Research Article

Down-Hole Heat Exchangers: Modelling of a Low-Enthalpy Geothermal System for District Heating

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In order to face the growing energy demands, renewable energy sources can provide an alternative to fossil fuels. Thus, low-enthalpy geothermal plants may play a fundamental role in those areas—such as the Province of Viterbo—where shallow groundwater basins occur and conventional geothermal plants cannot be developed. This may lead to being fuelled by locally available sources. The aim of the present paper is to exploit the heat coming from a low-enthalpy geothermal system. The experimental plant consists in a down-hole heat exchanger for civil purposes and can supply thermal needs by district heating. An implementation in MATLAB environment is provided in order to develop a mathematical model. As a consequence, the amount of withdrawable heat can be successfully calculated.

1. Introduction

The Directive 2009/28/CE—implemented in Italy in 2010—set ambitious targets in order to ensure a clean and sustainable future. Its aim is to reduce greenhouses gases emissions by 20%, to produce 20% of energy from renewable sources and to decrease the consumption by 20% improving the energy efficiency. These goals must be reached by 2020 [1].

The above-mentioned regulation led the public administrations and private stakeholders to investigate new technologies which may face the growing energy demands by the use of renewable sources alternative to fossil fuels. Thus, energy supply might change from being predominantly fossil fuelled to being fuelled by locally available sources. In this scenario, low-enthalpy geothermal plants for heating and cooling buildings can be successfully used [2].

Basically, ground source heat pump systems can be distinguished in two different types: earth-coupled or closed-loop and groundwater or open-loop. In the first case, heat exchangers are underground and located horizontally (known as GSHP, acronym for "ground source heat pump"), vertically (known as DHE, acronym for "down-hole heat exchanger") or obliquely. Heat is transferred from or to the ground thanks to a heat-carrying which circulates within the exchanger [2].

In the present paper, the use of DHE is taken into account. The exploitation of geothermal resources by DHEs is not characterized by mass withdrawal from the aquifer: more precisely, they permit heat transfer without extracting any fluid from the ground. This is to avoid the depletion of the aquifer, as requested by legislative restrictions. However, an important aspect has to be considered: the amount of withdrawable heat may be limited (usually less than 100 kW). This phenomenon is mainly due to the interaction between heat exchanger, well, and aquifer. As a consequence, DHEs are mostly used in small applications, such as buildings, greenhouses, and thermal baths [3, 4].

In order to increase vertical circulation of water and the natural mass transfer between aquifer and well, promoters can be used [5]. The exchangers consist in pipes or tubes which are located within the well. Because of the low capacity, these systems are successful up to 150 m of depth. Several designs are nowadays available but the most common one is a U-tube which extends to near the bottom of the well. Multiple tubes can be alternatively used [6].

Several studies were carried out in the past and led to the reconstruction of the stratigraphy, the evaluation of heat flow, the probable origin of hot waters and the chemical properties of gas and hydrothermal emissions. Della Vedova et al. developed a new heat flow map as shown in Figure 1: it can be seen how the highest values (red and orange areas) are mostly located in the Tyrrhenian Sea and in Central Italy (western coastline, especially in Tuscany and northern Latium) [7].

In the province of Viterbo hydrogeological settings and shallow groundwater basins seem to be particularly suitable for a wide implementation of DHE systems. Moreover, performances of geothermal heat pumps are significantly limited since groundwater basin temperatures vary from 40°C up to 90°C. Thus, their use is not recommended and implemented in the area.

The province of Viterbo is located in northern Latium and hosts several thermal springs in its territory. They had been already known by Romans who used them for therapeutic purposes. Bullicame Spring is one of the most famous hydrothermal source and is even mentioned by the poet Dante Alighieri. Nowadays, thermal waters are exploited for direct use or to supply spas and pools. Figure 2 shows the location of Viterbo hydrothermal area (dotted circle) within the regional geological picture. The investigated area lies between the Tyrrhenian coastline and the Apennines. From a geological point of view, the region is characterized by sedimentary basins belonging to the upper Miocene-Pleistocene age, elongated between ridges of Mesozoic-Paleogene rocks, which overlay a Paleozoic-Triassic metamorphic basement. Within this geological framework, Cimini volcanic complex consists of quartzolatitic domes and ignimbrites and lavas. The Vico complex is characterized by explosive activity and is a typical stratovolcano. The substrate beneath them is made of sedimentary rocks [8].

The province of Viterbo is characterized by overlapped interacting aquifers. More precisely, the shallow volcanic aquifer has fresh waters which come from the area around Cimini Mountains. It is limited at the bottom by the semiconfining marly-calcareous-arenaceous complex and low-permeability clays. Vertical upflows of thermal waters—consisting in sulphate-chloride-alkaline-earth type and gases—occur westwards of Viterbo.
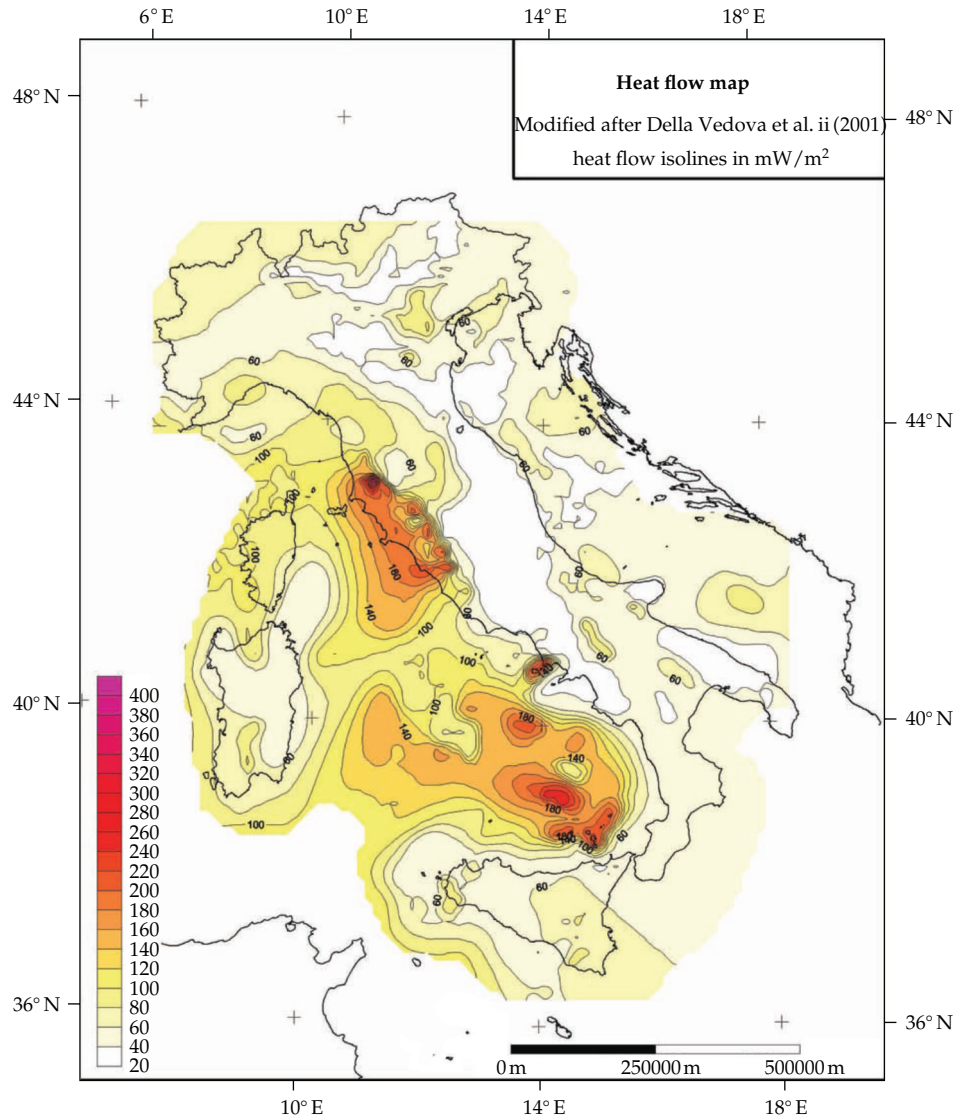
Figure 1: Heat flow map in Italy [7].

This phenomenon is mainly due to the uplifted carbonate reservoir, the limited thickness of the semiconfining layer, and the high local geothermal gradient. Hot waters are characterized by temperatures varying between 30 and 60°C thanks to the deep circulation in carbonate rocks. The minimum upward flow is $0.1\,\mathrm{m}^3/\mathrm{sec}$. Springs and deep wells are fed by it [8].

An appropriate interpretation of the stratigraphy is successfully reached by drilling wells. Moreover, it can be correlated to surface geology in order to get the reconstruction of the hydrostratigraphy of the thermal area. Formations of Cimini and Vico complexes occur from the first 10 m down to 100 m. The shallow unconfined aquifer consists in these rocks and its thickness decreases where there are more layers of travertine. Plio-Pleistocene deposits lie beneath the volcanic aquifer and marly-calcareous-arenaceous flysh occurs below them [8].
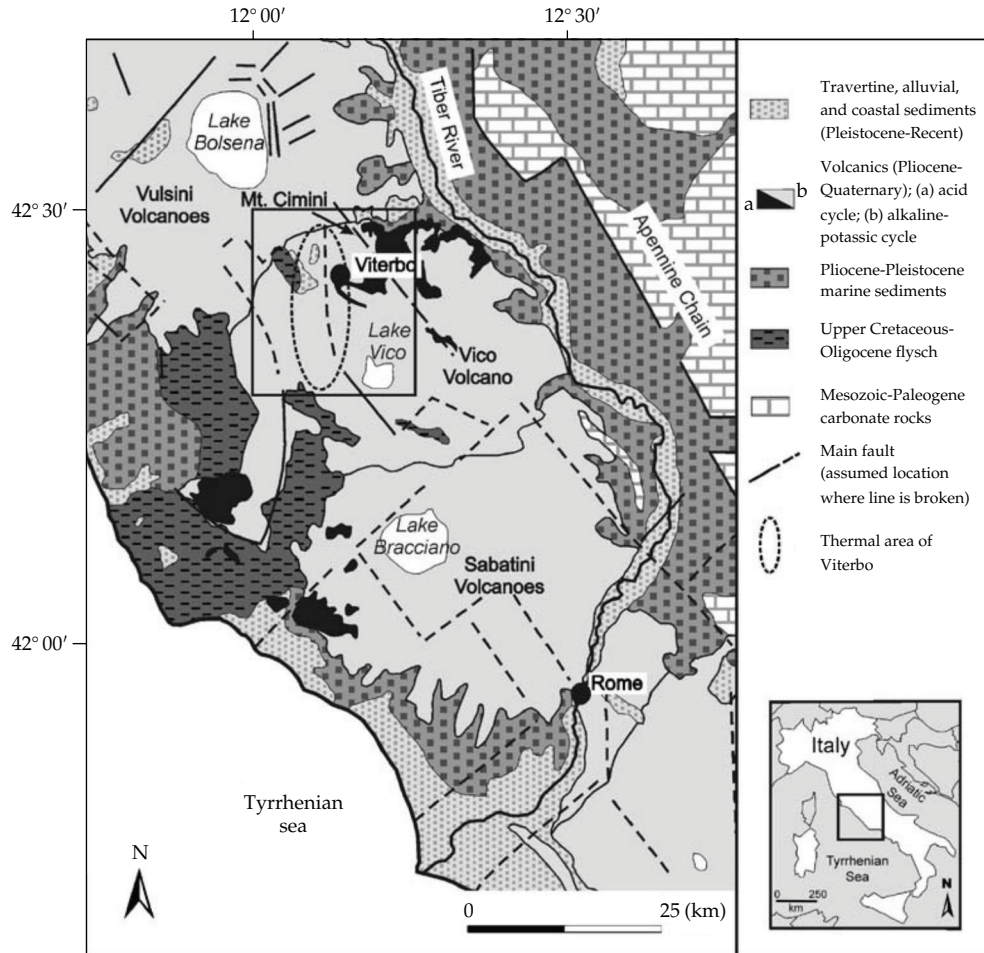
Figure 2: Viterbo Hydrothermal area within the regional geological picture [8].

A high concentration of wells and thermal springs occurs in the central area of the province of Viterbo. Data—such as elevation, discharge, and temperature—are available. With specific regard to the most important thermal springs in the province, the data are given in Table 1 [8].

The aim of the present paper is to exploit the heat coming from a low-enthalpy geothermal plant for civil purposes, that is, district heating, as shown in Figure 3. In order to evaluate the withdrawable amount of heat, an implementation in MATLAB environment is developed. The goal is reached using real data which have been obtained by specific measurements *in situ*.

2. Models and Methods

The experimental plant is located in the central thermal area of Figure 2 and has been provided by Mr. Daniele Cortese, who owns the company "Plants and Bulbs". Since regulations discourage the drilling of new wells, an existing one is chosen to develop the

Table 1: Data of the main thermal springs in the province of Viterbo [8].

Spring or group of springs	Name	Elevation (m a.s.l.)	Discharge (l/s)	Temperature (°C)
3	Bagnaccio	310–390	10	38–64
4	Monterozzo	305–319	5	27–51
7-8	Zitelle	289–308	6.5	39–65
9	Carletti	285	1.5	57
10	Bullicame	298	10.4	57
17	S. Cristoforo	245	0.1	53
21	S. Sisto	230	3	57
26	Bacucco	315–320	2	36–49
27	Urcionio	305–319	20	28–60
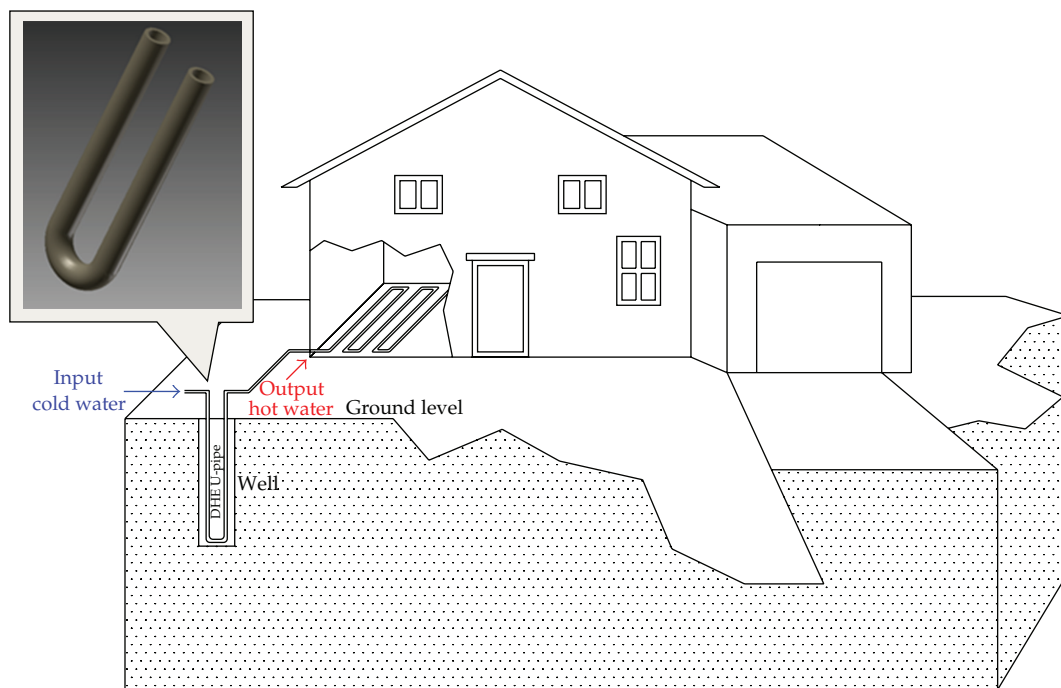
Figure 3: Low-enthalpy geothermal plant for civil purposes.

system. Moreover, the well is linked to the volcanic aquifer which is characterized by low hydraulic gradients and lays between swampy deposits and travertine. The local substratum is more than 50 m deep and consists in marly-calcareous-arenaceous complex [8].

The low-enthalpy geothermal system can be easily drafted as a reservoir which contains hot water and a pipe. Measurements of temperature in the groundwater basin were carried out at different depths: 2, 22, and 44 m, respectively. The temperature inside the well can be considered as constant and equal to 60°C, since the range of its variability is limited. According to the drilling log, the well is 60 m deep below the ground level. Its diameter is 150 mm and reaches the bottom of the aquifer. Moreover, a steel flanged pipe is located on the top of the well in order to contain the upflow water, which is generated by gases pressure

(a)   (b)
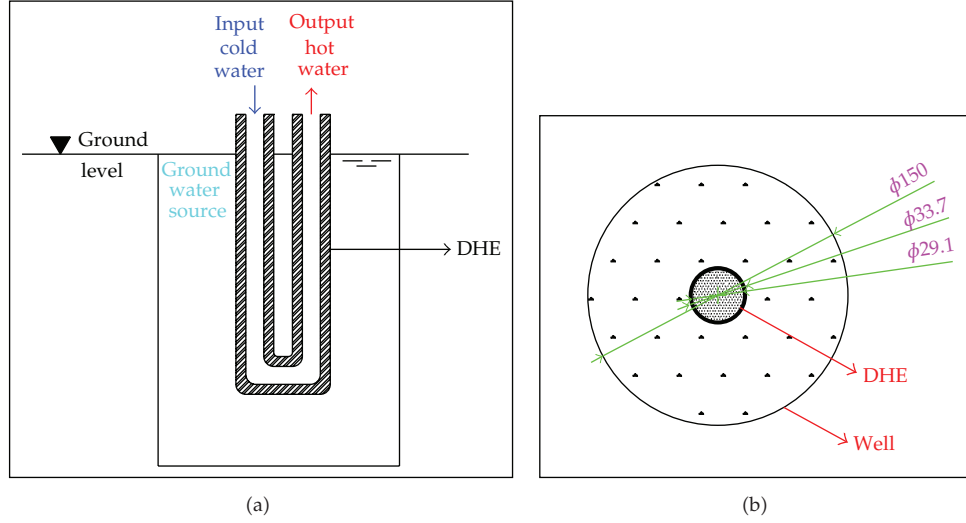
Figure 4: Schematic model (a) and size of the heat exchanger within the well (b).

and reaches 1.5 m above ground level. The heat exchanger consists in a vertical single U-pipe, as shown in Figure 4: the internal and external diameters are 29.1 mm and 33.7 mm, respectively and the total length is 110 m. The pipe is made of steel and its thickness is 4.6 mm. Three different modes of heat transfers occur: natural convection in the ground water basin, conduction within the wall of the pipe, and forced convection inside the heat exchanger. The latter is due to the pumping of water. The groundwater within the well is characterized by convective motions which are due to differences of density and consequently cause heat transfers [9].

In order to evaluate the total amount of withdrawable heat using the above-described system, an implementation in MATLAB is developed. The overall heat transfer rate Q is formally represented by [9–11]

$$Q = A \cdot U_D \cdot \Delta T_{\mathrm{LM}}, \tag{2.1}$$

where A: overall heat exchange area (m^2); U_D: overall heat transfer coefficient (W/m^2/K); ΔT_{LM}: logarithmic mean temperature difference (K). U_D can be successfully calculated using the following formula [9–11]:

$$\frac{1}{U_D} = \frac{1}{h_{i0}} = \frac{d_{\mathrm{ext}}}{2k} \cdot \mathrm{Ln}\left(\frac{d_{\mathrm{int}}}{d_{\mathrm{ext}}}\right) + \frac{1}{h_{e0}} + R, \tag{2.2}$$

where h_{i0}: heat transfer coefficient inside the pipe (W/m^2/K); h_{e0}: heat transfer coefficient in the groundwater basin (W/m^2/K); d_{ext}: external diameter of the pipe (m); d_{int}: internal diameter of the pipe (m); k: thermal conductivity of the wall (W/m/k); R: fouling factor (dimensionless).

The second term in the definition of U_D is related to conduction but can be neglected since the thickness of the tube is limited. Moreover, k results from the type of material and R is tabulated depending on type of fluid, heat exchangers, and temperature. Figure 5 shows
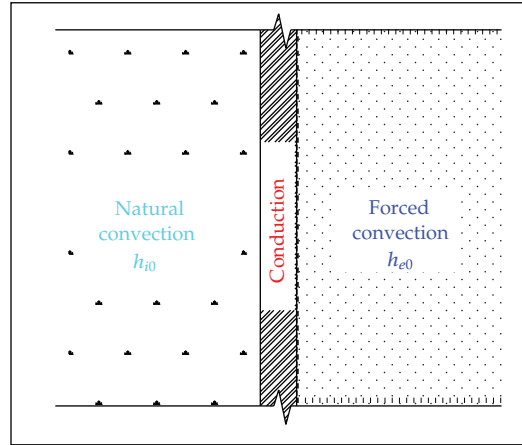
Figure 5: Heat transfers and heat transfer coefficients.

a schematic model with the different modes of heat transfers and the heat transfer coefficient related to them [12–15].

MATLAB is a high-level language and interactive environment which enables you to perform numerical computations and intensive tasks. It is an abbreviation for "MATrix LABoratory" and is designed to operate primarily on matrices and arrays [16].

With specific regard to the above-described plant, an implementation in MATLAB allows to develop a mathematical model for the DHE in the shallow groundwater basin. The model results from measurements *in situ* so that it is possible to evaluate its quality, repeatability, and use in other areas [17–24].

In (2.2), h_{i0} can be calculated using Reynolds number and the heat transfer coefficient J_h which depends on fluid motion conditions inside the pipe. The so called "laminar flow" occurs when Reynolds number is less than 2100. When its value is higher than 10000, the flow becomes "turbulent". If it is in the range between 2100 and 10000, the motion is in transition conditions. Furthermore, Reynolds number is related with water speed inside the heat exchanger. The latter can be easily calculated using the values of flow rate at the entrance of the pipe and the cross section. h_{e0} depends on several parameters—such as the density of the fluid in the groundwater basin and the coefficient of thermal expansion—which result from the temperature of the film (T_{film}) between the thermal water and the wall of the heat exchanger. Thus, (T_{film}) is linked to the water temperature inside the well (T_{ext}) and the temperature of the wall (T_{wall}). (T_{wall}) is obtained using ($T_{\text{m,fluid}}$) (mean temperature of the fluid in the pipe) and (T_{ext}). In order to calculate ($T_{\text{m,fluid}}$) the values of water temperature at the beginning (T_{in})—which is known—and at the end (T_{out}) of the tube are required [9, 10]. The mean temperature profile within the pipe (**Figure 6**) can be defined by the following equation:

$$T_{\text{out}}\,(x) = T_{\text{ext}} - (T_{\text{ext}} - T_{\text{in}}) \cdot \exp\left(\frac{p \cdot U_{\text{D}}}{m \cdot C_p} \cdot x \right), \tag{2.3}$$
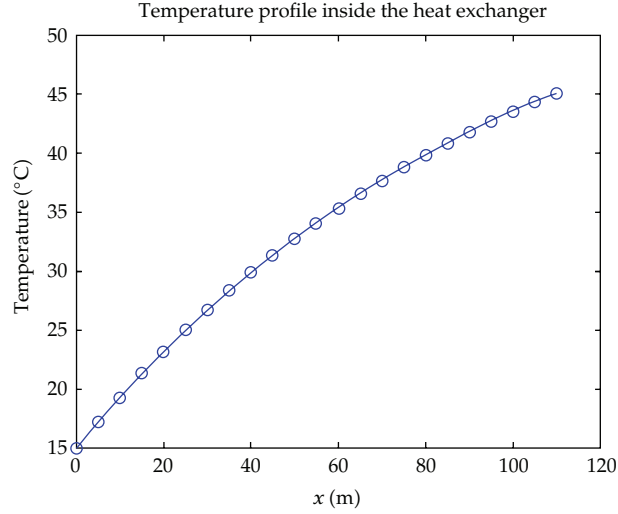
Temperature profile inside the heat exchanger

Figure 6: Temperature profile of the water within the heat exchanger.

Table 2: Output values.

Output	
Re	34543
$T_{m,\text{fluid}}$	30
T_{wall}	31
T_{film}	45.5
T_{out}	45
h_{i0}	4269
J_h	137.61
h_{e0}	146
U_D	138
A	11.65
ΔT_{LM}	27.31
Q	43386

where T_{ext} water temperature inside the well (K); T_{in}: water temperature at the beginning of the pipe (K); P: perimeter (m); m: flow rate (m^3/sec); c_p: specific heat at constant pressure (joule/kg/K).

Since T_{out} depends on U_D which results from h_{i0} and h_{e0}, an iteration loop is developed in MATLAB: an initial value for T_{out} and h_{e0} is adopted and the iteration process continues until the convergence is reached.

3. Results and Discussions

The results in Table 2 are given by the implementation in MATLAB environment.

The low-enthalpy geothermal system can be successfully used for civil purposes, such as district heating, which provides energy to supply thermal needs. The total energy demand to heat a building depends on the so called "heat degree days", whose acronym is "HDDs".

Figure 7: Heating degree day map in Italy according to [25].

The heating requirements for a given structure at a specific location are considered to be directly proportional to the number of HDDs at that location. HDDs are defined relative to a base temperature which is the outside temperature above which a building does not need heating. In order to evaluate HDDs, an approximation method is to take the average temperature on any given day and to subtract it from the base temperature. If the value is less than or equal to zero, that day has zero HDDs; if the value is positive, that number represents the number of HDDs on that day. Thus, only the positive differences of temperature must be considered. HDDs are calculated as follows:

$$\text{HDD} = \sum_{i=1}^{\text{nhd}} (T_0 - T_i), \tag{3.1}$$

where i: value varying from 1 to the number of heating days nhd; T_0: base temperature (°C); T_i: mean daily external temperature (°C).

According to the value given by (3.1), Italy is divided into six different areas—from "zone A" (the hottest one) to "zone F" (the coldest one), as Figure 7 shows. More precisely, HDD increases when the climate becomes colder. Viterbo belongs to "zone D" [25].

Table 3: Area heated by the down-hole heat exchanger in the experimental plant.

Classes of buildings	Energy supply (W/m^3)	Area heated by DHE (m^2)
A	10	1446
B	15	964
C	20	723

The total amount of withdrawable heat Q—which comes from the implementation in MATLAB—leads to the determination of the thermal needs of a specific building. Buildings can be distinguished in seven classes considering the level of consumption of primary energy. Since the energy supply to heat the house is known for each class, the area —which can be heated by the DHE in the experimental plant—can be calculated. The results are shown in Table 3 and are referred to the lowest consumption buildings.

4. Conclusion

The mathematical model—provided by the useful implementation in MATLAB environment—leads to the evaluation of withdrawable heat using a DHE in a low-enthalpy geothermal plant. As a consequence, the thermal needs, supplied by the system, can be calculated. As it can be seen in Table 3, buildings of different sizes can be heated by low-temperature systems, such as radiant floors or thermoconvectors. The surface area depends on the energy class: 1446 m^2—which approximately corresponds to 14 flats, 100 m^2 each—can be heated if the building belongs to class A. The amount of surface —heated by DHE— decreases from class A to class C. In the latter case, it is equal to 723 m^2.

Moreover, other situations can be easily considered in the model by simply changing the input data, such as geometry of the heat exchangers (d_{int}, d_{ext} and L), T_{in}, or considering the variability of T_{ext} in the well.

It is important to underline that the implemented model can be successfully used in those areas where shallow thermal ground basins occur and if their temperature is close to 60°C. Furthermore, the result of modelling is a correct sizing of DHEs for civil purposes, that is district heating.

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