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A review of the design aspects of ground heat exchangers

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ABSTRACT

The advancement of technology and renewable energy systems (RES) have evolved considerably through the years. Geothermal energy was first introduced in Italy in 1904 and has ever since dramatically increased in efficiency. One of the main types of RES, Ground Source Heat Pumps (GSHPs), are used for heating and cooling a space when coupled with Ground Heat Exchangers (GHEs). GSHPs extract or reject heat to the Earth via a network of tubes. The closed loop system, either vertical or horizontal, is the most common of the configurations. Alternatively, pipes can run all the way down to utilize natural underground water sources, when present, in an open loop configuration. GHEs have significantly higher performance over conventional air-to-air heat exchanger systems and the reduction of their cost and the improvement of their overall efficiency through their design are crucial in research.

In this paper are presented and reviewed the design aspects of GHE systems. In particular are discussed the types of GHEs such as open or closed loop systems, vertical or horizontal, U-tube or spiral, energy piles and hybrid systems. A comparative analysis through the literature of the various geometrical aspects of GHEs and the geothermal investigation of the ground environment and the materials used in the construction of GHEs are also presented. Then is analyzed the modeling – experimental and mathematical – of GHEs, with terms that have been extensively studied, like borehole thermal resistance, thermal characteristics, thermal response test, line-source and cylindrical-source models, discussed in detail. Next a demonstration of designing a numerical model of a GHE system through a software, taking into consideration the thermal characteristics, is given. Finally, a comparative detailed list in the form of a table of more than 30 mathematical and/or experimental GHE studies is provided, focusing on the important factors analyzed and findings of each. The overall aim of the current review study is to help improve the efficiency and the total manufacturing cost of GHEs.

1. Introduction

The advancement of technology and renewable energy systems have evolved considerably through the years. This path results in the reduction of fossil fuels used in energy production as well as in keeping the environment unpolluted by reducing carbon dioxide emissions. Geothermal energy was first introduced as an energy source in Larderello, Italy in 1904 [1] and has ever since dramatically increased in efficiency. On a later stage it was introduced as a heat source for heat pump systems and the first known record was found in a Swiss patent in 1912 [2]. It can be used for either a power plant, to produce energy for a number of houses, or for space heating and cooling. In both cases, heat is extracted or rejected in the ground at a specific depth (different for each case) [3].

Yet, Geothermal Energy has not reached a stable and popular state to be widely used. This is due to the high manufacturing and installation cost compared to similar not so effective systems. One of the main types of Renewable Energy Systems (RES), Ground Source Heat Pumps (GSHPs), are used for heating and cooling of a space when coupled with Ground Heat Exchangers (GHEs). GSHPs extract or reject heat to the Earth via a network of tubes. Although GHEs have significantly higher performance over conventional air-to-air heat exchanger systems [4], they are not widely used due to their higher installation cost and limited availability. The reduction of the cost and further advancement of the overall efficiency are the parameters that many researchers are focused on. Only recently the GSHP systems have gained more recognition due to the energy shortage. It is noted that GSHP installations have increased dramatically in recent years (after 2010) with a rate of 10–30% annually [5].

A GSHP can be classified as the system that connects the heat pump system with the ground and allows heat rejection or injection into the ground. There are several types of GHE and they can be broken down into three general type categories: open loop systems, closed loop systems and other type systems. In an open type system, there are two sub-

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Nomenclature

COP	Coefficient of performance
c_p	Specific heat [J kg^{-1} K^{-1}]
Ei	Exponential Integral
erfc	Complementary Error Function
h	Convection heat transfer coefficient [W m^{-2} K^{-1}]
J, Y	Bessel functions
L	Borehole depth [m]
m	Borehole mass
$\dot{q}$	Heat transfer rate per unit length [W m^{-1}]
Q	Heat transfer rate per volume [W m^{-3}]
r	Radial coordinate [m]
r_b	Borehole radius [m]
R_b	Borehole Thermal resistance [KW^{-1}]
T	Temperature [K]
t	Time [s]
u	Velocity [m s^{-1}]

Greek Letters

α	Thermal diffusivity [m^{2}s^{-1}]
Γ	Gamma function
ρ	Density [kg m^{-3}]
γ	Euler's constant
λ	Thermal conductivity [W m^{-1} K^{-1}]

sections where a medium can be used, where the groundwater can be used as a medium, whereas in a closed system a heat exchanger is located in the ground and the medium (refrigerant) is circulated through the pipes transferring heat from/to the ground. In a closed system, there is no contact between the heat carrier (refrigerant) and the ground (soil/rock) in contrast with the open system where there is no separation [6]. There is also a third category for some cases where they do not fall exactly in the open or closed loop systems. Some examples of these systems are the standing column wells as well as mine water wells, which usually consist of a borehole filled with water transferred from the bottom of the well to the heat pumps and then rejected either in the well itself or in another rejection well ([7,8]).

The closed loop system, either vertical or horizontal, is the most common of the configurations. Pipes can be buried by drilling either vertical boreholes or horizontal trenches. Alternatively, if the building has access to an aquifer, pipes can run all the way down to utilize this natural underground water source as an open loop configuration.

Fig. 1 is a schematic of the factors affecting the design of GHEs. The overall aim of the present paper is to undergo a review study of the design aspects of GHEs. The most important factors that one should consider before building a GHE system include (not necessarily in order of importance): (i) the choice of an open or closed loop; (ii) the choice between a horizontal GHE, a vertical GHE, or an energy pile; (iii) a U-tube, a spiral, a co-axial, a helical, a slinky tube configuration, (iv) the choice of a single or multiple tubes (in parallel or series connection), (v) the length and the diameter of the borehole and the pipes and the flow direction; (vi) the center-to-center distance between pipes; (vii) the characteristics of the backfill grout material; (viii) the thermal characteristics of the ground; (ix) the experimental methodology and the mathematical model chosen for the computation and the behavior of parameters affecting the GHE system. Note that the current review is not concerned with the efficiency of GHEs (see for instance [9]).

In the following sections, an overview of such factors is given. In Section 2, GHE systems are introduced and separated into groups according to their sources. Section 3 presents a comparative study on the Geometry of GHEs, while materials of the GHE are introduced in Section 4. In Section 5, the widely used analytical and computational models are presented and discussed, while the borehole thermal resistance and Thermal Response Test are being introduced. A numerical model demonstration is presented in Section 6, along with a detailed list of mathematical and/or experimental GHE studies for comparison reasons. Section 7 concludes with a discussion and future recommendations.

2. Types of GHE systems

2.1. Open loop systems

The open loop GHE systems can be separated into two sub-categories: ground pre-heating/pre-cooling of air or ground water heat pump (see Fig. 2). The basic principle of the pre-heating or pre-cooling the air is to increase the efficiency of the air-to-air heat exchanges and this is achieved with the ambient air passing through the tubes that follow down in the ground before it enters a convectional air conditioning unit [10].

Overall the open loop systems are considered to have better thermodynamic performance and lower cost compared with the closed loop systems [6]. This is due to the fact that they have low drilling requirements (in the case of one well) and the groundwater delivered is at ground temperature. In contrast the water availability may not always exist and also the heat exchanger is subject to corrosive agents, scaling and bacterial contents [6]. In addition, for the case where a re-injection well is required, the cost is relative high. The larger water flow requirements point to a higher pumping power desired compared with the closed loop systems.

2.2. Closed loop systems

In a closed loop system the heat carrier fluid is circulated within the heat exchanger as opposed to the open loop system where the fluid is the ground water and is not circulated in the system. The closed loop system is separated into the categories of the horizontal and the vertical systems. In both systems pipes are buried in the ground.

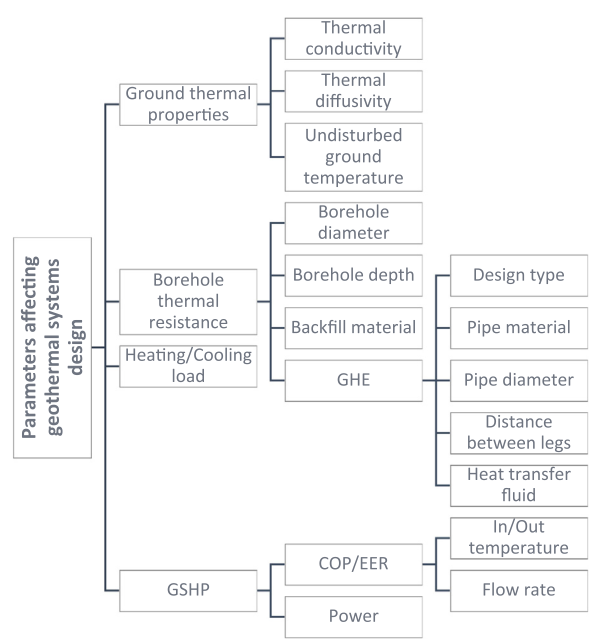

Fig. 1. Factors affecting the design of GHEs (modified from [9].