

EFFECT OF SOIL TYPE ON VERTICAL CLOSED-LOOP GEOTHERMAL HEAT EXCHANGERS SIZING

S. KORICHI^{*1}, B. BOUCHEKIMA¹

¹Laboratory of New and Renewable Energy in Arid and Saharan Zones – LENREZA.

University of Kasdi Merbah Ouargla

Ouargla, Algeria

*E-mail: sabrinskemr@gmail.com

Abstract:

The closed ground source heat pump systems are one types of ground source heat pump (GSHP) systems and are classified as low enthalpy geothermal systems since they make use of low temperature differences, it consists of heat exchanger loops that utilize the heat conduction mechanism of the ground to reject or extract heat. The design of geothermal heat exchangers strongly depends on the properties of the soil as they affect soil resistance, which is an indication of the amount of energy that can be transferred to/from the ground.

Because of the unavailability of experimental data in the selected region, particularly those concerning the nature of the soil, this study was conducted to examine the influence of the kind of soil (Three different soils) on the design of a vertical closed loop for a residential unit under the meteorological conditions of Tamenrasset, city located in the south of Algeria, using analytical design procedures (ASHRAE) which highlight the influence of heat exchanger properties and ground parameters.

Keyword: Ground-source heat pumps, Ground Heat exchanger, vertical closed loop, Geothermal energy, thermal properties of soil.

I. INTRODUCTION

The consumption of energy in residential buildings has gained an increasing interest recently due to the rising demand for efficient energy use and higher comfort standards.

Shallow geothermal energy is a clean and sustainable solution for the heating and cooling of buildings especially in areas where the amount of energy stored in the subsurface is greater than its annual requirements for heating and cooling. Compared with other renewable sources, the shallow geothermal energy has important advantages such as its no location restriction for employing and no time dependant nature which means that it can be used everywhere in the world. These characteristics mean that it can be used as a base-load power source.

In the last decade, Shallow geothermal systems are increasingly applied for heating and cooling of residential and

infrastructure. The ground source heat pump (GSHP) system is a shallow geothermal technology of pumping heat from or to the shallow subsurface to provide heating or cooling to the buildings.

In recent years, many studies dealing with the influence of soil types on ground heat pump performance have been published by various researches (design, simulation and testing of GCHP systems) [1] and [2].

Deng and Fedler [1] examined the Heat transfer in multi-layered ground (coarse sand, clay, fine sand) with a vertical ground heat exchanger. The heat transfer rates were found to be discontinuous between soil layers and the effectiveness of heat distribution in coarse and fine sandy soils was higher by 62% and 27%, respectively, than in clayey soils, during 24 hours of operation.

W. H. Leong et al [2] Three different soils with five different degrees of saturation (0, 12.5, 25, 50 and 100%) were used in computer simulations. The performance of a ground heat pump system was found to depend strongly on the moisture content and the soil type (mineralogical composition).

The above literature review shows the benefits of conducting a pre-design analysis to determine the influence of soil types on ground heat pump performance. Developing a software program based on a proper model of ground source heat pump and obtaining the total length of the heat exchanger.

There are many methods outlined in literature refer to simplified procedures applicable to small systems Where the design depends on values of specific heat extraction rate related to ground thermal conductivity. One way to perform this calculation is to use the sizing method proposed by Kavanaugh and Rafferty¹. As stated by S, Kavanaugh (2014) [3].

Ioan Sarbu et al. [4] proposed a new design approach based on hourly load data in order to compare the ground model and to see the effect of using hourly loads versus monthly loads.

The length calculation of vertical bore with the aid of ASHRA handbook equation was compared with the software program EED.

Min-Jun Kima et al. [5] proposed a design method for the horizontal spiral-coil GHEs by modifying the boundary conditions of ASHRA handbook equation. A laboratory thermal response test was conducted to validate the proposed design method.

In this paper, a simulation and design evaluation has been used to examine the influence of three different standard soils on ground source heat pump (GSHP) system performance integrated with a vertical ground heat exchange for residential buildings located in the south of Algeria. A dynamic simulation system is developed using TRNSYS used to calculate the hourly loads.

II. METHODOLOGY

A. System modelling :

This study is based on ASHRAE handbook design equations to determine the required vertical borehole lengths for heating and cooling application.

This method and based on the work of Kavanaugh and Rafferty suggests the following relations for the length of the borehole for cooling and heating loads, the required length is [3]:

For cooling:

$$L_c = \frac{q_a R_{ga} + q_{cond} (R_b + PLF_m R_{gm} + F_{sc} R_{gst})}{T_g - \frac{ELT + LLT}{2} + T_p} \quad (1)$$

For heating:

$$L_h = \frac{q_a R_{ga} + q_{evap} (R_b + PLF_m R_{gm} + F_{sc} R_{gst})}{T_g - \frac{ELT + LLT}{2} + T_p} \quad (2)$$

Where:

F_{sc} is the short circuit heat loss factor.

L_c, L_h are the required borehole field lengths for cooling and heating modes.

PLF_m is the part load factor during the design month.

q_a is the net annual average heat transfer to the ground.

R_{ga}, R_{gm}, R_{gst} are the effective thermal resistances of the ground for the annual, monthly, and daily pulses.

T_g is the undisturbed ground temperature.

ELT, LLT are the design heat pump inlet and outlet fluid temperatures.

T_p is the temperature penalty.

q_{cond}, q_{evap} are the heat rate to/from ground at cooling and heating modes (W).

The heat rate to/from ground calculation using the following relations:

The heat pump condenser heat rate to ground:

$$q_{cond} = q_{lc} \left(\frac{COP_c + 1}{COP_c} \right) \quad (3)$$

The heat pump evaporator heat rate from ground:

$$q_{evap} = q_{lh} \left(\frac{COP_h - 1}{COP_h} \right) \quad (4)$$

Where:

q_{lc} is the building design cooling block load.

q_{lh} is the building design heating block load.

Tables with examples of various properties associated with closed-loop systems are presented in Kavanaugh and Rafferty (2014) for the locations B of the tubes (The position (B) centered and spaced evenly in the bore) (as show in the figure1). Abridged samples of these tables are reproduced below:

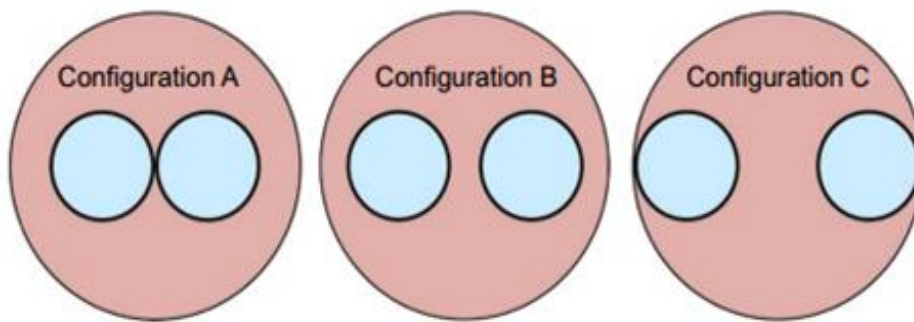


Figure1. Borehole configurations [6].

Table 1. Thermal Resistances of the bore (R_b) for Polyethylene U-Tubes [3].

Tube Diameter and Dimension	Tube Location	Bore Diameter mm	Thermal Resistance of Bore [$m^{\circ}C/W$]								
			Fluid Reynolds No =2000			Fluid Reynolds No = 4000			Fluid Reynolds No. = 10,000		
			Grout Conductivity [$W/m^{\circ}C$]			Grout Conductivity [$W/m^{\circ}C$]			Grout Conductivity [$W/m^{\circ}C$]		
			0,7	1,4	2,1	0,7	1,4	2,1	0,7	1,4	2,1
32 mm DR 11 HDPE U-Tube	B	100	0,24	0,16	0,13	0,21	0,13	0,1	0,21	0,13	0,1
		125	0,26	0,17	0,14	0,23	0,14	0,1	0,23	0,14	0,11
		150	0,28	0,18	0,14	0,26	0,15	0,1	0,25	0,15	0,11

Table 2. Reynolds Numbers in DR 11 HDPE Pipe for Various Pipe Diameters and Flow Rates [3].

Fluid	Temperature $^{\circ}C$	Reynolds Numbers								
		10 L/min			20 L/min			40 L/min		
		25 mm	32 mm	40 mm	25 mm	32 mm	40 mm	25 mm	32 mm	40 mm
Water	20	10030	7769	6293	20129	15657	12616	13342	15165	20080
To estimate loop water flow: $L/min = q (kW) \div [0.0692 \times \Delta t (^{\circ}C) \times \text{No. of Parallel U-Tubes}]$										

Table 3. Approximate Liquid Temperature Change Through GCHP Units [3].

System Flow (L/s/kW)	Temperature Rise [$^{\circ}C$]	Temperature Drop [$^{\circ}C$]
0,054	5,6	3,3
0,045	6,7	5
0,035	6,7	5

B. Case study

B.1. Description of the building model on TRNSYS:

A two-story residential house with a floor area of $248 m^2$ and an internal height of 3 m is used for the performance analysis. The houses with northern orientation consist of a ground floor, an upper floor. On the ground floor there are three bedrooms a kitchen, a living room and two toilets. The upper floor is symmetrical with the ground floor.

The following suggestions are also included in the building model and load characteristics topics:

- The flat roof made with 20 cm heavy concrete block, 8 cm screed and 1 cm asphalt.

- The walls made with 24 cm brick, 10 cm insul and 1,5 cm plaster.
- The houses each have a eight doubles glazing windows with $3m^2$.
- The ground made with 0,5cm floor, 6 cm stone, 4 cm silence, 24 cm concrete and 8 cm insul.

The house model was developed in TRNSYS simulation studio, and is shown in Figure 2.

B.2. Heat pump and heat exchanger:

The proposed GSHP system includes the heat pump unit used for both heating and cooling and the vertical ground heat

exchangers which were designed to satisfy the loads of the house.

The GHE consists of a 32 mm DR11 high-density polyethylene (HDPE) pipe placed in a 127 mm diameter bore with the configuration B of the U-tubes, where the circulating fluid (water with anti-freezer) flows as a heat transfer fluid.

A typical borehole with a single U-tube is illustrated in the following Figure.

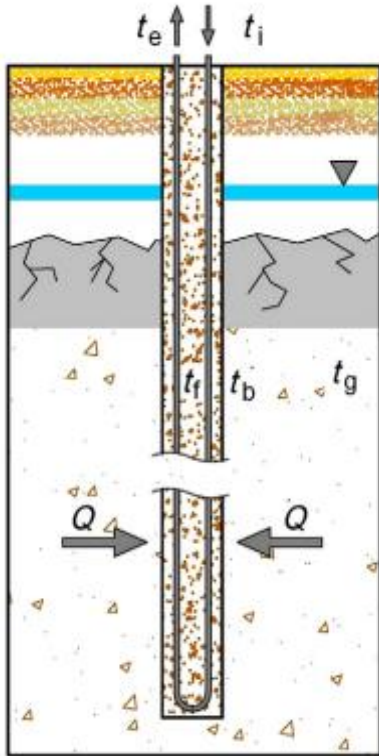


Figure 2. Schematic of a vertical grouted borehole [4].

B.2.1. Component sizing:

The input parameters were determined based on the design load in order to determine the vertical heat exchanger length for the different kinds of soil defined in the next sections.

The most important input parameters are summarized in the table 4.

Table 4: Specifications of the GSHP system.

Loads[W]		
Cooling block load [W]	q_{lc}	410
Heating block load [W]	q_{lh}	400
heat pump		
Hours of operation in heating mode[h]	$EFLH_h$	450
Hours of operation in cooling mode [h]	$EFLH_c$	900
Coefficient of performance	COP_c	4,1
Coefficient of performance	COP_h	3,5
ground properties		
Ground temperature [°C]	T_g	10
pipe		
Borehole diameter [mm]	BHE_d	125
Internal pipe diameters [mm]	IP_d	32

III. Results :

The building loads calculations were done using the TRNSYS simulation software based on a residential application in a south climate (Sahara of Algeria). Figure 2 show the typical project in the simulation studio workspace:

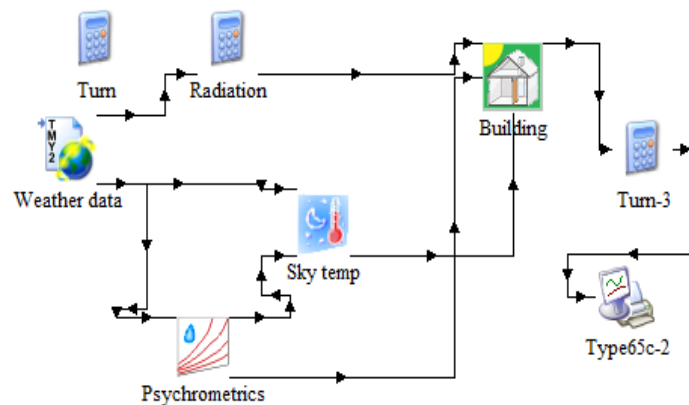


Figure 3. TRNSYS graphical interface containing the simulation schema.

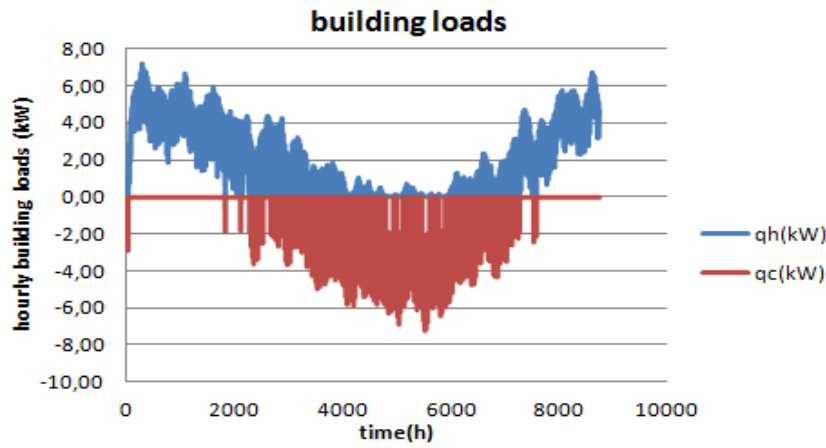


Figure 4. Hourly building loads for the example building.

In this case, the building loads are typical of this kind of climate, asking for a very high heating and cooling loads in winter and summer, which it requires more than one borehole in order to meet the demand.

The input parameters were chosen in order to determine the vertical heat exchanger length for the different types of soil (Clay, Limon clay-sandy and Sand), defined in the previous sections.

The most important input parameters are listed in Table 4 and 7, while the outcome of the design methods is presented in Tables 5,6, and 8.

The Typical effective ground thermal resistances calculated for a bore diameter of 125 mm are described in Table 4.

Table 5. The effective ground thermal resistances.

type of soil	R_{ga} [m·K/W]	R_{gm} [m·K/W]	R_{gst} [m·K/W]
Clay	0,23	0,185	0,095
Limon clay-sandy	0,308	0,22	0,126
Sand	0,428	0,387	0,122

The typical equivalent borehole thermal resistances for B pipe spacing (B configuration) are described in Table5.

Table 6. Borehole thermal resistances.

Location	Equivalent Borehole Thermal Resistance [m.K/W]	Borehole Diameter [mm]	Pipe Nominal Diameter [mm]
B	0,133	125	25

Table 7: Thermal characteristics of different types of soil [6] et[7].

Type of soil	Thermal conductivity	soil specific heat	soil density	Thermal diffusivity
Clay	1,28	880	1500	0,083
Limon clay-sandy	1,5	1340	1800	0,053
Sand	0,98	1390	1780	0,032

The total required bore length for cooling and heating mode computed using Equations (1) and (2) is presented in the table below.

Table 8: Ground exchanger length.

type of soil	Length of BHE for configuration B [m]			
	Heating mode		Cooling mode	
	total length	Length/bore	total length	Length/Bore
Clay	257,26	85,75	214,23	71,41
Limon clay-sandy	361	120,33	292,54	97,51
Sand	320,83	100,34	249,59	83,13

The bigger value of the required trench length in heating and cooling modes was selected as the length of VGHX. The mean difference between the results obtained of soils influence on the length of vertical ground heat exchanger is remarkable.

IV. Conclusion :

In this work we have studied under the meteorological conditions of the city Tamenrasset, the effect of the kind of soil on the depth of the ground heat exchangers. The results indicate that the depth of the GHX is significantly influenced by the kind of soil.

The comparison between the three identified types of soil showed that there is a great discrepancy between the determined lengths. For Limon clay-sandy, it was found that the GHE depth exceeds 360 meters, while it is only 321 m for sand and it is less than 258 m for clay, a difference in the GHE depth of 100 m between Limon clay-sandy soil and clay soil.

Nomenclature

COP_c	Coefficient of performance in cooling mode
COP_h	Coefficient of performance in heating mode
T_g	Ground temperature, [°C]
L_c	Required total bore length for cooling mode, [m]
L_h	Required total bore length for heating mode, [m]
q_{lc}	Cooling block load, [W]
q_{lh}	Heating block load, [W]
IP_d	Internal diameter of pipe, [mm]
BHE_d	Borehole diameter, [mm]
R_b	Thermal resistance of the borehole, [m.K/W]

Abbreviation

GSHP	ground source heat pump
BHE	borehole heat exchangers
HDPE	high-density poly-ethylene

DR	dimension ratio (outside diameter/wall thickness)
GCHP	ground couple heat pump

Greek letters

α_g	Ground diffusivity, [m^2/day]
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