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Second law analysis of horizontal geothermal heat pump systems

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ABSTRACT

This paper presents an exergetic analysis of the operating conditions of a shallow horizontal ground source heat pump. The analysis is conducted through theoretical evaluation of the exergy potential and the evaluation of the main sources of unavoidable irreversibilities. This approach can be used to assess the main causes of performance reduction and degradation, as well as to select the optimal installation (depth, position) or to modify the operating parameters.

The analysis of a real installation in then considered. This is a horizontal ground heat exchanger, constituted of a network of pipes installed 1 m below the surface, covering an area of about 210 m^2. A comparison of the current installation with a deeper installation, 2 m below the surface, shows that the exergy output can be increased of more than 60%. This improvement can be easily compared with the increase in the installation costs in order to evaluate the optimal depth.

1. Introduction

Geothermal energy is a renewable and diffuse alternative energy source which is expected to play a significant role in sustainable energy development. Geothermal heating and cooling systems are good solutions in terms of investment and operating costs, especially in temperate climates [1]. Horizontal ground source heat pumps (GSHPs) are closed-loop systems that utilize shallow ground as a heat sink or source. In heating mode, heat absorbed from the ground feeds the evaporator of the heat pump; its thermal level is then increased by the compressor. Heat is then supplied to the heating system of the building by the condenser. In cooling mode, heat is absorbed from the building and transferred to the evaporator and then discharged, at higher temperature, to the ground by the horizontal ground heat exchangers (HGHEs) connected to the condenser. In GSHP systems using conventional HGHEs, a network of straight polyethylene pipes lie at the bottom of horizontal trenches [2] or excavations.

Considerable research has been focused on modelling and simulation of vertical borehole ground heat exchangers, with less focus on the modelling of HGHE systems, due to complex transients at the ground surface caused by weather and climatic conditions. The reliable quantification of vertical transient heat fluxes across a topographic surface directed to the ground is often impeded by a lack of suitable meteorological data. In the absence of appropriate data, the topographic surface is usually considered as adiabatic, and heat transfer from the surface is disregarded [3–11]. The main input data for calculation models for GHEs generally include the geometric characteristics of the system, thermal characteristics of the ground and pipes, and undisturbed ground temperature during system operation [12].

Several recent works on slinky-coil horizontal ground heat exchangers are also available in the literature. Fujii and co-workers [13] have applied a numerical analysis using the software FEFLOW to predict the performances of a horizontal heat exchanger. Congedo and coworkers [14] have developed a numerical model using the software Fluent to evaluate the effects of fluid velocity and depth of installation on the annual performances. In Ref. [15] a numerical analysis is performed in order to investigate the effects of the coil diameter on the heat extraction.

In the present work, a numerical analysis of ground heat exchangers is combined with exergy analysis. There are various papers in the literature proposing exergy analysis of geothermal heat pumps (see for example Refs. [16–18]). These are mainly focused on the design and analysis of the heat pump. This work, instead, is focused on the analysis of the ground heat exchangers, with the goal of highlighting possible improvements in the design or operation. In fact, exergy analysis allows one obtaining quantitative and coherent evaluation of the possible sources of irreversibilities that limit the energy performance of the entire system.

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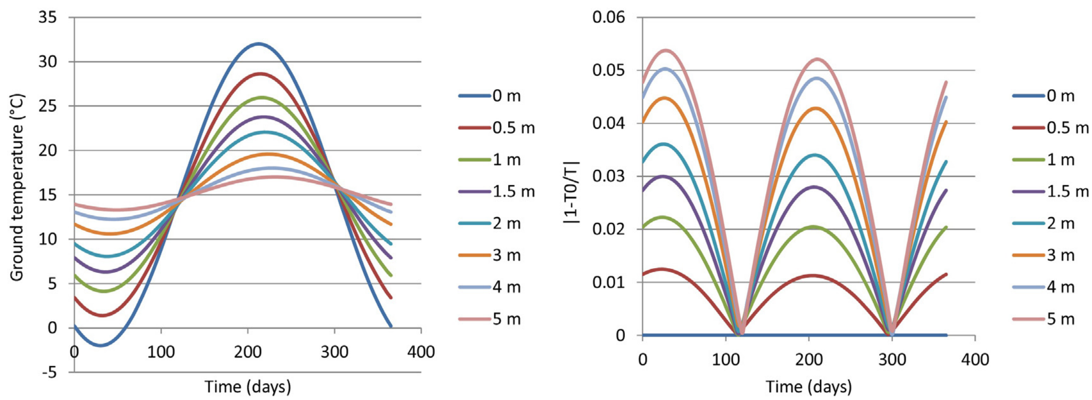

Fig. 1. Ground temperature (a) and specific exergy of a heat flux exchanged with the ground (b).

The proposed procedure is alternative to parametric simulation of the complete ground heat exchanger and can be based on a simpler thermofluid dynamic model. This allows one to overcome problems related with the typically large aspect ratios that are involved in the simulation of the full system.

2. Exergy analysis of ground heat exchangers

One of the most interesting uses of the concept of exergy consists in comparing different forms of energy, or energies of different quality. Through the concept of exergy, all forms of energy are converted into the same form, i.e. work. Exergy is the maximum amount of work that can be obtained from an amount of energy, using it in a device which only interacts with the biosphere.

In the case of ground heat exchangers, exergy allows one to analyze the heat fluxes exchanged in a system also taking the temperatures of the source and external environment into account. The first temperature depends on the characteristics of the location, the depth of the ground heat exchanger and the operating conditions. In the case of shallow installations in urban areas, possible interactions between the ground heat exchanger and buildings, underground stations or tunnels, etc. might be also relevant. The temperature of the external environment, for a specific location, depends on the season, day and hour. Exergy associated with an amount of heat, extracted from the ground or injected, increases with increasing difference between these two temperatures.

An evaluation of the ground temperature as the function of time and depth can be obtained using the Kasuda equation [19], which behaviour is shown in Fig. 1a in the particular case of a soil with thermal diffusivity of 0.4 m^2/s, annual average temperature of 15 °C and temperature variation amplitude of 17 °C. The specific exergy of a heat flux exchanged with the ground can be obtained as

$$\theta = \left|1 - \frac{T_0}{T}\right| \tag{1}$$

where T_0 is the ambient temperature and T the local temperature of the ground (both in K). The reason for the absolute value is related with the sign of the heat flux, which is positive when subtracted from the ground and negative when injected. In the first case, ground temperature is generally larger than ambient temperature while the opposite occurs in the second case. The specific exergy corresponding to temperature distributions of Fig. 1a is shown in Fig. 1b.

These curves show that there is no exergy transfer involved in the case of an installation on the surface. Specific exergy increases with the depth. Moreover, the largest advantage of deeper installations is particularly evident in the case of the coldest and warmest days. These are also the days with the largest heating and cooling requests and the largest heat fluxes exchanged with the ground. The marginal advantage in deeper installations decreases with the depth. This quantity is about 0.02 1 m^{-1} for installations at 0.5 m and 0.001 1 m^{-1} for installations at 5 m.

This evaluation is ideal since it does not consider two major effects: the resource degradation during its utilization and the temperature gradients in the portion of ground close to the heat exchanger. Both effects are related with the finite surface of the ground heat exchanger and can be evaluated using a numerical model. Using the continuum approach, exergy destruction can be calculated by applying the Guy–Stodola theorem and considering the expression of entropy generation due to heat transfer [20]:

$$\Psi_d = T_0 \cdot \Sigma_i = T_0 \cdot \int \frac{k}{T^2} (\nabla T)^2 \cdot dV \tag{2}$$

where k is the ground conductivity. This quantity mainly depends on the time variation of the heat flux. In the case of balanced heat request, exergy destruction does not depend significantly on the depth, as highlighted by the comparison shown in Fig. 2. This figure reports the distributions of exergy destruction per unit volume for two installations at different depths: 1 m (Fig. 2 left) and 2 m (Fig. 2 right). These plots refer to the maximum heat request in the coldest winter day (about 38 W/m^2). It is shown that irreversibilities due to the heat transfer with the ground do not significantly depend on the depth of installation. This means that this quantity is not particularly affected by the differences in the temperature distributions. Similar conclusions can be drawn in the case of smaller heat flux, therefore it is possible to state that, for a given heat flux, an increase in the exergy of the resource (the ground) becomes an equal increase in the exergy associated with the product (the fluid).

3. Application to a real installation

The horizontal GSHP system considered in this study is installed at the Caleffi Research Centre, located in Fontaneto d'Agogna, in the North of Italy. The building connected to the existing GSHP plant, called the "Cubo Rosso" (which means the red cube), is used for research offices and laboratories. This system has been selected in the present work as it is a good example of the advantages of a second-law design approach with respect to parametric simulation of the full system.

The HGHEs are buried about 1 m below the surface and cover an area of 210 m^2. This closed-loop system is designed to meet heating and cooling requirements of the building during periods of high energy demand. The exchangers are separated into 3 circuits of 70 m^2. Each area is formed by 160 m of high density polyethylene pipes (HDPEs) 32 mm × 2.9 mm. The fluid in the pipes is a solution of water and propylene glycol (50%). The pipes are connected in series, and the wheelbase between the pipes is about 40 cm. The