DETERMINATION OF THE THERMAL CHARACTERISTICS OF THE GROUND IN CYPRUS AND THEIR EFFECT ON GROUND HEAT EXCHANGERS

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

Since the ancient years, human beings were using holes and caves to protect themselves from weather conditions making it the first known form of exploiting ground's heat, known as Geothermal Energy. Nowadays, geothermal energy is mainly used for electricity production, space heating and cooling, Ground Coupled Heat Pump (GCHP) applications, and many other purposes depending on the morphology of the ground and its temperature.

This study presents results of investigations into the evaluation of the thermal properties of the ground in Cyprus. The main objectives were i) to determine the thermal characteristics of the ground in Cyprus, ii) investigate how they affect the sizing and positioning of Ground Heat Exchangers (GHE) and iii) present the results for various ground depths, including a temperature map of the island, as a guide for engineers and specifiers of GCHPs. It was concluded that there is a potential for the efficient exploitation of the thermal properties of the ground in Cyprus for geothermal applications leading to significant savings in power and money as well.

Six new boreholes were drilled and two existing ones were used for the investigation and determination of i) the temperature of the ground at various depths, ii) its thermal conductivity, iii) its specific heat and iv) its density. The thermal conductivity was determined by carrying out experiments using the line source method and was found to vary in the range between 1.35 and 2.1 W/mK. It was also observed that the thermal conductivity is strongly affected by the degree of saturation of the ground.

The temperature of the undisturbed ground in the 8 borehole locations was recorded monthly for a period of 1 year. The investigations showed that the surface zone reaches a depth of 0.25 m and the shallow zone 7 to 8 m. The undisturbed ground temperature in the deep zone was measured to be in the range of 18.3 °C to 23.6 °C and is strongly dependent on the soil type. Since the ground temperature is a vital parameter in ground thermal applications, the temperature of the ground in locations that no information is available was predicted using Artificial Neural Networks and the temperature map of the island at depths of 20 m, 50 m and 100 m was generated. Data obtained at the location of each borehole were used for the training of the network.

Data for the sizing of GHEs based on the ground properties of Cyprus were presented in an easily accessible form so that they can be used as a guide for preliminary system sizing calculations. With the aid of Computational Fluid Dynamics (CFD) software the capacity of the GHEs in each location and the optimum distance between them was estimated. Additionally, the long term temperature variation of the ground was investigated.

For the first time since a limited study in the 1970's, a research focusing on the determination and presentation of the thermal properties of the ground in Cyprus has been carried out. Additionally, the use of Artificial Neural Networks (ANNs) is an innovative approach for the prediction of data at locations where no information is available. The publication of this information not only contributes to knowledge locally but also internationally as it enables comparison with other countries with similar climatic conditions to be carried out.

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Declaration

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

Publications for this PhD research

- Florides, G., Pouloupatis, P. D., Kalogirou, S., Messaritis, V., Panayides, I., Zomeni, Z., . . . Koutsoumpas, K. (2013). Geothermal properties of the ground in Cyprus and their effect on the efficiency of ground coupled heat pumps. Renewable Energy, 49, 85-89.
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- Florides, G. A., Pouloupatis, P. D., Kalogirou, S., Messaritis, V., Panayides, I., Zomeni, Z., . . . Koutsoumpas, K. (2011). The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus. Energy, 36(8), 5027-5036.
- Pouloupatis, P. D., Florides, G., & Tassou, S. (2011). Measurements of ground temperatures in Cyprus for ground thermal applications. Renewable Energy, 36(2), 804-814.

Other publications related to the research

- Florides, G. A., Christodoulides, P., & Pouloupatis, P. (2013). Single and double U-tube ground heat exchangers in multiple-layer substrates. Applied Energy, 102, 364-373.
- Florides, G., Theofanous, E., Iosif-Stylianou, I., Tassou, S., Christodoulides, P., Zomeni, Z., . . . Panayiotou, G. (2013). Modelling and assessment of the efficiency of horizontal and vertical ground heat exchangers. Energy, 58, 655-663.
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Finally, I would be arrogant and selfish if I do not dedicate this thesis to my family and parents who stood by me all these years expressing my appreciation and many thanks in this way.

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Nomenclature

∞	Infinity symbol
COP	Coefficient Of Performance of a heat pump
Cp	Specific heat (KJ/kgK)
D	Diameter (m)
D_{eq}	Equivalent diameter (m)
E_1	Exponential integral
EER	Energy Efficiency Ratio of a heat pump
ln(t)	Natural logarithm of time
L_s	Center-to-center distance between the tubes of a GHE (m)
PE	Polyethylene pipe
PN	Pipe Nominal Pressure grade (bar)
q_c	Constant heat injection rate per active length of borehole (W/m)
r	Radius (m)
R_b	Effective borehole thermal resistance (mK/W)
r_b	Radius of the borehole (m)
SDR	Standard Dimension Ratio of a pipe (outside diameter over pipe wall thickness)
t	Time (s)
$T_{(r,t)}$	Ground temperature at distance, r, from a line source after a time period, t, (˚C)
$T_{(t=0)}$	Initial temperature of the ground (˚C)
T_b	Temperature at the boundary of a borehole (˚C)
T_f	Temperature of fluid (˚C)
$T_{f(t)}$	Mean fluid temperature flowing in a GHE (˚C)
T_{fin}	Inlet fluid temperature flowing in a GHE (˚C)
T_{fout}	Outlet fluid temperature flowing in a GHE (˚C)
u	Integration variable (unitless)
α	Thermal diffusivity (m^2/s)
$\alpha t/r^2$	Dimensionless time-to-pipe ratio parameter
γ	Euler's constant = 0.5772
λ	Thermal conductivity (W/mK)
π	Mathematical constant ≈ 3.14159
ρ	Density (Kg/m^3)

Chapter 1: Introduction

Since ancient times, human beings observed that during the cold months of the year the ground temperature was higher than that of the ambient air and during the warm months, lower. The exploitation of this phenomenon and of the thermal properties of the ground is known as Geothermal Energy. Since then and following technological evolution, geothermal energy in its broad sense, has mainly been used for electricity production, space heating and cooling, Ground Coupled Heat Pump (GCHP) applications, industrial, agriculture and many other purposes depending on the properties of the ground layers and their temperature.

Geothermal energy is considered a sustainable and renewable energy source. It mainly depends on the climatic conditions of the specific location (solar radiation, mean yearly temperature, wind, rainfall, surface cover etc), the formation of the ground and its thermal characteristics, degree of saturation and geothermal gradient. Geothermal energy can minimise the use of fossil fuels and lead to reductions in pollution and greenhouse gas emissions. Also, it can lead to a reduction in the dependence of a country on imported fuel. The direct use of geothermal energy is the most common application and is usually used for the heating or cooling of buildings or for water heating purposes.

The Energy Service of the Ministry of Energy, Commerce, Industry and Tourism of Cyprus has the overall responsibility of energy matters in Cyprus, including the promotion of Renewable Energy Sources (RES). Since 2006, GCHP applications have been funded through a very generous grant scheme designed to encourage the use of RES technologies.

Partasides *et al.* (2011) reported that from evaluations of the installed geothermal systems in Cyprus, it was identified that they could offer energy savings of 40-70% for cooling and heating, depending on the size of the building and the thermal loads compared to conventional heating and cooling systems. It was also pointed out, however, that the lack of reliable information on the thermal properties of the ground in Cyprus was the main barrier in the design and application of energy efficient geothermal systems.

The knowledge of the thermal properties of the ground at the design stage assists in the correct sizing of a Ground Heat Exchanger (GHE). The Thermal Response Test (TRT) is mainly used for the in-situ determination of the thermal properties of the ground. Although, this method is relatively easy to apply and is used by many researchers to model and evaluate the response of a GHE, it is also an expensive and time consuming method to implement.

This research presents results of investigations into the evaluation of the thermal properties of the ground in Cyprus and in particular the undisturbed temperature of the ground, and thermal conductivity, specific heat and density of each type of material encountered in various locations. For the first time this information is made available in a relatively complete and reasonably accurate database. In addition, the ground temperature map of Cyprus at various depths has been established. Data for the sizing of GHEs based on the ground properties of Cyprus are also made available and can be used as a guide for preliminary system sizing calculations.

The innovation of the thesis focuses on the determination and presentation of the thermal properties of the ground in Cyprus. Additionally, it gives emphasis on the generation of the ground temperature map of Cyprus at various depths by using Artificial Neural Networks (ANNs) for the prediction of the ground temperature at locations where no information was previously available. The publication of this information not only contributes to knowledge locally but also internationally as it enables comparison with other countries with similar climatic conditions.

1.1 Main aim and objectives

The main aim of this study was to determine the thermal characteristics of the ground in Cyprus in order to investigate how they affect the sizing and positioning of Ground Heat Exchangers (GHEs) and to present the results, including a temperature map of the island at various depths as a guide for engineers.

To achieve the main aim of the study, the following specific objectives were set:

i. To estimate the temperature, thermal conductivity, specific heat and density of the ground in representative locations in Cyprus by applying established methods.

This objective is vital for the achievement of the main aim since the information collected is useful for the preparation of the temperature map of Cyprus and the determination of its influence on the sizing and positioning of GHEs.

The geology of the island and a review of the established methods to determine the thermal properties are presented. Boreholes in representative locations were drilled to analyse the formation of the ground and measure the thermal conductivity, specific heat and density of each type of material. To estimate the overall thermal conductivity of each borehole, the thermal response test was used. For this, U-tube ground heat exchangers of various hose diameters and lengths were installed in each of the boreholes. Also, the undisturbed ground temperatures in each of the boreholes at various depths were recorded for period of 12 months. For this, thermocouples were installed in each of the boreholes.

ii. To present the collected data in an easy accessible and distinctive form.

It is very important that all the data collected are presented in a comprehensible form and be easily accessible. In this way engineers can have access to a library of data related to the sizing and positioning of GHEs. Therefore, for each of the boreholes the recorded ground temperatures at various depths were plotted and the thermal properties of the characteristic ground types tabulated.

iii. To prepare the temperature map of Cyprus at various depths.

The availability of ground temperature map of Cyprus at depths of 20 m, 50 m and 100 m is very important for sizing and positioning of GHEs. Since the data collected were limited, additional data were generated using Artificial Neural Networks (ANNs) to predict the ground temperature at locations where no information was available. Various factors that could affect the temperature of the ground were considered in the training of the ANNs and the relevance of each factor was established.

iv. To examine how the ground data affect the sizing and positioning of GHEs and to determine the long term temperature variations of the ground.

A main objective of the project is to provide engineers with a useful guide for sizing and positioning GHEs in Cyprus. This will be achieved through the investigation of the influence of the temperature, thermal conductivity, specific heat and density of the ground as well as pipe diameter on the performance of GHEs using Computational Fluid Dynamics (CFD) modelling in conjunction with test data.

1.2 Structure of thesis

In Chapter 2, a general review of the geothermal energy and its exploitation is presented. The thermal properties of the ground, the factors affecting them and the calculation models developed by previous studies for their prediction are examined. A brief description of the share of geothermal energy in the world's renewable energy production is given, including the potential of geothermal energy in Cyprus.

A more detailed analysis of the thermal properties of the ground and the factors affecting the design of GHE follows in Chapter 3. The line source method, the cylindrical heat source method and the devices usually used for carrying out a Thermal Response Test (TRT) are described. The geology of the island is described and the selection of representative locations for drilling test boreholes is outlined.

Chapter 4 describes the methods, equipment used and findings related to the investigation of the temperature profile of the ground in Cyprus. Results such as the daily and monthly ground temperature distribution for each borehole location are presented graphically. Comparison of the findings with past data is also presented.

In Chapter 5, the ground temperatures recorded in Chapter 4 along with other useful data are used for the generation of the ground temperature maps of Cyprus at depths of 20 m, 50 m and 100 m using Artificial Neural Networks (ANNs). The information generated is presented in a unique way so that it is easily accessible by engineers and other interested parties.

Chapter 6 considers the factors affecting the sizing of GHEs. Using the data collected from the selected boreholes (temperature, thermal conductivity, specific heat and density of the ground) along with the pipe diameter and with the aid of Computational Fluid Dynamics (CFD) software the capacity of the GHEs in each location was estimated. Additionally, the optimum distance between GHEs and the long term temperature variation of the ground is examined. The results are tabulated and can be used as a guide for engineers designing GHEs despite the fact that some of them still need validation.

The most important conclusions arising from this study and future work are discussed in Chapter 7.

Chapter 2: Literature review

2.1 Introduction

Since the ancient times, human beings like all other living organisms on the planet were using holes and caves to protect themselves from weather conditions. Not only did they used the ground itself as a heat barrier to protect themselves against the rainfall and wind but also were exploiting the residual ground heat to keep themselves warm during the cold days of the year. Additionally, during the warm months, they were protected from solar heat and were using the lower temperature of the earth to cool themselves. This was the first known form of exploitation of the thermal properties of the ground.

Nowadays, the capacity of the ground to store heat is most widely known as Geothermal Energy. According to ASHRAE Handbook (2011), 'Geothermal energy is the thermal energy within the earth's crust'. This thermal energy exists in the rocks in depths up to 50 km on land and up to 30 km in the oceans and is also transferred in the fluids that fill the pores and fractures within them. The fluids usually in the form of water, steam or water containing large amounts of dissolved solids come to the surface naturally through the open spaces in the rocks. Where rock permeability is low, the energy extraction rate is low.

Geothermal energy is mainly used for electricity production or direct use depending on the properties of the ground layers and the temperatures produced. The following classification by temperature is used in the geothermal industry (ASHRAE Handbook, 2011):

High temperature, $t > 150°C$
Intermediate temperature, $90°C < t < 150°C$
Low temperature, $t < 90°C$

For electricity production high ground temperatures are required. Areas with such capacities are not easy to exploit mostly because of the difficulty to be connected to the grid.

On the other hand, direct use of geothermal energy is possible in areas where the thermal capacity of the ground takes place in intermediate or low ground temperatures. According to data presented by Lund *et al.* (2010) in the paper "Direct utilization of Geothermal Energy 2010 Worldwide Review" at the World Geothermal Congress 2010 (WGC2010), Geothermal Energy is directly used in 78 countries, 36 of them in Europe. The estimated installed thermal power for direct utilization at the end of 2009 was 50583 MWt while the thermal energy used is approximately 121696 GWh/year. 49% of this thermal energy is used in Ground Source Heat Pump (GSHP) applications, 24.9% for bathing and swimming, 14.4% for space heating, of which 85% is for district heating, 5.3% for greenhouse and open ground heating and the remainder for industrial process heating, aquaculture pond and raceway heating, agriculture drying, snow melting and cooling.

2.2 Ground thermal properties

The ground temperature varies with depth and is affected by the weather conditions. It is higher than that of the ambient air during the cold months of the year and lower during the warm months. At the surface, the ground is affected by short term weather variations, changing to seasonal variations as the depth increases. At the deeper layers ground temperature remains almost constant throughout the seasons and years.

Surface layer temperature varies with solar radiation, ambient temperature, wind, rain and vegetation or surface cover. Below 1 m depth and up to 8–20 m (depending on the saturation of the ground), the temperature variation is reduced and is affected by the seasonal changes only (shallow layer), while for the deeper layers the variation in the temperature is almost negligible, tending to be warmer than the ambient temperature in winter and cooler than the ambient temperature in the summer, Popiel *et al.* (2001).

Florides and Kalogirou (2005) carried out an experiment at the Athalassa area in Cyprus and discussed the factors affecting ground temperature and the temperature variation with depth. It was found that the daily temperature variations in winter only reach up to a depth of approximately 0.5 m. The temperature variation of the ground at a depth of 3 m during the year was between 15 °C to 25 °C while at a depth of 25 m the temperature remained constant at about 22 °C. The temperature measurements were also compared to calculated values using the Kasuda formula adopted by the TRNSYS program, type 501. Measured and calculated temperatures showed good agreement. A factor that can have an influence on the accuracy of simulated ground temperatures are the physical properties of the undisturbed ground which can vary from location to location.

Solar radiation is probably the most important factor affecting the temperature of the ground at the surface and shallow zones. Other climatic conditions like the wind and rain are also important. The temperature of the ground at the deeper layers is mostly affected by the structure and physical properties of the soil with the thermal conductivity being the most important. The rate of heat flow in the ground is called thermal diffusivity and is defined as the ratio of the thermal conductivity to the thermal capacity of the ground, Hepbasli et al. (2003). Another important property of the ground is the geothermal gradient which is a measure of how rapidly the temperature increases at constant heat flow and is a function of the ground thermal conductivity. Ground layers with low thermal conductivity result in higher geothermal gradients and vice versa, Kelley (2005). The thermal properties of various soil types are presented in Table 2.1 below.

Table 2.1: Thermal properties of various soil types at 20°C, ASHRAE Handbook (2011)

Soil type	Thermal conductivity (λ) (W/mK)	Dry density (ρ) (Kg/m^3)	Thermal diffusivity (α) (m^2/day)
Heavy clay, 15% water	1.4 – 1.9	1925	0.042 – 0.061
Heavy clay, 5% water	1.0 – 1.4	1925	0.047 – 0.061
Light clay, 15% water	0.7 – 1.0	1285	0.055 – 0.047
Light clay, 5% water	0.5 – 0.9	1285	0.056 – 0.056
Heavy sand, 15% water	2.8 – 3.8	1925	0.084 – 0.11
Heavy sand, 5% water	2.1 – 2.3	1925	0.093 – 0.14
Light sand, 15% water	1.0 – 2.1	1285	0.047 – 0.093
Light sand, 5% water	0.9 – 1.9	1285	0.055 – 0.12
Granite	2.3 – 3.7	2650	0.084 – 0.13
Limestone	2.4 – 3.8	2400 – 2800	0.084 – 0.13
Sandstone	2.1 – 3.5		0.65 – 0.11
Shale, wet	1.4 – 2.4	2570 – 2730	0.065 – 0.084
Shale, dry	1.0 – 2.1		0.055 – 0.074

The structure and moisture content of the ground in the Athalassa region in Nicosia was examined by Florides and Kalogirou (2004). The ground is mainly formed by calcareous sandstone and marl (details on the soil type are given in Appendix 4). Clay layers contain about 30% of water (by mass) while layers below the water table which starts at 15 m, contain about 50% of water (by mass) and has a discharge of about 2-3 m^3/h. The mean density of the undisturbed ground is about 1900 kg/m^3 and the mean specific heat capacity is about 1400 J/kg K.

Similarly, boreholes in the Agia Fyla, Agios Georgios and Saittas regions were examined by Pouloupatis et al. (2009). In the region of Agia Fyla the ground is mainly hardcore material consisting of marl, chalk and gravel. In the Agios Georgios region the ground consists of red soil, silty sand with gravels and yellow and green marl. The structure of the ground in the Saittas region is top soil up to 8 m depth and the rest, up to 178 m is diabase.

2.3 Prediction of ground temperature

For the prediction of the ground temperature behaviour several calculation models have been developed by a number of researchers. Kusuda and Achenbach (1965) presented a simplified formula describing the temperature distribution in the ground. According to that formula, the temperature of the ground is affected by the time of the year; the depth and the thermal diffusivity of the ground. Williams and Gold (1976) used this simplified formula to estimate the range of ground temperatures in Canada. For their calculations they assumed the effect of factors such as solar radiation, wind, rain, snow and water content, cancelled each other out so that the temperature variation of the ground could be estimated by using the variation of the ambient temperature only. This showed ground surface temperature to be very close to that of the ambient air, decreasing with depth. For depths below 5-6 m, ground temperature tended to stabilise with a geothermal gradient of 1 °C per 50 m depth. The variation of ground temperature occurred with time lag in relation to ambient temperature reaching a 6 month lag for a 5 m depth.

Similarly, Florides and Kalogirou (2005) identified a time lag of about 160 days between the highest temperature on the ground surface and the ground temperature at 3 m depth in their tests at the Athalassa area of Cyprus. The temperature measurements were compared to the calculated values resulted from simulations performed with TRANSYS, showing general agreement.

For the prediction of the daily and annual variation of the ground surface temperature, a model based on the transient heat conduction differential equation using the energy balance equation at the ground surface as a boundary condition, was presented by Mihalakakou *et al.* (1997). The convective energy exchange between air and soil, the solar radiation absorbed by the ground surface, the latent heat flux due to ground surface evaporation and the long wave radiation were the main parameters used in the model. The model results were compared with measured temperatures of bare and short-grass covered ground in Dublin and Athens for the period 1981 to 1990. The comparison of the predicted set of data with the measured sets, showed a very good agreement. The sensitivity of the ground temperature to different energy balance factors was also studied.

The results of numerical simulations of ground temperature distribution are not always reliable, especially when inaccurate ground property data are used. For this reason, Popiel *et al.* (2001) examined the accuracy of a simple semi-empirical formula proposed by Baggs (1983), for Australian climate conditions. The formula is based on the transient heat conduction equation in a semi-infinite solid with the exposed surface temperature varying periodically with time. Factors like structure and physical properties of the ground, surface cover, air temperature and humidity, wind, solar radiation and rainfall are taken into consideration. The ground temperature distribution for Poznan, a city in Poland, was calculated using the above formula and was compared with the temperature distribution in the ground, measured for two different ground surfaces; for a car park area up to a depth of 7 m and for a lawn area up to a depth of 17 m. The calculated and measured values showed good agreement. For the lawn area, the temperature below 1 m depth was 4 °C lower than that of the car park for summer and is recommended for cooling purposes, whereas a depth between 1.5-2 m is recommended for horizontal ground heat exchange applications. Finally, Popiel *et al.* (2001), suggested the division of the ground in Poznan into the surface zone to 1 m depth and being affected strongly by weather conditions, the shallow zone, from 1-8 m depth for dry soil and 1-20 m depth for moist heavy sandy soil and affected mostly by seasonal weather changes and the deep zone, extending from the depths of 8 or 20 m, with the ground temperature influenced only by the geothermal gradient.

A synopsis of the characteristics of the calculation models for the prediction of the ground temperature presented above is shown in Table 2.2.

2.4 Ground Heat Exchangers

For the exploitation of the ground thermal energy Ground Heat Exchangers (GHE) or Earth Heat Exchangers (EHE) are used. A GHE is usually an array of buried pipes placed either horizontally or vertically into the ground. They use the ground as a heat source when operating in the heating mode and as a heat sink when operating in the cooling mode.

Table 2.2: Calculation models for the prediction of ground temperature behaviour

Researcher	Study	Factors studied	Conclusions
Williams and Gold (1976) Florides and Kalogirou (2005)	Kasuda formula for calculating the ground temperature	time of the year depth of the ground thermal diffusivity of the ground	Simple formula with reasonable results accuracy of the calculated results could be affected by the precision of the data related to the thermal properties of the ground and the actual weather conditions temperature variation of the ground surface is very close to that of the ambient air decreasing with depth variation of temperature occurs with a time lag in relation to depth
Mihalakakou *et al.* (1997)	model based on the transient heat conduction differential equation using the energy balance equation of the ground surface as a boundary condition	convective energy exchange between air and soil solar radiation absorbed by the ground surface latent heat flux due to ground surface evaporation long wave radiation various factors involved in the energy balance equation	very good agreement between predicted and measured sets of data the model can be used for the prediction of the ground temperature at the surface and at various depths with sufficient accuracy useful for the prediction of the thermal performance of buildings in direct contact with the ground and the energy efficiency of earth-to-air heat exchangers
Popiel *et al.* (2001)	simple semi-empirical formula based on transient heat conduction in a semi-infinite solid with the exposed surface temperature varying periodically with time	structure and physical properties of the ground ground surface cover air temperature and humidity wind solar radiation rainfall	good agreement between calculated and measured results depths between 1.5-2 m recommended for horizontal ground heat exchange applications surface zone up to 1m depth, affected strongly by weather conditions shallow zone, affected mostly by seasonal changes, reaching depths of 1-8 m for dry light soils or 1-20 m for moist heavy sandy soils deep zone, extending from 8 or 20 m, almost constant temperature, depending on the geothermal gradient

A fluid, usually air, water or a water–antifreeze mixture transfers the heat from or to the ground. Most commonly, GHEs are either of the open type, in which groundwater or ambient air is heated or cooled by the ground and used for the air conditioning of the space, or of the closed type, where the space is heated or cooled indirectly by the ground with the aid of a heat transfer fluid.

In an open GHE system, as shown in Figure 2.1, there is direct transfer of heat between the ground, groundwater and the heating or cooling coils. The characteristic part of the system is the groundwater wells used for the extraction and injection of groundwater. Rivers or lakes can also be used for the provision of the water, Mands and Sanner (2005).

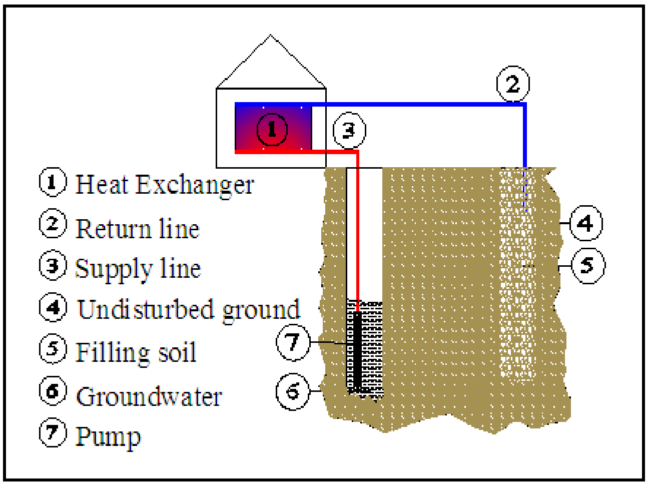

Figure 2.1: Open GHE system

In a similar way, as shown in Figure 2.2, ambient air can also be used as the heat transfer medium for air conditioning of a space. The main differences with the previous method are that the air flows in tubes buried horizontally or vertically in the ground and there is absence of heating or cooling coils.

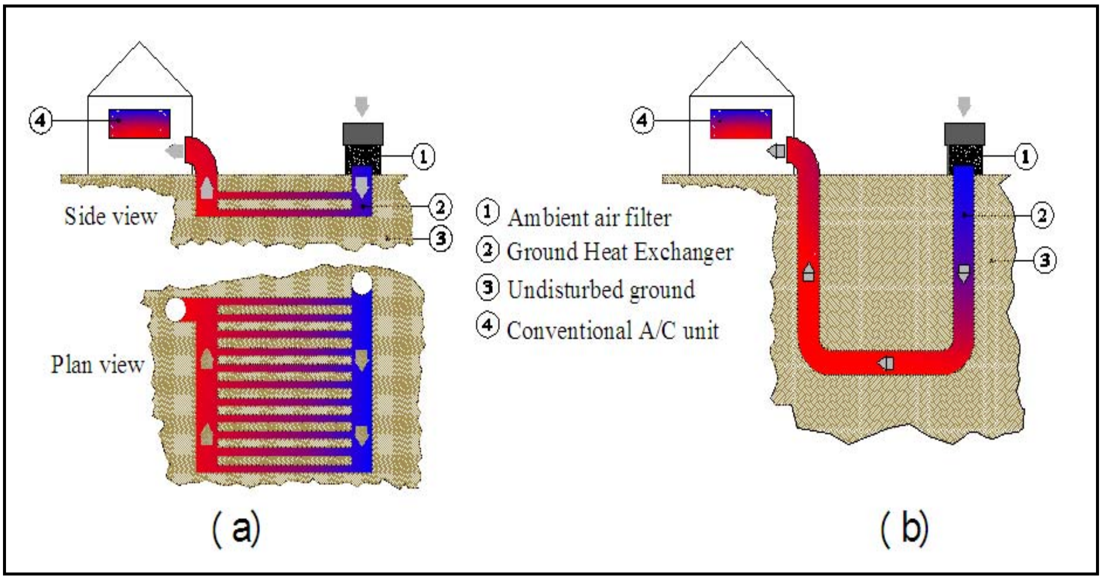

Figure 2.2: Open GHE preheating systems (a) Horizontal type and (b) Vertical type

In closed systems the ground may be used indirectly with the aid of a heat transfer fluid, circulated in the system for the air conditioning of the space. The pipes are buried in the ground either in horizontal, vertical or oblique position and a heat transfer fluid transfers the heat from the ground to the heating or cooling coils and vice versa. The heat transfer fluid usually flows through pipes made of durable materials like high-density polyethylene, polypropylene or copper. These materials are designed for a 50 year life time.

In the horizontal type, when adequate ground space is available and trenches of about 3 m deep are easy to dig, a number of pipes are connected together either in series or in parallel, as shown in Figure 2.3. It is easier and more cost effective for the system to be installed while a building is under construction; otherwise the horizontal drilling method can be used with minimal disturbance of the ground surface, for installing loops under existing constructions, Geothermal Heat Pump Consortium (2003). It is important in horizontal the type GHEs though, not to cover the ground above the heat exchanger since the main thermal recharge is mainly provided by solar radiation, Mands and Sanner (2005).

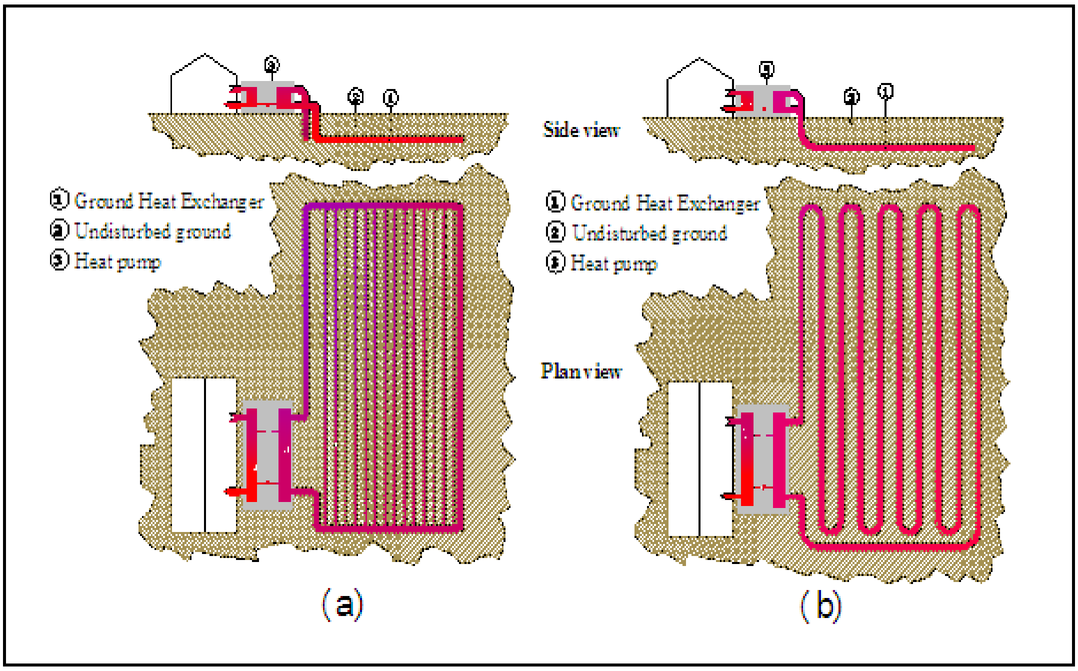

Figure 2.3: Closed system, horizontal GHE (a) in parallel and (b) in series connection

In a similar manner but with less ground space needed, pipes in a spiral shape can be laid into wide trenches. When pipes are laid horizontally the GHE is called a slinky collector (Figure 2.4(a)) and when placed vertically in narrow trenches the GHE is called Svec spiral collector (Figure 2.4(b)), Mands and Sanner (2005).

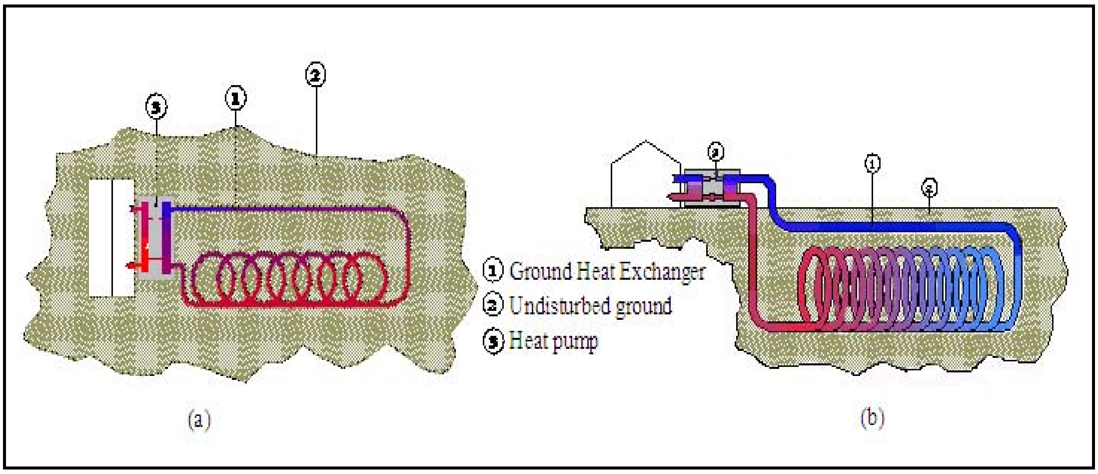

Figure 2.4: Closed GHE systems (a) Slinky shape collector and (b) Svec spiral collector

Vertical Ground Heat Exchangers (VGHEs) or Borehole Heat Exchangers (BHEs) are widely used when there is a need for sufficient heat exchange capacity under a limited ground space. Typical VGHE can be 20 m to 300 m deep, 10 cm to15 cm in diameter and have the ability to extract 40-70 W_{heat} per meter borehole depth for typical ground conditions. VGHEs are classified as U-tubes, consisting of a pair of straight pipes connected with a U-bend at the bottom, as shown in Figure 2.5, and as concentric or coaxial pipes, joined either in a very simple way with one straight pipe inside a bigger diameter pipe or forming complex configurations. A more complex configuration is formed with more than one pipes inside a bigger diameter pipe or more than one pipes placed around a central one as described by Mands and Sanner, 2005.

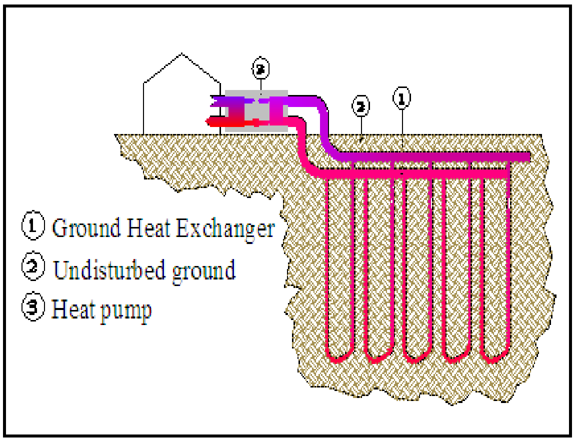

Figure 2.5: Closed system Vertical GHE

Boreholes usually are backfilled with a bentonitic clay mixture, with the possibility of using thermally enhanced additives in order to ensure good thermal contact with the ground. Due to the fact that the ground temperature increases with depth, VGHEs have the ability to exchange the required heat with the ground, with less piping than horizontal heat exchangers. VGHEs are generally more expensive to install than HGHEs. The fact that two or even three U-pipes could be installed in one borehole and the use of thermally enhanced backfilled material may reduce the number or depth of boreholes required for a specified heat extraction/rejection and lead to a reduction in the cost of the installation, Mands and Sanner (2005).

Some GHEs systems can be classified neither as open nor as closed systems. These are referred to as Miscellaneous or Unclassified GHE systems. One such system is the use of water from tunnels or mines, where the water is easily accessible and has a constant temperature. The standing column well is another type of unclassified GHE system. In this case, water is pumped from the bottom of the well and after passing through a heat pump is injected back to the well. The performance of this system for heating applications depends on the depth of the well. The deeper the well the more efficient it is. More details on the operation of GHE systems and their performance are given in section 4.3 of the thesis.

The operation of a GHE requires a continuous heat flow in the surrounding ground which takes place partly by heat conduction and to a certain degree by moisture movement. Consequently, the GHE efficiency, represented by the specific performance parameter which is the heat extraction rate per metre of hose depth, not only depends on the pipe material but also on the ground type and its thermal characteristics, Hepbasli *et al.* (2003). Table 2.3 lists the advantages and disadvantages of most GHE types.

Table 2.3: Advantages and Disadvantages of several Earth Heat Exchangers

Earth Heat Exchanger Type	Advantages	Disadvantages
Open system Ambient air or room air recirculation	Simplicity of the system High pre-heating and pre-cooling potential Low operational and maintenance costs	The influence of the pipe density on the energy gain is small Large number of pipes is required for high heat extraction rates
Closed system Horizontal type	Cost effective during building construction	Solar radiation as natural thermal recharge Not effective when the ground surface is covered
Closed system Spiral type	Less ground space required than the closed system Horizontal type	Can be used when natural thermal recharge is not vital
Closed system Vertical U-tube	Less ground space required and lower piping cost than all the other types	Higher drilling costs than the horizontal types
Heat Pump coupled to Vertical HE	Consumes less energy than air source HP The ground is more stable source than air No supplementary heat is needed in extreme ambient temperatures Less refrigerant	High initial cost

2.5 Evaluation of Ground Heat Exchanger

A number of researchers has used basic formulas to evaluate the ground heat exchanger (GHE) performance, each time taking into account different design parameters. The classic method to model the heat exchange process is through the cylindrical heat source theory proposed by Carslaw and Jaeger (1947). The method is relatively easy to apply and was used by many researchers to model and evaluate the response of ground heat exchangers. With improvements in the performance of computers, a number of software packages can now handle the finite element method and simultaneously give solutions to the arising partial differential equations for a massive cell number. Depending also on the software package, a number of modules are built-in in order to handle various forms of heat transfer at the boundaries, facilitating the formulation of the problem for a numerical solution.

De Paepe and Willems (2001) studied the performance of a ground-coupled air heat exchanger in Belgium, considering transient and three dimensional conduction heat transfer in the ground and heat transfer by convection in the pipe. They ignored the heat transfer by moisture in the ground. The heat flux from the ambient air to the surface was calculated by considering constant and uniform temperature deep in the ground. A 3D unstructured finite volume model was derived and the ‘FLUENT’ solver was used to obtain the numerical solutions. It was identified that the pipe affects the temperature of the ground around it up to a distance twice its diameter. Burying the pipes deeper than 2.5 m and calculating their optimal length by using the calculation model, an efficient heat exchanger can be obtained exploiting to the maximum the available ground thermal capacity.

The performance of three Earth-to-Air Heat Exchangers (EAHXs) for mid European office buildings, located at Hamm, Freiburg and Weilheim in Germany were examined and presented by Pfafferott (2003), aiming to characterise their efficiency. The main characteristics of the examined EAHXs are presented in Table 2.4.

Each of the evaluated EAHXs was shown to have certain advantages. The EAHX located at Hamm showed the outlet air temperature to be closer to the undisturbed earth temperature with Θ=0.944 and to have the smallest ratio of temperature variation with R_T = 0.28. The smallest the value of R_T the more cooling energy is supplied to the building. The system located at Freiburg supplied the highest specific energy gain based on the total surface area, h_{mean} = 51.3 kWh/m^2 per annum for heating and h_{mean} = 23.8 kWh/m^2 per annum for cooling. The COP is the ratio of the overall energy gain supplied by the EAHX and the mechanical dissipation energy during operation time. All the tested EAHXs had high COP values mostly because of the low energy dissipation. The COP is the ratio of the energy supplied by the EAHX divided by the mechanical energy used during operation. The highest COP of 380 was obtained by the EAHX located at Weilheim due to the large pipe diameter and the low air velocity in the pipes. It was concluded that the evaluation of an EAHX depends on project-specific criteria. Pipe lengths up to 100 m and pipe diameters of around 250 mm are effective, Pfafferott (2003).

Table 2.4: Description of the main characteristics of the three EAHXs in Germany

	Hamm	Freiburg	Weilheim
Diameter (mm)	200 - 300	250	350
Total surface area of ducts (m^2)	1650	522	198
Mean air flow (m^3/h)	10300	7000	1100
Specific surface area ($m^2/(m^3/h)$)	0.16	0.075	0.18
Air speed (m/s)	≈ 2.2	5.6	1.6
Soil type	Dry, rocky	Dry, gravel	Moist, clay
Hours of operation (h)	3701	4096	3578
Specific heating energy gain (kWh/m^2 per annum)	16.8	51.3	16.2
Specific cooling energy gain (kWh/m^2 per annum)	13.5	23.8	12.1
RT (K/K) = $(T_{outmax}–T_{outmin})/(T_{inmax}–T_{inmin})$	0.28	0.47	0.36
h_{mean} ($W/(m^2K)$)	5.5	5.0	3.2
Θ (K/K) = $(T_{in}–T_{out})/(T_{in}–T_{earth})$	0.944	0.766	0.804
COP (kW_{hth}/kW_{hmech})	88	29	380

Nam *et al.* (2008) developed a numerical model to predict heat exchange rates for a ground-source heat pump system. The model combined a heat transport model with ground water flow and a heat exchanger model with an exact shape. FEFLOW was adopted to calculate the heat exchange rate between the ground heat exchanger and the surrounding ground and to estimate the distribution of subterranean temperature. FEFLOW is an analysis code that uses the finite element method for the simulation of heat and material transport in the ground based on the three preservation equations for mass momentum and energy conservation. Comparison between experimental results and numerical analysis showed a good agreement. Finally, the developed model was used to predict the heat exchange rate for an actual office building in Japan.

Cui *et al.* (2008) used a numerical model for the simulation of the ground heat exchangers in alternative operation modes over a short time period for ground-coupled heat pump applications. A two-dimensional transient heat conduction was used as the finite element model and the commercial code ANSYS was used to perform the transient numerical simulations of heat transfer in the borehole domain. The ANSYS program can automatically generate a finite element model that consists of nodes and elements dealing with arbitrary geometries and non-homogenous media. For a simplified analysis, a symmetrical arrangement of the two legs of the U-tube inside the borehole was assumed. Then only half of the borehole domain was modelled because of the axisymmetric configuration. An adiabatic boundary condition was applied to the symmetric plane on the centre of the borehole. The borehole domain is physically divided into three regions, the inner is the pipe wall; the middle is the grout backfilled in the borehole and the outer region is the soil surrounding the borehole. The governing equations for each region in the borehole domain were represented with cylindrical coordinates. The comparisons with experimental results showed a reasonable agreement within the range of ±6.5%. The variation of the U-tube pipe wall temperatures demonstrated that the discontinuous operation mode and the alternative cooling/heating modes could effectively alleviate the heat build-up in the surrounding soil.

Schiavi (2009) analyzed simulated Thermal Response Test data in order to evaluate the effect of a three-dimensional model in determining the actual value of the soil thermal conductivity and borehole thermal resistance. These values are necessary for the design of geothermal energy storage systems. For the 3D system simulation the finite element method, implemented within the Comsol Multiphysics environment, was adopted. The analysis confirmed that the Line Source Model applied to the Thermal Response Test represents a sufficiently accurate approach for the U-tube configuration.

Kim *et al.* (2010) developed a numerical model for the simulation of temperature changes in a borehole heat exchanger (BHE). The model calculated the thermal power transferred from heat pumps to BHEs while considering the nonlinear relationship between the temperature of the circulating fluid and the thermal power. To simulate the vertical closed-loop ground heat pump (GHP) system, three modules were added to the 3D numerical simulator TOUGHREACT. The modules calculated the heat transfer between the U-tube and the circulating fluid, the circulation of the fluid in the BHE and the rate of energy transfer from a heat pump to a BHE. The developed model was validated by comparison with two experimental datasets and was used for the BHE design of an actual system that was numerically evaluated with respect to the temperatures of the circulating fluid at the

BHE inlet and outlet, the heat pump efficiency, the heating power and electric power of the heat pumps.

Eslami-nejad and Bernier (2011) presented an analytical model to predict steady-state heat transfer in double U-tube boreholes with two independent circuits operating with unequal mass flow rates and inlet temperatures. For the modelling it was assumed that the heat capacities of the grout and pipe inside the borehole were negligible, the ground and the grout were homogeneous and their thermal properties were constant, the borehole wall temperature was uniform over the borehole depth, heat conduction in the axial direction was negligible and the combined fluid convective resistance and pipe wall thickness conduction resistances were assumed to be equal in both circuits. This two-region model was validated experimentally and was in very good agreement with experimental data in the steady-state regime. The proposed model was then used to study a double U-tube borehole configuration with one circuit linked to a ground-source heat pump operating in the heating mode and the other to thermal solar collectors.

Concluding from what was described before, the thermal performance of GHEs is strongly dependent on the thermal properties of the ground in relation to depth. Pipe depth, pipe length and pressure drop in the pipe increase the thermal capacity of the system while the pipe diameter, air flow and air speed, are factors affecting negatively the earth-to-air heat exchangers when they are increased. Although moisture in the ground is another factor that was widely studied, it appeared to have almost negligible influence on the total heat transfer in the ground, Gauthier (1994) and Puri (1986).

2.6 Ground Coupled Heat Pumps

Ground Coupled Heat Pumps (GCHP) or Geothermal Heat Pumps (GHP), are heat pumps coupled to GHEs, to improve the heat pump efficiency. They are used mostly for the air conditioning of a space and/or water heating purposes. They exchange heat between indoor air (for space heating or cooling) or water (for heating or cooling water) and a liquid (either water or a water-coolant mixture) circulating in the closed loop heat exchanger.

GCHP systems are more efficient than conventional heat pump systems because of the improved efficiency of their compressors. This can be achieved since the ground temperature is more stable than that of ambient air providing cooler condensation temperatures during cooling operation and warmer evaporating temperatures during heating operation. Unlike air source units, GCHP systems do not need auxiliary heat, for defrost cycles or backup electric resistance heat, at extreme outdoor air temperatures, Collins *et al.* (2001).

The improved efficiency and the lower running cost of GCHP systems over conventional heat pump systems can make them an attractive choice for air conditioning and water heating provided the installation cost is not excessive, Collins *et al.* (2001).

For the effective sizing of a GCHP and related GHE, specific ground thermal characteristics are required. Several models based on Fourier's law of heat conduction can be used for this purpose. The most widely used is the thermal response test, first presented by Mogensen in 1983 and used by Sanner *et al.* on several boreholes. This method requires a specified heat load to be applied on a borehole through a circulating fluid, measuring its temperature changes and allowing calculation of the thermal conductivity of the borehole. The formula calculating the thermal conductivity of the system, including the influence of the groundwater flow and grouting, takes into account the heat exchanged, the length of the borehole and the slope of the curve of temperature against logarithmic time. From the thermal response test, the borehole thermal resistance can be calculated. Results of thermal response tests carried out in 5 different locations in Germany are listed in Table 2.5. The differences in the thermal conductivities are due to the differences in the geology of the locations, Sanner *et al.* (2000).

Table 2.5: Results of various thermal response tests carried out in Germany

Location	Geology	Thermal conductivity λ_{eff} (W/mK)	Resistance R_b K/(W/m)
Attenkirchen	Quarternary and tertiary silt and clay	1.62	0.50
Erfurt	Mesozoic sediments	2.78	0.18
Langen	Quarternary and tertiary sand and clay	2.79	0.11
Minden	Marly clay	2.51	0.12
Werne	Cretaceous marl, clayey	1.45	0.11

Pahud and Matthey (2001) carried out thermal response tests for several boreholes to investigate the effect of the filling materials on the borehole thermal performance. Fill materials like standard bentonite and cement mixture, bentonite and cement with quartz sand as additive or plain quartz sand were used. The use of spacers to keep the plastic pipes apart from each other and close to the borehole wall was also investigated. The use of quartz sand as a filling material showed an increase in the thermal performance by 30%. With a common heat extraction rate of 50 W per meter of borehole length, the temperature gain in a heat pump evaporator was +2 K. In Switzerland, boreholes of 100-200 m deep and pipe diameters of 10-15 cm are used for residential buildings. They are sized for a heat extraction rate of 50 W per meter length of borehole.

2.7 Environmental aspects of geothermal energy

Geothermal energy is considered a sustainable and renewable energy source able to replace fossil fuels and lead to reductions in pollution and greenhouse gasses emissions. Also, for many countries geothermal energy leads to a reduction in their dependence on imported fuel. According to data presented by Rybach at the World Geothermal Congress 2010, in 2008 geothermal power production exceeded by more than three times that produced by photovoltaics, Rybach (2010).

Although geothermal energy has the largest capacity amongst the renewable energy sources as stated by Rybach (2010) its current growth is slow in comparison to wind and solar PV. Nowadays, the development of geothermal energy is based on the increasing deployment of GCHPs mainly due to the fact that this technology is mature and the systems can be installed in most ground formations.

The Energy Service of the Cyprus Ministry of Commerce, Industry and Tourism has the overall responsibility for Energy matters and specifically for preparing and implementing programmes for energy conservation, the promotion of renewable energy sources (RES). The Government of Cyprus being aware of the benefits of geothermal energy and in order to increase the share of energy from renewable sources promotes geothermal energy systems through a Scheme that provides financial incentives for the utilization of RES for heating and cooling. However, the lack of data for the thermal properties of the ground in Cyprus was one of the main barriers to the design of efficient geothermal systems, the implementation of the support scheme in the field of geothermal energy and the calculation of the share of energy from renewable sources for heating and cooling.

The use of geothermal systems for the air conditioning of buildings in Cyprus had a significant increase in the last few years. The technology is already used in hospitals, hotels, industrial buildings and households. From evaluations of the installed geothermal systems in Cyprus, it was observed that the use of geothermal systems can offer an energy saving between 40-75% for heating and cooling of buildings compared to conventional systems. In 2006 the applications submitted for grant support were only 14 reaching 55 in February 2010. Since then, the increase in the installed capacity has been rising steadily, Partasides *et al*. (2011).

The knowledge of the thermal behaviour of the ground at various locations and depths is valuable for improving the design of geothermal applications in Cyprus. As discussed previously, the thermal behaviour of the ground depends on many factors and varies in different locations. This is the reason that each location is considered unique and its thermal behaviour needs to be investigated or predicted.

The measurement of the thermal behaviour of the ground at a specific location is costly and in many cases might be unaffordable. On the other hand, prediction is easier, faster and more economic. This is the reason that calculation models have been developed for this purpose.

The provision of important information on the structure of the ground in different areas of the island and the definition of their thermal characteristics are of significant importance. One of the objectives of the thesis is to draw maps that will indicate the temperature of the ground at different locations and depths in Cyprus in order to assist in the efficient design of geothermal systems. Furthermore, this will also support the future drawing of isothermal and thermal conductivity maps of the island and provide appropriate information to consultants to improve design accuracy and techno-economical studies.

2.8 Summary

GHEs are used for the utilisation of the ground’s thermal capacity for air conditioning and domestic water heating. The temperature of the earth is always higher than that of the ambient air in winter when the ground can be used as heat source and lower in summer when the ground can be used as a heat sink.

For the prediction of the ground thermal capacity, several calculation models were presented. The temperature variation of the ground surface is found to be very close to that of the ambient air, decreasing with depth and tending to stabilise after a certain depth which depends on ground lithology (i.e. the characterisation of a rock in all those visible features that in the aggregate impart individuality to the rock). The variation of the ground temperature occurs with a time lag from the variation of the ambient air temperature. The time lag is a function of the depth from the surface.

An array of buried pipes in the ground, either horizontally or vertically, can be used for the heat exchange process. GHEs are classified as open or closed systems and can be used either for the preheating or precooling of a heat exchange fluid or can be coupled to heat pumps to improve the efficiency of operation.

For the prediction of the thermal performance of GHEs several calculation models were presented and validated against experimental results. These models can also be used for system sizing. The thermal performance of GHEs is strongly dependent on the thermal properties of the ground and their variation with depth.

The reduction in gas and oil supplies and the increase in energy prices will increase the economic attractiveness of geothermal energy. Research and development and the application of geothermal energy systems is expected to increase in the future.

Limited information in the area of space cooling using geothermal energy is reported. According to Lund et al. (2010), space cooling is reported only in five countries, amounting to 56 MWt and 281 TJ/yr. In warm climates and especially in the Eastern Mediterranean countries like Greece, Italy Egypt, Turkey and Middle East where the climatic conditions are similar to the ones in Cyprus, geothermal energy is reported to be used mainly for space heating, in greenhouses and aquaculture, for bathing, in spas etc. In addition to this, Iran reported the installation of GCHPs in demonstration projects for the evaluation of their efficiency under different climatic conditions.