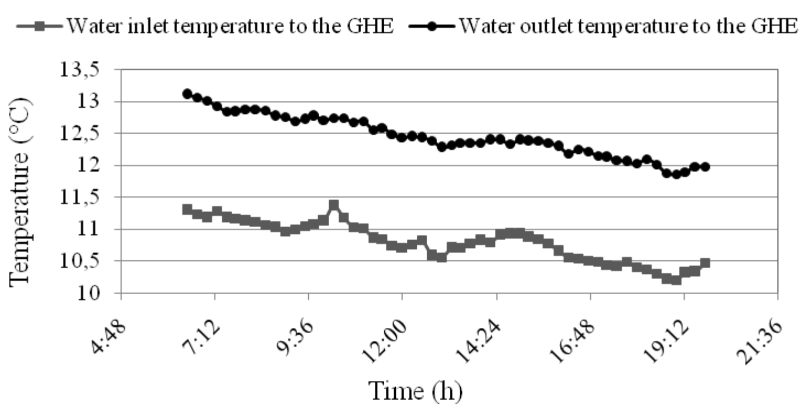

Figure 5. Comparison between water inlet and outlet temperatures of the GHE

This figure shows that difference in temperature between outdoor air and the ground can be used as a preheating means in winter by operating a ground heat exchanger

CONCLUSION

The main conclusions that can be drawn from the present study are listed below:

∗ A pre-design analysis of the GHE component is needed to determine optimal system parameters that would ensure minimum energy consumption and favourable economics. Indeed the heat exchanger dimensionning shows that the different exchanger characteristics have a great influence on the quantity of energy recovered from ground.

∗ Measurements show that the ground temperature below a certain depth remains relatively constant throughout the year. This is due to the fact that the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases because of the high thermal inertia of the soil

∗ Ground source heat exchangers systems offer some proven advantages over conventional heating and cooling systems, particularly in terms of efficiency, maintenance costs and overall operating costs. Many countries have a very good potential for GSHE systems.

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