PAPER 1

Renewable Energy 89 (2016) 1–12

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Analysis of the process of design of a geothermal installation

Cristina Sáez Blázquez*, Arturo Farfán Martín, Pedro Carrasco García, Luis Santiago Sánchez Pérez, Sara Jiménez del Caso

Department of Cartographic and Land Engineering, University of Salamanca, Higher Polytechnic School of Avila, Hornos Caleros 50, 05003, Avila, Spain

ARTICLE INFO

Article history:
Received in revised form
23 November 2015
Accepted 26 November 2015
Available online xxx

Keywords:
Geothermal
Perforation
Fourier law
Principles of thermodynamics
Earth energy designer

ABSTRACT

The present study shows a new way to calculate a geothermal installation. The process consists in measuring the temperatures inside a perforation. Once we have this parameter, we'll be able to determine the total depth of the perforations in a geothermal installation.

With this method, it'll be possible to dispense with other studies which are being used at the moment in this kind of installations. This fact will mean important economic savings and easier works.

Based on the "Principles of Thermodynamics and Fourier Law", and using the temperature values and other initial data, it was possible to determine the total perforation depth. During this process the software "Earth Energy Designer" was also used.

1. Introduction

Geothermal comes from the Greek word "Geos", which means earth, and "Thermos", which signifies heat. Therefore, geothermal energy is the internal heat of the earth. This kind of energy plays an increasingly important role in the field of renewable energies. The main applications of geothermal energy are the production of electrical energy at geothermal plants, the production of SHW (Sanitary Hot Water) and to heat or cool a certain space. The present study has been focused on this last application [1,2,13,14,19].

A conventional geothermal installation used to warm a building up or to produce SHW consists of one or more drillings where a number of pipes are placed. A heat pump carries a fluid situated in these pipes from the inside of the drilling to the building, producing at the same time a transfer of heat from the earth to the building [7,15].

When it's necessary to measure this kind of installation, specific software is usually used to provide data of relevant importance, such as the heat pump power and the length of drilling required. During the process of calculation, this software requests some information from the area where the installation is going to be placed. This information includes the parameter of thermal conductivity of the ground, a coefficient that determines the capacity of a material to conduct heat.

The determination of the real value of thermal conductivity can be achieved by two different methods: the first one lies in taking samples from different stratums of the hole in order to measure this parameter in the lab. This process could be quite arduous and expensive. The second one is called TRT (Thermal Response Test), which is a test used on the ground to determine the conductivity of the underground heat. This second method consists in applying an amount of heat to the subsoil for a period of 48–72 h. During this time, the temperature at the beginning and of the drilling and the power provided will be measured and stored in a computer to calculate the thermal conductivity. The data obtained by this test are qualitatively greater that the data obtained in the lab because its methodology does not modify the physical parameters of the earth [4].

The main disadvantage of a TRT is related to its price, because doing one of these tests involves a high cost. For this reason the present study has a huge importance because it suggests an alternative solution to calculate the thermal conductivity of the ground with a lower cost.

By measurements of temperatures made in the drilling, it has been possible to determine the thermal conductivity value and the length of drilling required as we will see in a more detailed way throughout this study.

Therefore, the novelty character of the presented method is the way used to determine the thermal conductivity and the following geothermal calculation. It just uses the value of temperature

* Corresponding author.
E-mail address: u107596@usal.es (C.S. Blázquez).

http://dx.doi.org/10.1016/j.renene.2015.11.067
0960-1481/

measured inside a hole in order to estimate the conductivity without complex equipment, only a temperature sounding line. The proposed method shows clear differences with respect to the TRT method. They both have the same objective, the calculation of the thermal conductivity; however, there are a lot of different points between them. The next Table 1 presents these differences:

Table 1
Differences between the suggested method and TRT essay.

TRT	Proposed method
Measurement "in situ" of the thermal conductivity parameter.	Measurement "in situ" of the internal temperature parameter.
The equipments utilized are complex and require the circulation of water through the pipes placed in a drilling.	It uses a temperature sounding line easily placed inside a hole.
Data are downloaded into specific software.	Data are downloaded into specific software.
The duration of the essay fluctuates between 48 and 72 h.	The essay finishes when the register of temperatures is constant.
The execution of this study means a high cost around 4000–5000 Euros.	The price is low given that the equipments used are also quite cheap.

2. Materials and methods

2.1. Method and initial data

The experimental methodology proposed tries to deduce the thermal conductivity parameter of a certain piece of ground. In order to achieve this objective, this study has been based on the "Fourier Law". This law allows us to quantify the heat flow carried in a zone when the temperature distribution in that area is known. It also establishes that the heat flow between two objects is directly proportional to the difference in temperature between them and this flow can travel in only one direction: the heat can only flow from the hottest object to the coldest one. The mechanical paths are conversely reversible: the opposite process can always be imagined. There is a diversity of phenomena that has not been produced by mechanic strengths, but they come from the heat present and accumulation. This part of the Natural Philosophy cannot be explained under dynamic theories; it has particular principles, using a similar method to the rest of sciencea [10,9,11,16].

The expression that materializes this law and has been used to estimate the thermal conductivity is the following one:

Constant Thermal Conductivity (Eq. (1)):

$$K_T = \frac{q_x x}{\Delta T} \tag{1}$$

This equation will be the basis of the calculation of the parameter followed throughout this work. However, in order to succeed in its determination, it is necessary to know the elements included in the mentioned equation. These elements are: Heat or flow transfer rate (qx), Distance (x) and the Temperature Differential (ΔT).

A series of data common in every process of calculation of a geothermal installation are required to deduce the three parameters involved in the Equation (1) which will make the estimation of the thermal conductivity possible. Given that this study is general and not related to any specific installation, some values considered as usual in a geothermal installation will be initially used. Nevertheless, when this method is applied to a particular case, as it will be described in the Section 4 "Discussion", the real values will be used and the calculation will be carried out similarly to the ones explained along this work.

In this way, the initial data proposed are:

- The initial drilling depth supposed is 90 m.
- The diameter of the holes considered is 200 mm.
- Every hole has a double-U polyethylene pipe. According to the "Second Law of Thermodynamics" there is heat transfer from the geothermal pipes to the ground, so finally they both reach the same temperature.
- The diameter of the supposed pipes is 32 mm.
- The distance between pipes in the same hole is 35 mm.

Once estimated those values, the next step to determine each of the already mentioned parameters that are part of the equation (1).

➢ Heat or flow transfer rate (q_x)

In the first place, to establish the heat transfer rate (q_x) expressed in W/m^2, it is necessary to specify what type of geothermal installation is going to be used, as it was said before, this work is an experimental test that is not related to any specific building, so, three different hypotheses recounted to three dwellings of 90 m^2, 130 m^2 y 360 m^2 will be selected. The firm "Vaillant" has established the power of the heat pumps required to warm those buildings up. Every calculation included in this work will be made for each of these three hypotheses.

The next table (Table 2) shows the three heat pumps that supply the thermal needs of three dwellings of 90 m^2, 130 m^2 and 360 m^2:

Table 2
Relation between dwelling m^2 and heat pump power [18].

Dwelling (m^2)	90	130	360
Total Power pump (W)	5900	8100	21100
Number of holes	1	1	3
Power pump per hole (W)	5900	8100	7033

According to this table, those values represent the heat transfer rate usually named with the letter "Q" whose units are watts (W). But, as the equation (1) shows, the parameter needed is the heat transfer rate per unit of area (q_x). Therefore, the area must be considered to obtain q_x from Q.

In this way, as it can be observed below, the equation (1), basis of the current study, can be also expressed including the parameters "Q" and "A" (Eq. (2)) instead of "q_x" (Eq. (1)).

$$K_T = \frac{q_x x}{\Delta T} \quad (1) \sim K_T = \frac{Q\,x}{A\Delta T} \tag{2}$$

Thus, equations (1) and (2) are identical, the only difference is that equation (1) is expressed using "q_x" and equation (2) "Q". However, in this case, it deals with a specific geometric configuration constituted by two parallel pipes, for this reason, to calculate "q_x"; another parameter must be had in mind to get to know the mentioned area "A". This parameter is known as form factor (S) and will be used to obtain "q_x".

The form factor of two parallel pipes, (given that the ones supposed are double- U pipes) follows the next expression (Eq. (3)) [6].

$$S = \frac{2\pi L}{\left(\left[COSH^{(-1)}\right]\right)\frac{\left(4Z^2-\left[D\_1^2\right]-\left[D\_2^2\right]\right)}{\left(2D_1\cdot D\_2\right)}} \tag{3}$$

Where: L is the pipe length; Z is the distance between pipes and D is the geothermal pipes diameter. Therefore, in this case, those parameters are: L = 90 m, Z = 35 mm and $D_1 = D_2 = 32$ mm.

Substituting values, the form factor (S) obtained is 658.01 m. For the three hypotheses studied, this form factor is the same because the pipes are identical and the power of the heat pumps is not used in its calculation.

By the calculation of this factor, only one of the two dimensions of the plane is being evaluated. Nevertheless, given that $L >> D_1, D_2$, z, the remaining dimension that should be considered is so small in comparison with the first one that it can be regarded as void, being thus disregarded. In this way, the area used in the calculation of q_x has a value of 658.01 m^2.

Once known the power of the pumps and the area, it is possible to deduce the heat transfer per unit of area (q_x) for each one of the hypotheses. The next Table 3 shows these results:

Table 3
Heat Transfer Rate of each one of the three hypotheses.

	Heat pump power "Q" (W)	Heat transfer rate "qx" (W/m^2)
Dwelling 1	5900	8.96
Dwelling 2	8100	12.31
Dwelling 3	7033	10.68

➢ Distance (x):

This distance is the total drilling depth, as it was seen before; the initial distance considered is 90 m.

➢ Temperature Differential (ΔT):

The other parameter that takes part in the equation (1) is the temperature inside the hole. It is not a known value so a temperature sounding line is required to get that data in a concrete way. Depending on the area where the hole is placed, this value of temperature will be different. Given that in the beginning the study is not focused on a certain drilling, it is necessary to take an interval of temperature that allows covering different possibilities of calculation, for that reason the interval comprises temperatures from 2 °C to 30 °C. At the end of this work, the method will be applied to a specific hole where the temperature will be measured inside. Once known the value of this parameter, it will be possible to determine simultaneously and thanks to this procedure the thermal conductivity of that ground.

Once these three parameters are known, the next step is to calculate the thermal conductivity using the equation (1) as it will be described in the section 3 "Results" where that parameter will be obtained for each heat pump and for each datum of temperature contained in the interval 2 °C and 30 °C.

In this way, this parameter will be got without a TRT study, with a temperature sounding line which will reduce significantly the price of the process managing the principal objective of the present work.

Once they are certain, the values of thermal conductivity for each datum of temperature and each heat pump, they are entered into the software "Earth Energy Designer". Using this programme, we are able to obtain the total drilling depth for each assumption, that is, for each value of thermal conductivity and heat pump.

In this way, this method proposes tables so that, knowing the value of temperature inside a hole, we can determine the parameter of thermal conductivity making the process of calculation of a geothermal installation faster and easier.

2.2. Materials

For practical purposes, the temperature record inside a hole is considered estimated by the periodic measurement of a temperature recorder suitable to work in presence of water and another one capable of working in a drilling without water. Fortunately, this

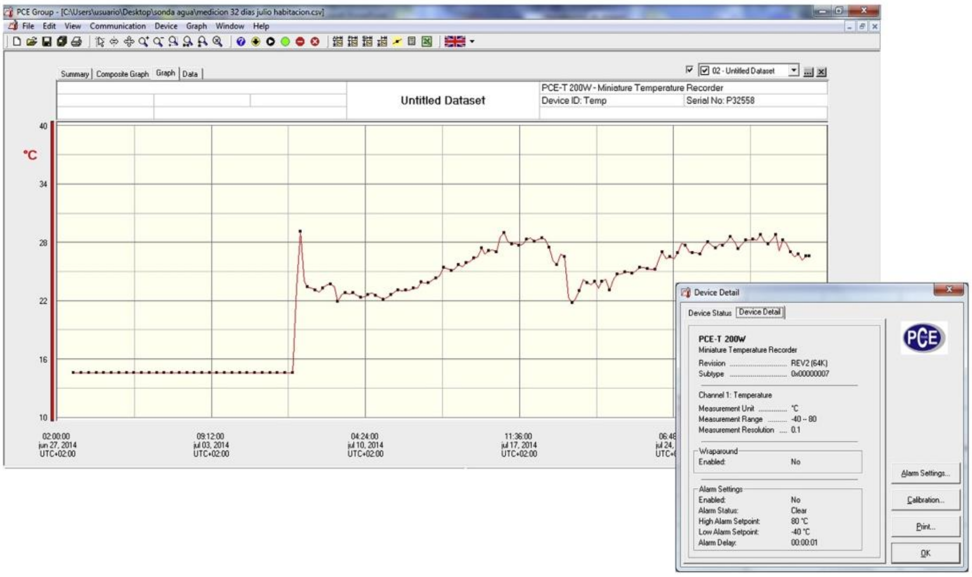

Fig. 1. Temperature graphic obtained by the register.

equipment is able to download the data to specific software (PCE Group 2.06), which makes these data available in a graphic way directly. This equipment will be used to measure the temperature in a certain hole with the goal of applying the suggested method (Fig. 1).

On the other hand, in order to complete this study, it has also been necessary to use design software of a geothermal installation, the programme mentioned above "Earth Energy Designer" (EED). This software allows us to establish the most important parameters of these kinds of installations: the number of holes and the drilling depth. This programme has been developed by "Blocon Software". The mathematical work of [8] and [12] concerning borehole field heat movement and storage is the basis for the calculations performed by the software, EED (Fig. 2).

drilling length [5].

Therefore, on the one hand, the input data required by the software are parameters from the ground in question like the thermal conductivity, annual medium temperatures of the area, as well as the energetic demand of the building or parameters of the installation such as the drilling diameter, the type of geothermal pump and pipes. On the other hand, the outputs of the software are the total drilling depth required in the geothermal installation, the number of holes and the depth of those drillings.

After concluding the description of the procedure purpose of this paper, the method will be applied in a certain hole as an example. The execution of the drilling took place on 11th March 2014.

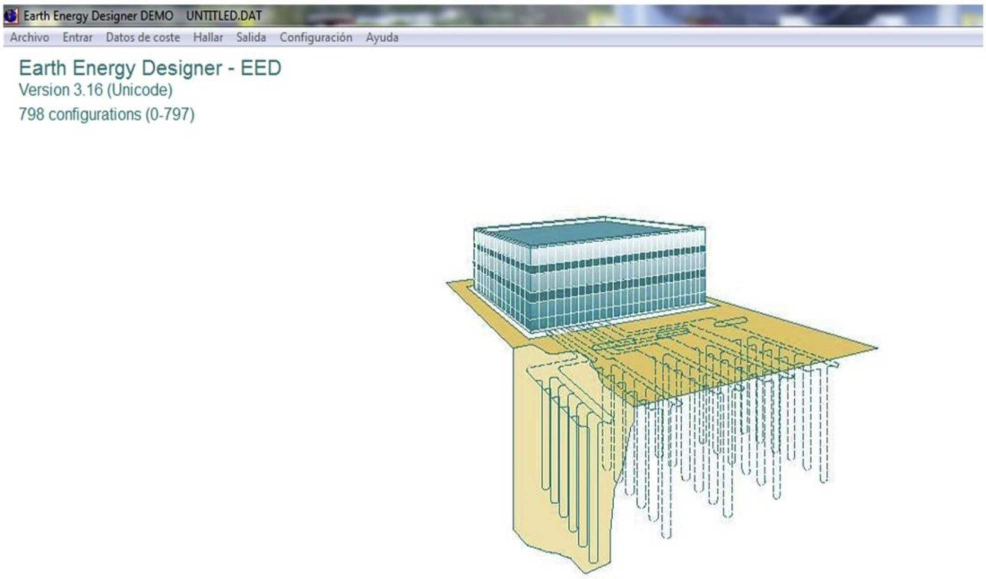

Fig. 2. Principal window "Earth Energy Designer" (Building Physics).

During the process of calculation of this software, a series of characteristic data of the ground, where the geothermal installation is going to be set up, must be introduced. One of these required data is the thermal conductivity that will be estimated with the present study.

Other parameters requested by the software are: the drilling diameter, type of geothermal pipe, type of working fluid and the energetic demand corresponding to the power of each heat pump.

Once these data are introduced, the programme proceeds to estimate the number of holes required in the geothermal installation as well as the drilling depth. Once the optimization process has finished, this software offers us different solutions, the first of them being the most suitable one, that is to say, the one with the least

The mentioned drilling has the next characteristics:

- Location: province of Avila (Spain)
- UTM coordinates:

X = 358.017 Y = 4.501.350.

- Hole diameter: 220 mm
- Drilling length: 90 m
- Drilling method: Rotary percussive drilling with hammer.
- Exploitation of the resource: study of temperature on it.

The following images show the whole drilling process (Figs. 3–5):

Fig. 3. Stage 1. Drilling. (a) Positioning of the drilling machine. (b) First meters drilled. (c) Adding new drilling rods.

Fig. 4. Stage 2. Piped. (a) Piping the first meters. (b) Joining pipes with different tools.

Fig. 5. Stage 3. (a) Placing of the manhole. (b) Closing of the hole.

2.3. Test procedure

The proposed method allows us to analyze the variations of the drilling depth required in a geothermal installation according to the value of thermal conductivity of the ground in question.

The study has been carried out following the next procedure:

- Selection of three heat pumps "Vaillant" with different powers to carry out the present work.
- Estimation of a series of initial data, characterization of the drilling and the geothermal pipes.
- Selection of a range of temperatures given that the temperature inside the hole will not be the same everywhere, it will fluctuate in the supposed range.
- Calculation of the thermal conductivity for each value of temperature, applying the "Fourier Law".
- Once this parameter has been estimated, the next step will be the calculation of the drilling depth using the software "Earth Energy Designer" for different values of thermal conductivity.
- Upon finishing this process of calculation, we will finally compare the variation of temperature of the subsoil with its thermal conductivity and the variation of the drilling depth with the thermal conductivity for each supposed case.

3. Results

The Tables (4–6) show the values of thermal conductivity in W/mk obtained for each value of temperature included in the interval of 2 °C to 30 °C for each of the three heat pumps considered. These values have been calculated using the equation 1based on the Fourier Law. Once obtained the values of thermal conductivity, they have been evaluated by comparing them with the normal values of conductivity of a granitic ground because the study has been made on that kind of land. Since the thermal conductivity of a granitic ground fluctuates around 3 W/mK and the values of the tables change around 2–4 W/mK, the validity of the data is demonstrated.

Table 4
Thermal conductivities corresponding to the heat pump of 5.9 Kw.

Dwelling 1		
Area: 90 m^2	Pipe Diameter: 32 mm	
Pump Power: 5.9 kW	Form Factor (S) = 658.01	
Number of holes: 1	Distance between pipes in the hole (z) = 35 mm	
Distance (x): 90 m	Heat Transfer Speed (qx): 8.96 W/m^2	
Temperature increase (ΔT) °C	Temperature increase (ΔT) K	Thermal conductivity (k) W/mk
2	275.15	2.93
4	277.15	2.91
6	279.15	2.89
8	281.15	2.87
10	283.15	2.85
12	285.15	2.83
14	287.15	2.81
16	289.15	2.79
18	291.15	2.77
20	293.15	2.75
22	295.15	2.73
24	297.15	2.71
26	299.15	2.70
28	301.15	2.68
30	303.15	2.66

Table 5
Thermal conductivities corresponding to the heat pump of 8.1 Kw.

Dwelling 2		
Area: 130 m^2	Pipe Diameter: 32 mm	
Pump Power: 8.1 kW	Form Factor (S) = 658.01	
Number of holes: 1	Distance between pipes in the hole (z) = 35 mm	
Distance (x): 90 m	Heat Transfer Speed (qx): 12.31 W/m^2	
Temperature increase (ΔT)°C	Temperature increase (ΔT)K	Thermal conductivity (k) W/mk
2	275.15	4.03
4	277.15	4.00
6	279.15	3.97
8	281.15	3.94
10	283.15	3.91
12	285.15	3.89
14	287.15	3.86
16	289.15	3.83
18	291.15	3.81
20	293.15	3.78
22	295.15	3.75
24	297.15	3.73
26	299.15	3.70
28	301.15	3.68
30	303.15	3.65

Table 6
Thermal conductivities corresponding to the heat pump of 21.1 Kw.

Dwelling 3		
Area: 360 m^2	Pipe Diameter: 32 mm	
Pump Power: 21.1 kW	Form Factor (S) = 658.01	
Number of holes: 3	Distance between pipes in the hole (z) = 35 mm	
Distance (x): 90 m	Heat Transfer Speed (qx): 10.68 W/m^2	
Temperature increase (ΔT)°C	Temperature increase (ΔT)K	Thermal conductivity (k) W/mk
2	275.15	3.49
4	277.15	3.47
6	279.15	3.44
8	281.15	3.42
10	283.15	3.39
12	285.15	3.37
14	287.15	3.35
16	289.15	3.32
18	291.15	3.30
20	293.15	3.28
22	295.15	3.26
24	297.15	3.23
26	299.15	3.21
28	301.15	3.19
30	303.15	3.17

It should be clarified that the temperature values are reported in Celsius Degrees because the temperature sounding line measures in theses unities and also in Kelvin given that, that is the unity used at the International System.

The next Tables (7–9) show for different values of thermal conductivity, the results of depth drilling obtained by the software "Earth Energy Designer" for each heat pump considered.

In the Figs. 6–8 we can see in a graphic way the relations between temperature-thermal conductivity and depth-thermal conductivity.

Finally, the next tables contain, for each heat pump, a summary of the aim pursued in the present work, that is, from a value of

Table 7
Calculation with "Earth Energy Designer" for the heat pump of 5.9 Kw.

Pump 1

Power Pump: 5.9 kW
Number of Holes: 1

Form factor (S)	Heat transfer speed (qx)W/m^2	Thermal conductivity (W/mK)	Depth (m)	Temperature (K)	Temperature (°C)
701.87	8.41	1.5	96	537.99	264.84
679.93	8.68	1.6	93	504.37	231.22
665.31	8.87	1.7	91	474.70	201.55
650.69	9.07	1.8	89	448.33	175.18
628.76	9.38	1.9	86	424.73	151.58
621.44	9.49	2	85	403.50	130.35
606.82	9.72	2.1	83	384.28	111.13
592.20	9.96	2.2	81	366.81	93.66
577.58	10.22	2.3	79	350.87	77.72
570.27	10.35	2.4	78	336.25	63.10
562.96	10.48	2.5	77	322.80	49.65
548.33	10.76	2.6	75	310.38	37.23
541.02	10.91	2.7	74	298.89	25.74
533.71	11.05	2.8	73	288.21	15.06
526.40	11.21	2.9	72	278.27	5.12
519.09	11.37	3	71	269.00	−4.15
511.78	11.53	3.1	70	260.32	−12.83
504.47	11.70	3.2	69	252.18	−20.97
497.16	11.87	3.3	68	244.54	−28.61
489.84	12.04	3.4	67	237.35	−35.80
482.53	12.23	3.5	66	230.57	−42.58
475.22	12.42	3.6	65	224.16	−48.99
475.22	12.42	3.7	65	218.11	−55.04
467.91	12.61	3.8	64	212.37	−60.78
460.60	12.81	3.9	63	206.92	−66.23
453.29	13.02	4	62	201.75	−71.40
453.29	13.02	4.1	62	196.83	−76.32
445.98	13.23	4.2	61	192.14	−81.01
445.98	13.23	4.3	61	187.67	−85.48
438.67	13.45	4.4	60	183.41	−89.74
438.67	13.45	4.5	60	179.33	−93.82

Table 8
Calculation with "Earth Energy Designer" for the heat pump of 8.1 Kw.

Pump 2

Power Pump: 8.1 kW
Number of Holes: 1

Form factor (S)	Heat transfer speed (qx)W/m^2	Thermal conductivity (W/mK)	Depth (m)	Temperature (K)	Temperature (°C)
943.13	8.59	1.5	129	738.60	465.45
921.20	8.79	1.6	126	692.44	419.29
899.27	9.01	1.7	123	651.71	378.56
877.33	9.23	1.8	120	615.50	342.35
862.71	9.39	1.9	118	583.11	309.96
840.78	9.63	2	115	553.95	280.80
826.16	9.80	2.1	113	527.57	254.42
811.53	9.98	2.2	111	503.59	230.44
796.91	10.16	2.3	109	481.70	208.55
782.29	10.35	2.4	107	461.63	188.48
767.67	10.55	2.5	105	443.16	170.01
760.36	10.65	2.6	104	426.12	152.97
745.73	10.86	2.7	102	410.33	137.18
731.11	11.08	2.8	100	395.68	122.53
723.80	11.19	2.9	99	382.04	108.89
716.49	11.31	3	98	369.30	96.15
701.87	11.54	3.1	96	357.39	84.24
694.56	11.66	3.2	95	346.22	73.07
687.24	11.79	3.3	94	335.73	62.58
679.93	11.91	3.4	93	325.85	52.70
672.62	12.04	3.5	92	316.54	43.39
665.31	12.17	3.6	91	307.75	34.60
658.00	12.31	3.7	90	299.43	26.28
650.69	12.45	3.8	89	291.55	18.40
643.38	12.59	3.9	88	284.08	10.93
636.07	12.73	4	87	276.98	3.83
628.76	12.88	4.1	86	270.22	−2.93
621.44	13.03	4.2	85	263.79	−9.36
614.13	13.19	4.3	84	257.65	−15.50
614.13	13.19	4.4	84	251.80	−21.35
606.82	13.35	4.5	83	246.20	−26.95

Table 9
Calculation with "Earth Energy Designer" for the heat pump of 21.1 Kw.

Pump 3					
Power Pump: 21.1 kW Number of Holes: 3					
Form factor (S)	Heat transfer speed (qx)W/m^2	Thermal conductivity (W/mK)	Depth (m)	Temperature (K)	Temperature (°C)
899.27	7.82	1.5	123	641.31	368.16
877.33	8.02	1.6	120	601.22	328.07
855.40	8.22	1.7	117	565.86	292.71
833.47	8.44	1.8	114	534.42	261.27
818.84	8.59	1.9	112	506.29	233.14
804.22	8.75	2	110	480.98	207.83
789.60	8.91	2.1	108	458.08	184.93
774.98	9.08	2.2	106	437.25	164.10
760.36	9.25	2.3	104	418.24	145.09
745.73	9.43	2.4	102	400.82	127.67
731.11	9.62	2.5	100	384.78	111.63
716.49	9.82	2.6	98	369.98	96.83
701.87	10.02	2.7	96	356.28	83.13
694.56	10.13	2.8	95	343.56	70.41
679.93	10.34	2.9	93	331.71	58.56
672.62	10.46	3	92	320.65	47.50
658.00	10.69	3.1	90	310.31	37.16
650.69	10.81	3.2	89	300.61	27.46
643.38	10.93	3.3	88	291.50	18.35
636.07	11.06	3.4	87	282.93	9.78
628.76	11.19	3.5	86	274.85	1.70
614.13	11.45	3.6	84	267.21	−5.94
606.82	11.59	3.7	83	259.99	−13.16
599.51	11.73	3.8	82	253.15	−20.00
592.20	11.88	3.9	81	246.66	−26.49
592.20	11.88	4	81	240.49	−32.66
584.89	12.02	4.1	80	234.62	−38.53
577.58	12.18	4.2	79	229.04	−44.11
570.27	12.33	4.3	78	223.71	−49.44
562.96	12.49	4.4	77	218.63	−54.52
555.64	12.66	4.5	76	213.77	−59.38

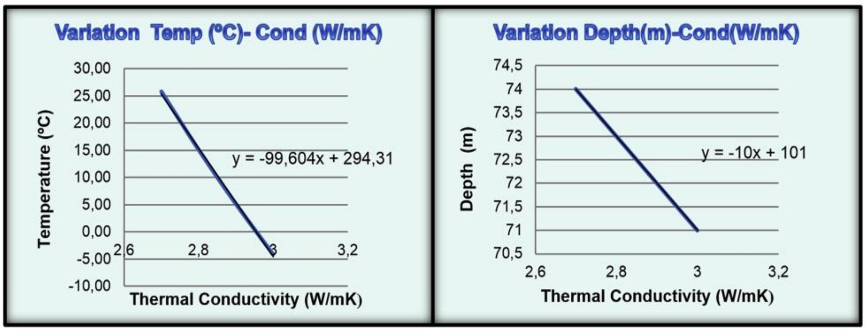

Fig. 6. Comparative temperature-thermal conductivity and depth-thermal conductivity (Pump I).

temperature measured in the area in question, it has been possible to obtain directly the value of thermal conductivity of that piece of ground and the drilling depth required.

4. Discussion

As shown in the Tables (4–6), a different value of thermal conductivity has been obtained for each value of temperature, that is to say, the value of thermal conductivity in the ground depends on the temperature registered in that ground. As we can see, when the temperature increases, the thermal conductivity decreases, that is, they are inversely proportional (as expected according to Fourier equations).

In the following Tables (7–9) there is a first estimation of the drilling depths obtained with the program "Earth Energy Designer". As we can see, the relation between the drilling depth and the thermal conductivity is inversely proportional too. As the thermal conductivity grows, the drilling depth required reduces. However,

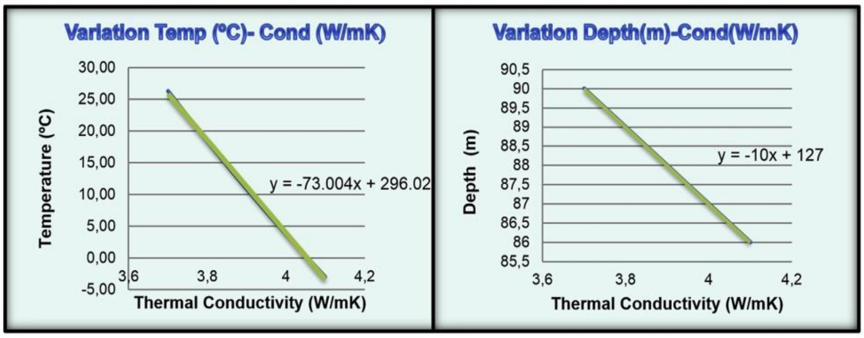

Fig. 7. Comparative temperature-thermal conductivity and depth-thermal conductivity (Pump II).

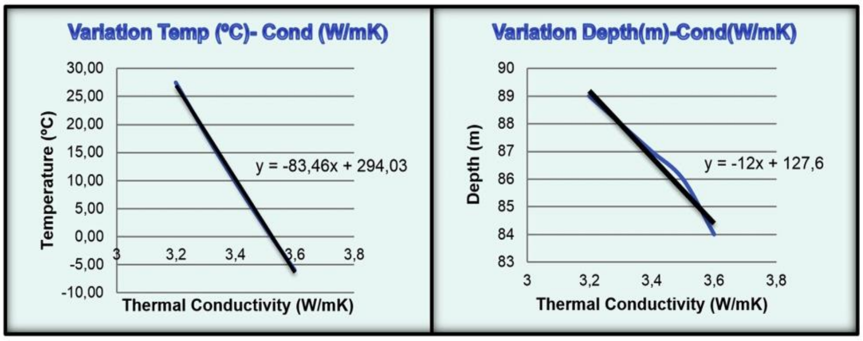

Fig. 8. Comparative temperature-thermal conductivity and depth-thermal conductivity (Pump III).

when the temperature of the ground decreases, the drilling depth also does so, thus, there is a directly proportional relationship between them.

Finally, the last Tables 10–12 provide for each heat pump the existing relations between the temperature registered inside the hole, the thermal conductivity of that ground and the depth to be drilled. In this way, the process of calculation of a geothermal installation is solved without the need to turn to more expensive procedures.

Table 10
Relation temperature-conductivity-depth (Pump I).

Pump 1			
Temperature (K)	Temperature (°C)	Thermal conductivity (W/mK)	Depth (m)
297.15	24	2.71	73.94
295.15	22	2.73	73.74
293.15	20	2.75	73.54
291.15	18	2.77	73.34
289.15	16	2.79	73.14
287.15	14	2.81	72.94
285.15	12	2.83	72.74
283.15	10	2.85	72.54
281.15	8	2.87	72.34
279.15	6	2.89	72.14
277.15	4	2.91	71.94
275.15	2	2.93	71.74
273.15	0	2.95	71.54
271.15	−2	2.97	71.33
269.15	−4	2.99	71.13

Table 11
Relation temperature-conductivity-depth (Pump II).

Pump 2			
Temperature (K)	Temperature (°C)	Thermal conductivity (W/mK)	Depth (m)
297.15	24	3.73	89.85
295.15	22	3.75	89.58
293.15	20	3.78	89.30
291.15	18	3.81	89.03
289.15	16	3.84	88.76
287.15	14	3.86	88.48
285.15	12	3.89	88.21
283.15	10	3.92	87.94
281.15	8	3.95	87.66
279.15	6	3.97	87.39
277.15	4	4.00	87.11
275.15	2	4.03	86.84
273.15	0	4.05	86.57
271.15	−2	4.08	86.29
269.15	−4	4.11	86.02

Table 12
Relation temperature-conductivity-depth (Pump III).

Pump 3			
Temperature (K)	Temperature (°C)	Thermal conductivity (W/mK)	Depth (m)
297.15	24	3.24	88.89
295.15	22	3.26	88.61
293.15	20	3.28	88.32
291.15	18	3.31	88.03
289.15	16	3.33	87.74
287.15	14	3.36	87.46
285.15	12	3.38	87.17
283.15	10	3.40	86.88
281.15	8	3.43	86.59
279.15	6	3.45	86.31
277.15	4	3.48	86.02
275.15	2	3.50	85.73
273.15	0	3.52	85.44
271.15	−2	3.55	85.16
269.15	−4	3.57	84.87

4.1. Practical example

As a practical application of the whole process exposed throughout this study, the temperature inside a drilling has been registered in a specific area of the province of Ávila.

It is a 90 m deep drilling located in an eminently granitic area. A part of this hole is taken up by water.

The register of temperature has been made at a depth of 45 m by a recorder suitable to work in the presence of water. The next figure displays an image of it (Fig. 9).

Fig. 9. Recorder PCE-T 200 W.

The register of temperature in the mentioned depth of 45 m has been carried out three times a day, that is to say, every 8 h over a prolonged period in order to cover different months of the year, from the hottest months to the coldest ones.

The results obtained show a constant value of temperature of 14.6 °C (values of 14.5° C and 14.7 °C have been obtained only eight times) in that depth regardless of external atmospheric conditions, that is, that value of temperature is not influenced by the different seasons in which we are.

By way of example, the following graphics show the results of the temperature recorder in a hot period like the month of June and in another colder period from October to December. In the rest of the months the results have been the same (Figs. 10 and 11).

Given that no physical quantity can be measured with perfect certainty, there are always errors in any measurement. This means that if we measure some quantity and, then, repeat the measurement, we will almost certainly measure a different value the second time.

When a measurement is repeated several times, the measured values are grouped around some central value. This grouping or distribution can be described with two numbers: the mean, which measures the central value, and the standard deviation which describes the spread or deviation of the measured values about the mean.

For a set of N measured values for some quantity x, the mean of x is represented by the symbol <x> and is calculated by the following formula (Eq. (4)):

$$<x> = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{1}{N}(x_1 + x_2 + x_3 + \ldots + x_{N-1} + x_N) \quad (4)$$

Where xi is the i-th measured value of x. The mean is simply the sum of the measured values divided by the number of measured values.

The standard deviation of the measured values is represented by the symbol σx and is given by the formula (Eq. (5)) [3,17].

$$\sigma x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x - <x>)^2} \quad (5)$$

In this case, the total number of measured values of temperature is 163, that is to say, N = 163, of those measurements, the value 14.5 °C was measured 6 times, the value 14.6 °C 155 times and finally the value 14.7 °C only 2 times. With these data, the above equations are solved following (Eq. (6)):

$$<T> = \frac{1}{163}(2263 + +29.4 + 87) \sim 14.6\,^{\circ}C \quad (6)$$

The standard deviation is given by (Eq. (7)):

$$\sigma_T = \sqrt{\frac{1}{163-1}\sum_{i=1}^{163}(T_i - 14.6)^2} = 0.022\,^{\circ}\mathrm{C} \quad (7)$$

Thus, the difference between the average and the considered value of the temperature in that extent of the subsoil differ for a quantity lower than the measure precision.

Once the temperature in the area of study is known, we can establish by the (Tables 10–12), the thermal conductivity of the ground and the drilling depth required in the installation for each hypothesis (the three geothermal heat pumps with different

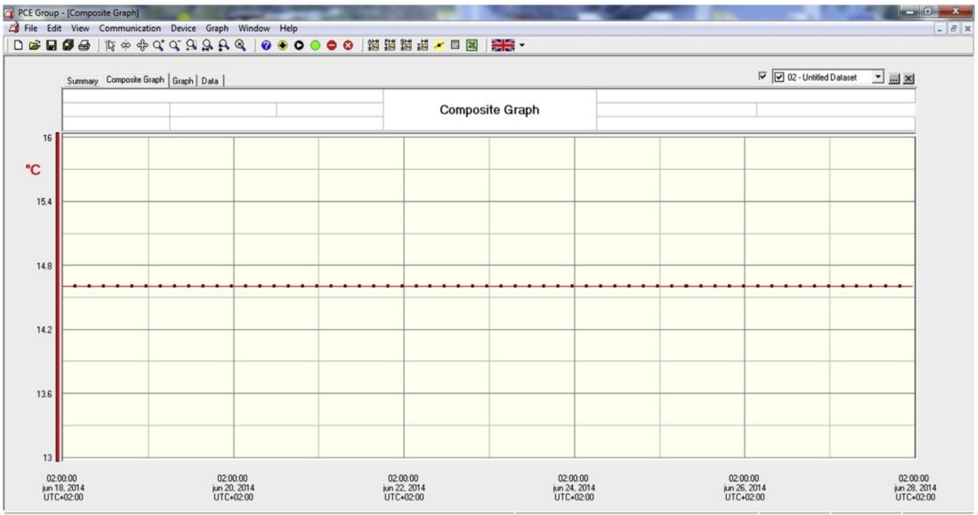

Fig. 10. Register of temperatures in the month of June.

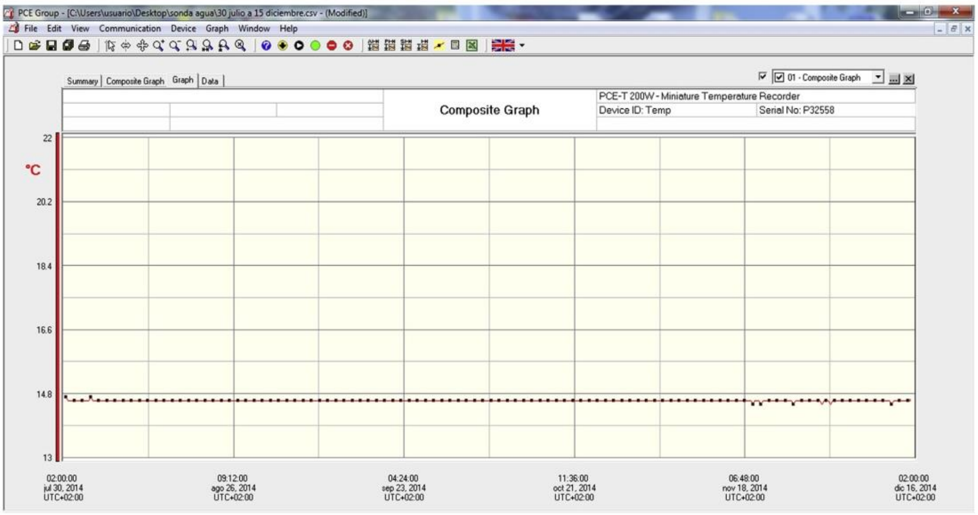

Fig. 11. Register of temperatures from October to December.

powers).

The Table 13 includes the results mentioned.

It is important to remember that in the case of pump 3, three drillings will be needed, so there will be three holes of 87.52 m

Table 13
Final results for the practical assumption.

	Temperature (K)	Temperature (°C)	Thermal conductivity (W/mK)	Drilling depth (m)
Pump 1	287.75	14.6	2.8	73
Pump 2	287.75	14.6	3.85	88.4
Pump 3	287.75	14.6	3.35	87.4

each one.

5. Conclusions

The present work has presented an experimental methodology to obtain the parameters required in the process of calculation of an installation that uses the geothermal energy.

The results have been achieved by three kinds of geothermal pumps currently on the market. However, this study is applicable to any other pump with different power.

The existing relations between the two most important parameters in this kind of installations, the temperature of the subsoil and its thermal conductivity or the capacity of the ground to carry the heat, have been verified throughout this study. Knowing these relations, we have been able to connect the thermal conductivity with the total drilling depth, in this way the installation is defined.

The explained methodology has proved to be suitable to calculate the real values (given that the initial data are the temperature values measured "in situ") demanded for the calculation in installation which works with geothermal energy. In this sense, it is possible to apply the suggested method wherever we want and with geothermal pumps different to the ones used in this study.

In the future, the method will be applied to other areas with different types of grounds comparing the results with the ones obtained in the current manuscript.

Acknowledgments

Authors would like to thank the Department of Cartographic and Land Engineering of the Higher Polytechnic School of Avila, University of Salamanca, for allowing us to use their facilities and their collaboration during the experimental phase of this research.

References

[1] Asim Balbay, Mehmet Esen, Experimental investigation of using ground source heat pump system for snow melting on pavements and bridge decks, Sci. Res. Essays 5 (24) (2010) 3955–3966.
[2] Asim Balbay, Mehmet Esen, Temperature distributions in pavement and bridge slabs heated by using vertical ground-source heat pump systems, Acta Scientiarum-Technology 35 (4) (2013) 677–685.
[3] R. Philip Bevington, Keith Robinson, Data Reduction and Error Analysis for the Physical Sciences, 2nd Edition, WCB/McGraw-Hill, 1992.
[4] Pedro Casanova Pelaez, José Manuel Palomar Carnicero, Rafael López García, Fernando Cruz Peragon, Desarrollo de equipo para la realización de test de respuesta térmica del terreno (TRT) en instalaciones geotérmicas, Dyna 89 (2014) 316–324.
[5] A. Casasso, R. Sethi, Technology and potentiality of geothermal heat pumps, Geoing. Ambient. Mineraria 138 (1) (2013) 13–22.
[6] Yunus A. Cengel, Afshin J. Ghajar, Heat and Mass Transfer, Fundamentals and Applications, 2014.
[7] Mehmet Esen, Tahsin Yuksel, Experimental evaluation of using various renewable energy sources for heating a greenhouse, Energy Build. 65 (2013) 340–351.
[8] P. Eskilson, Thermal analysis of Heat Extraction Boreholes, PhD Thesis, Dept. of Mathematical Physics. University of Lund, 1987.
[9] Jean-Baptiste Joseph Fourier, Remarques Générales Sur Les Températures Du Globe Terrestre Et Des Espaces Planétaires, Ann. de Chimie de Physique 27 (1824) 136–167.
[10] Jean-Baptiste Joseph Fourier, Théorie analytique de la chaleur, 1822.
[11] Jean-Baptiste Joseph Fourier, Mémoire sur les températures du globe terrestre et des espaces planétaires, Mémoires l'Académie R. Sci. 7 (1827) 569–604.
[12] G. Hellstrom, Ground Heat Storage: Thermal Analyses of Duct Storage Systems, Dept. of Mathematical Physics. University of Lund, 1991.
[13] M. Kabar, W. Nowak, R. Sobanski, Principles of Exploitation Geothermal Energy Water at Targets of Heating Builgings Project KBN, 1999.
[14] K.C. Lee, Classification of geothermal resources by energy, Geothermics 30 (4) (2001) 431–442.
[15] W. Nowak, R. Sobanski, M.,M. Kabar, T. Kujawa, Systems of Recruiting and Exploiting the Geothermal Energy, Szczecin University of Technology, 2000.
[16] S.-C. Pei, M.-H. Yeh, Improved discrete fractional Fourier transform, Opt. Lett. 22 (14) (1997) 1047–1049.
[17] R. John Taylor, An Introduction to Error Analysis: the Study of Uncertainties in Physical Measurements, 2d Edition, University Science Books, 1997.
[18] Vaillant Group, Estimates for the Energy Needs of Each Home, 2010.
[19] B. Zheng, J. Xu, T. Ni, M. Li, Geothermal energy utilization trends from a technological paradigm perspective, Renew. Energy 77 (2015) 430–441.