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GROUND HEAT EXCHANGERS – A REVIEW

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ABSTRACT

The temperature distribution in the ground is distinguished in three zones. The *Surface zone*, which reaches a depth of about 1m, the *Shallow zone* extending at a maximum depth of 20 m, and the *Deep zone*, where the ground temperature remains nearly constant throughout the year. To effectively exploit the heat capacity of the soil a heat-exchanger system has to be constructed. Usually an array of buried pipes running along the length of the building, a nearby field or buried vertically into the ground is utilised. A circulating fluid (water or air) is used in summer to extract heat from the hot environment of the building and dump it into the ground and vice versa in winter. A heat pump may also be coupled to the ground heat exchanger to increase its efficiency. In the literature several calculation models are found for ground heat exchangers. One-dimensional models were devised in the first stages of the system study which were replaced by two-dimensional models during the nineties and three-dimensional systems during the recent years.

The present models are further refined and can accept any type of grid geometry that may give greater detail of the temperature variation around the pipes and in the ground. Monitoring programs have been set-up to test various prototype constructions with satisfactory results.

INTRODUCTION

Measurements show that the ground temperature below a certain depth remains relatively constant throughout the year. This is due to the fact that the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases because of the high thermal inertia of the soil. Also, there is a time lag between the temperature fluctuations at the surface and in the ground. Therefore, at a sufficient depth, the ground temperature is always higher than that of the outside air in winter and is lower in summer. This difference in temperature can be utilised as a preheating means in winter and pre-cooling in summer by operating an earth heat exchanger. Also, because of the higher efficiency of a heat pump than conventional natural gas or oil heating systems, a heat pump may be used in winter to extract heat from the relatively warm ground and pump it into the conditioned space. In summer, the process may be reversed and the heat pump may extract heat from the conditioned space and send it out to an earth heat exchanger that warms the relatively cool ground.

GROUND HEAT EXCHANGER TYPES

In an open system the ground may be used directly to heat or cool a medium that may itself be used for space heating or cooling. Also, the ground may be used indirectly with the aid of a heat carrier medium that is circulated in a closed system. The loop of the heat exchanger is made of a material that is extraordinarily durable but allows heat to pass

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through efficiently. Loop manufacturers typically use high-density polyethylene which is a tough plastic, with heat fuse joints. This material is usually warranted for as much as fifty years. The fluid in the loop is water or an environmentally safe antifreeze solution. Other types of heat exchangers used directly for heating and cooling utilise copper piping placed underground. As refrigerant is pumped through the loop, heat is transferred directly through the copper to the earth. The length of the loop depends upon a number of factors such as the type of loop configuration, the house heating and air conditioning load, the soil conditions, local climate etc.

Earth heat exchangers are classified as (Mands and Sanner, 2003):

1. Open system

In this case ambient air passes through tubes buried in the ground for preheating or pre-cooling and then the air is heated or cooled by a conventional air conditioning unit.

In a similar way the ground water of a water bearing layer is used as a heat carrier medium and is brought in direct contact with the heat pump coils. In most cases two wells are required, one for extracting the ground water and one for injecting it back into the water bearing layer as indicated in Fig. 1.

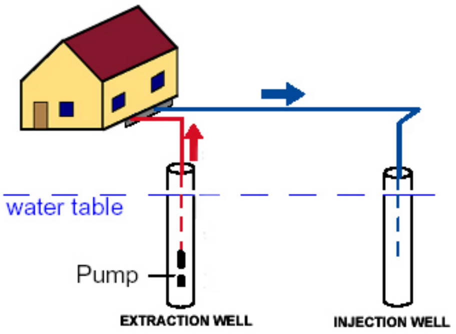

Figure 1. Ground Water Heat Pump

2. Closed System

Heat exchangers are located underground, either in horizontal, vertical or oblique position and a heat carrier medium is circulated within the heat exchanger, transferring heat from the ground to a heat pump or vice versa. Fig. 2 indicates the horizontal type which has a number of pipes connected together either in series or in parallel.

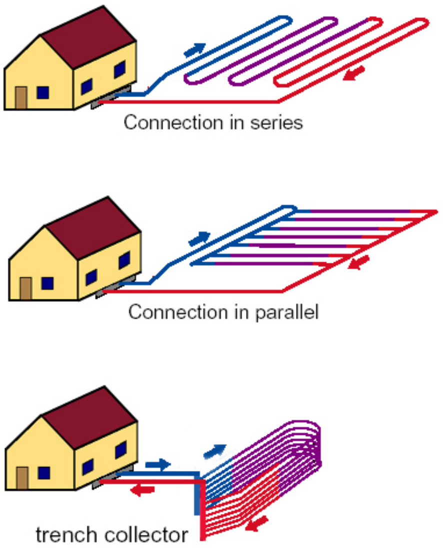

Figure 2. Horizontal type ground heat exchangers

This configuration is usually the most cost effective when adequate yard space is available and trenches are easy to dig. The trenches have a depth of one to two meters in the ground and usually a series of parallel plastic pipes is used. Fluid runs through the pipe in a closed system. A typical horizontal loop is 35 to 60 meters long per kW of heating or cooling capacity. Horizontal ground loops are easiest to install while a building is under construction. However, new types of digging equipment allow horizontal boring and thus it is possible to retrofit such systems into existing houses with minimal disturbance of the top soil and even allow loops to be installed under existing buildings or driveways (Geothermal heat pump consortium, 2003).

For all horizontal systems in heating-only mode, the main thermal recharge is provided by the solar radiation falling on the earth surface. Therefore, it is important not to cover the surface above the ground heat collector.

Vertical ground heat exchangers or borehole heat exchangers (Fig. 3) are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area such as when the earth is rocky close to the surface, or where minimum disruption of the landscaping is desired. This is possible because the temperature below a depth of 15 m to 20 m remains constant over the year. In a standard borehole, which in typical applications is 50 to 150 meters deep, plastic pipes (polyethylene or polypropylene) are installed, and the space between the pipe and the hole is filled with an appropriate material to ensure good contact between the pipe and the undisturbed ground and reduce the thermal resistance (Geothermal heat pump consortium, 2003).

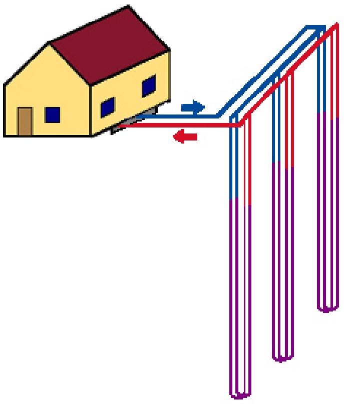

Figure 3. Vertical ground heat exchangers

Vertical loops are generally more expensive to install, but require less piping than horizontal loops because the Earth deeper down is cooler in summer and warmer in winter. Several types of borehole heat exchangers were tested and are widely used. These are classified in two basic categories which are:

a. U-pipes, consisting of a pair of straight pipes, connected with a U-turn at the bottom. Because of the low cost of the pipe material, two or even three of such U-pipes are usually installed in one hole.

b. Concentric or Coaxial pipes, joint either in a very simple way with one straight pipe inside a bigger diameter pipe, or joint in complex configurations.

3. Miscellaneous systems

A number of ground systems cannot be categorised neither as open nor as closed. Such a system is the standing column well, where water is pumped from the bottom of the well to the heat pump. The leaving water is percolated through gravel in the annulus of the well in order to absorb heat. Other sources of heat are the use of water in mines and tunnels. This water has a steady temperature the whole year round and is easily accessible.

GROUND THERMAL BEHAVIOUR

The use of direct or indirect earth-coupling techniques for buildings and agricultural greenhouses requires knowledge of the ground temperature profile at the surface and at various depths. The ambient climatic conditions affect the temperature profile below the ground surface (Fig. 4) and need to be considered when designing a heat exchanger. Actually the ground temperature distribution is affected by the structure and physical properties of the ground, the ground surface cover (e.g. bare ground, lawn, snow etc), the climate interaction (i.e. boundary conditions) determined by air temperature, wind, solar radiation, air humidity and rainfall. The temperature distribution at any depth below the earth’s surface remains unchanged throughout the year with the temperature increasing with depth with an average gradient of about 30 °C/km. The geothermal gradient deviations from the average value are, in part, related to the type of rocks present in each section.

Mihalakakou *et al.* (1997), present a complete model for the prediction of the daily and annual variation of ground surface temperature. The model uses a transient heat conduction differential equation and an energy balance equation at the ground surface to predict the ground surface temperature. The energy balance equation involves the convective energy exchange between air and soil, the solar radiation absorbed by the ground surface, the latent heat flux due to evaporation at the ground surface as well as the long-wave radiation.

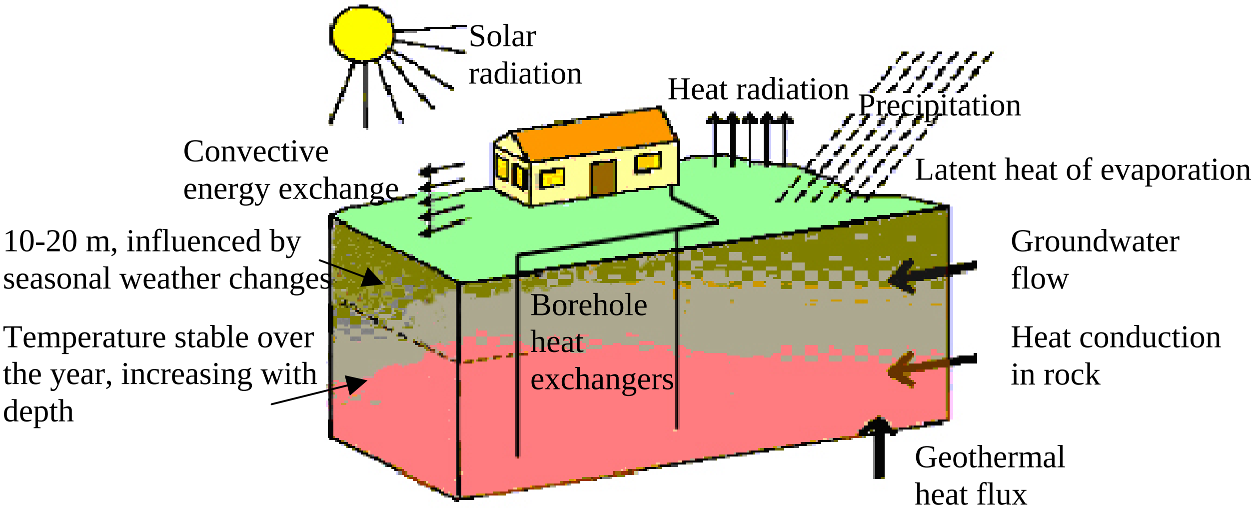

Figure 4. Energy flows in ground

The model is validated against 10 years of hourly measured temperatures for bare and short-grass covered soil in Athens and Dublin. The results are compared with the corresponding results of models using Fourier analysis. Furthermore, a sensitivity investigation is performed to investigate the influence of various factors involved in the energy balance equation at the ground surface on the soil temperature profile.

Popiel *et al.* (2001), present the temperature distributions measured in the ground for the period between summer 1999 to spring 2001. The investigation was carried out in Poland. From the point of view of the temperature distribution they distinguish three ground zones:

1. *Surface zone* reaching a depth of about 1m, in which the ground temperature is very sensitive to short time changes of weather conditions.
2. *Shallow zone* extending from the depth of about 1 to 8 m (for dry light soils) or 20 m (for moist heavy sandy soils) where the ground temperature is almost constant and close to the average annual air temperature; in this zone the ground temperature distributions depend mainly on the seasonal cycle weather conditions and,
3. *Deep zone* below the depth of the shallow zone, where the ground temperature is practically constant (and very slowly rising with depth according to the geothermal gradient).

CALCULATION MODELS AND EVALUATED PERFORMANCE OF GROUND HEAT EXCHANGERS

Several calculation models for ground coupled heat exchangers are found in the literature. Early models generally used a one-dimensional description of the pipe to derive a relation between its inlet and outlet temperature. Tzaferis *et al.* (1992), studied eight models to predict the performance of earth-to-air heat exchangers. The algorithms of the studied models either calculate the conductive heat transfer from the pipe to the ground mass or calculate the convective heat transfer from the circulating air to the pipe. Input data include the geometrical characteristics of the system, the thermal characteristics of the ground and the thermal characteristics of the pipe together with the undisturbed ground temperature during the operation of the system or only the temperature of the pipe surface. The algorithms of the eight models were introduced into computer programs to simulate the behaviour of the earth-to-air heat exchangers. Experimental results were also obtained for a PVC horizontal pipe, buried at a depth of 1.1 m and compared to the calculated values. Six of the eight models gave very close results to the actual values with an r.m.s. error in each case of about 3.5%. In the examined models the thermal capacity of the ground is not considered and therefore the influence of different pipes on each other and the temperature profiles in the ground cannot be studied.

Mihalakakou *et al.* (1996), investigated the heating potential of a single earth- to- air heat exchanger as well as the potential of a multiple parallel earth tube system. An accurate numerical model was used to investigate the dynamic thermal performance of the system during the winter period in Dublin. The model had been successfully validated against an extensive set of experimental data. The results showed that the heating potential of the system during winter is significantly important. The obtained results showed that the effectiveness of the earth-to-air heat exchanger increases with an increase in the pipe length (checked range 30 m to 70 m). Also there is an increase in effectiveness when the pipe is buried in greater depths (3 m instead of 1.2m). By increasing the pipe diameter from 100 to 150 mm it was shown that the heating capacity of the system was reduced. This is due to a reduction in the convective heat transfer coefficient and an increase in the pipe surface therefore providing a lower air temperature at the pipe outlet. Finally a higher air velocity in the pipe (checked range 5 m/s to 15 m/s) leads to a reduction of the systems heating capacity, mainly because of the increased mass flow rate inside the pipe.

Bojic *et al.* (1997), developed a model in which the soil is divided into horizontal layers with uniform temperature. All the pipes are placed in one layer at the same depth and parallel to each other. The heat transported to the soil by convection from the air and the solar irradiation is calculated. Also an equation describing the heat flow between the air flow in the pipe and the neighbouring soil layer is used. All equations used for the soil layers in each time step, are steady state-energy equations. This model is a 2-dimensional model therefore the influence that pipes have on each other may not be evaluated.

Gauthier *et al.* (1997), describe a fully three-dimensional model. A simple Cartesian co-ordinate system is used and the round pipes are replaced with square pipes of equivalent areas. The thermophysical properties of the soil are considered constant and temperature independent, but may not be homogenous. In this way the influence of different layers in the soil, concrete foundations and insulation can be evaluated. The heat transfer caused by moisture gradients in the soil is assumed to be negligible with respect to that caused by temperature gradients. Heat transfer in the pipes is dominated by convection in the axial direction but coupled with the temperature field in the soil via the boundary condition on the pipe surface. The model is thoroughly validated with experimental data taken from a soil heat exchanger storage system installed in a commercial-type greenhouse. Finally, the various parameters that affect the behaviour of the soil heat exchanger-storage system are examined.

De Paepe and Willems (2001), further refined the Gauthier *et al.* (1997), approach and the model was used to study the performance of a ground-coupled air heat exchanger in the Belgian climate. A 3D unstructured finite volume model was derived and the FLUENT solver was used to obtain the numerical solutions. The model considers transient and fully three dimensional conduction heat transfer in the soil and other materials. The heat transfer by moisture gradients in the soil is neglected and the heat transfer in the pipe is dominated by convection. The results show that the influence of the pipe on the temperature of the surrounding soil is limited to a distance of twice its diameter. To make optimal use of the thermal capacity of the soil and to eliminate the influence of the outside air, the tubes have to be buried below a depth of 2.5 m and the length of the tube can be optimised with the calculation model to obtain an efficient heat exchanger.

Hollmuller and Lachal (2001), examined the winter preheating and summer cooling potential of buried pipe systems under the Central European climate. The simulation model of the air-to-earth heat exchanger used, accounts for sensible and latent heat exchanges. The model additionally accounts for frictional losses and water infiltration and flow along the tubes. It further allows for control of air flow direction as well as for flexible geometry (inhomogenous soils, diverse border conditions, use of symmetries or pattern repetitions for run-time economy) and is adapted to TRNSYS (a modular energy system simulation environment). The basic equations of the model describe the mass and energy exchanges between air and tube. The study concludes that in Central Europe there is a fundamental asymmetry between heating and cooling potentials with the ground used as a seasonal energy buffer. In winter, preheating of fresh air acts as a saving function on energy demand, to which it is inherently linked by limitation of flow rate. In summer on the other hand, inertial cooling (smoothening of ambient temperature below comfort threshold) increases along with flow rate and hence becomes an energy producing service on its own. Air preheating with buried pipes is more expensive than with fuel (about twice the cost per kWh), which it cannot substitute completely. On the contrary, buried pipe inertial cooling, together with an (avoided) air conditioning system, is competitive and allows savings simultaneously on electricity, capital costs and refrigerant gases. Buried pipe systems may be subject to water infiltration, which can lower winter and enhance summer performance, but also raises sanitary problems related to stagnant water. These problems can be avoided by replacing buried pipes with a closed water underground circuit coupled to the fresh air system via a water/air heat exchanger. One of the economically important parameters to deal with is the pipe depth, which relates to surface temperature. Preliminary results in this climate show that for cooling purposes excavation should be kept to a minimum.

Pahud and Matthey (2001), in their paper, explain how the thermal performance of a borehole heat exchanger can be assessed with a response test. This test allows the in situ determination of the thermal conductivity of the ground in the vicinity of a borehole heat exchanger, and the determination of the effective thermal resistance. The thermal resistance (K/(W/m)) defines the proportional relationship between the fluid-ground temperature difference on the borehole wall and the heat rate exchanged by the borehole, per unit length.

The tested boreholes differ from one another by the filling material which may be a standard mixture of bentonite and cement, a standard mixture of bentonite and cement with the addition of quartz sand or only quartz sand, and the use or omission of spacers to keep the plastic pipes apart from each other and close to the borehole wall. Using an average estimated ground thermal conductivity is 2.5 W/(m-K), the tests show that the thermal resistance can be decreased by 30% when quartz sand is used instead of bentonite and when spacers are used to keep the plastic pipes in contact with the borehole wall. With a common heat extraction rate of 50 W per meter of borehole length, the temperature gain in a heat pump evaporator is +2 K. Also, it is mentioned that for a typical residential house in Switzerland, a borehole heat exchanger of 100-200 m is used with a diameter of 10-15 cm, depending on the energy demand and the ground conditions. For typical ground conditions and a single borehole heat exchanger, the borehole length is sized for a heat extraction rate per meter length of borehole of about 50 W/m.

De Paepe and Janssens (2003), used a one-dimensional analytical method to examine the influence of the design parameters of the heat exchanger on the thermo-hydraulic performance and devise an easy graphical design method which determines the characteristic dimensions of the earth-air heat exchanger in such a way that optimal thermal effectiveness is reached with acceptable pressure loss. The choice of the characteristic dimensions becomes thus independent of the soil and climatological conditions. This allows designers to choose the earth-air heat exchanger configuration with the best performance.

Their analysis considers the air mass flow rate, the inlet air temperature, the desired outlet air temperature, the ground temperature and the geometric sizing parameters which are the diameter of the tube, the length of the tube and the number of tubes in parallel in the heat exchanger.

As they emphasize, generally, lowering the diameter of the tube raises the effectiveness but on the contrary higher flow rates reduce the effectiveness. So it is better to have several tubes of small diameter over which the flow rate is divided. Long tubes with a small diameter are profitable for the heat transfer but at the same time the pressure drop in the tubes is raised, resulting in high fan energy. On the other hand having a small flow rate per tube and a large diameter gives the least pressure loss. This would mean that is better to use many tubes, with a large diameter, which is in conflict with the thermal demand of a small diameter. In both cases a large number of tubes is beneficial. The tube length and diameter combination have to be optimized and this is achieved by a graphical method by reducing the influencing parameters and introducing the specific pressure drop. The specific pressure drop is a measure for the pressure drop needed to achieve a given thermal performance. In this way a maximal specific pressure drop can be calculated when a value for the effectiveness of the earth-air heat exchanger is chosen. The effectiveness is dictated by the design requirements and climatic conditions, but often an effectiveness of 80% is considered to be an optimum value for an earth-air heat exchanger (IEA, 1999). A higher effectiveness is only achievable at the cost of a large increase in the tube length or in the number of tubes.

Zeng *et al*. (2003), in their paper present a new quasi-three-dimensional model for vertical ground heat exchangers (GHE) that accounts for the fluid axial convective heat transfer and thermal "short-circuiting" among U-tube legs. Analytical expressions of the borehole resistance have been derived for different configurations of single and double U-tube boreholes and analytical solutions of the fluid temperature profiles along the borehole depth have been obtained. As they mention, borehole depths usually range from 40 to 200 m with diameters of 75-150 mm. Analyses have shown that the single U-tube boreholes yield considerably higher borehole resistance than double U-tube boreholes. The double U-tubes in parallel configuration provide better thermal performance than those in series. Calculations show that the double U-tube boreholes are superior to those of the single U-tube with reduction in borehole resistance of 30-90%. Calculations on typical GHE boreholes indicate that the U-tube shank spacing and the thermal conductivity of the grout are the prevailing factors in all the configurations considered in determining the borehole thermal resistance.

Kujawa *et al*. (2003), studied the case of deep geothermal heat plants. These plants operate with one or two-hole systems. A computational model is presented which estimates the temperature of the geothermal water extracted to the earth's surface as well as the temperature of the water injected into a deposit level. The predicted characteristics do not take into account specific working conditions of the systems.

It is mentioned that the high expenditure incurred in drilling holes deters one from using this method in gaining thermal energy. The one-hole injection system or the use of existing single holes, made during crude-oil and or natural-gas exploration reduces the capital cost. In one hole systems the hole is adapted to locate in it a vertical exchanger with a double-pipe heat exchanger in which the geothermal water is extracted via the inside pipe. Published characteristics allow one to estimate geothermal heat-energy flux gained as a function of the difference of temperatures of extracted as well as injected water at different volume fluxes of the geothermal water. In general, the two-layer systems and two-hole systems are more advantageous than the one whole system.

CONCLUSIONS

In this paper various types of earth heat exchangers are described. Earth heat exchangers are used to exploit effectively the heat capacity of the soil and commonly they are coupled to heat pumps for increasing their efficiency. One, two and three-dimensional models can be found in the literature that simulate the heat transfer process. Simulation models may be used successfully for sizing and predicting the thermal performance of ground heat exchangers. These exchangers usually supply more heating and cooling energy than the primary energy they use for power input for the fan or pump. There are no studies undertaken so far related to the efficiency and cost estimation of ground heat exchangers systems in Cyprus and it is of interest to examine such systems in this environment. For this purpose we have recently installed a 50m deep U-tube, 40mm polyethylene heat exchanger, equipped with 20 thermocouples, which are installed at various depths, for recording the ground temperature and exploit the possibilities for using this type of systems.

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