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Research paper

Energy and exergy analysis of a geothermal heat pump air conditioning system

Roberto Baccoli [a,*], Costantino Mastino [a], Giuseppe Rodriguez [b]

[a] Institute of Technical Physics, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
[b] Department of Mathematics and Computer Science, University of Cagliari, Viale Merello 92, 09123 Cagliari, Italy

HIGHLIGHTS

- The energy and exergy analysis of a GSHP versus a ASHP system is considered.
- The model works on a time scale of a year, with a refinement of less than an hour.
- Flexibility and efficiency are combined by an analytical model and numerical inversion.
- For which order of λ and α the GSHP is not competitive respect to ASHP is determined.
- The economic feasibility of GSHP in mild climates lies on an annual operation.

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ABSTRACT

This paper considers the energy analysis of a heat pump system coupled to the ground by means of vertical exchangers, to verify which thermodynamic boundary conditions, in terms of thermal conductivity and diffusivity of the ground and the grout, make it competitive in comparison with other technologies harnessing atmospheric air as the heat source. The comparison is based on the maximum theoretical efficiency available in correspondence to the temperature effectively assumed by the thermal energy reservoirs in contact with the evaporator and the condenser during the operating conditions. The comparison of the two sources/sinks of heat, i.e. the ground and atmospheric air, represents the comparison between the time trend of the exergy of the two reservoirs required by an ideal GSHP and ASHP respectively. A fully transient heat transfer model able to handle on a time scale of a year or more and with a refinement of less than an hour is considered, since short term variations have significant effects on the overall performance of GSHP. In this paper the borehole heat transfer problem in the Laplace domain is solved for any trend and duration of thermal loads, taking into account an existing analytical approximation model of the full solution proposed by Lamarche and Beauchamp. A numerical inversion using the Inverse Discrete Fourier Transform is then applied to obtain the time domain solution. The method combines the flexibility and accuracy of the analytical model with the superior efficiency of the computational time offered by the numerical inversion if compared with that of methods based on the convolution scheme.

1. Introduction

Heat pump technology is one of the most efficient air conditioning devices for air-conditioning from the energy standpoint. The most widespread technology in areas with mild climates is that of the air source heat pump (ASHP) system, in which heat is extracted from or injected into the atmosphere. In regions with rigid winters the technology of heat pumps that absorb heat from the ground, known as the geothermal type, has long been widely adopted. Its use in mild climates can be justified only by its greater efficiency compared to simple air–air or air–water heat pump systems. There are two main factors that establish the economic feasibility of Ground Source Heat Pump (GSHP) systems: the length of the ground heat exchanger and potential energy savings. Both these factors are the subject of evaluations with the aid of dedicated mathematical models. The accuracy of such mathematical models

* Corresponding author. Tel.: +39 070 675 5262.
E-mail addresses: rbaccoli@unica.it (R. Baccoli), mastino@unica.it (C. Mastino), rodriguez@unica.it (G. Rodriguez).

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and thus the economic viability of GSHP also depend on a number of variables that can be achieved either by experimental measurements or by empirical relations. For instance:

1. The ground, grout and fluid thermal conductivity and capacity and the interference resistance between the pipes inside the borehole.

The thermal properties of the ground and the thermal resistance of the borehole are very important parameters that can lead to an erroneous estimate of the required borehole length and a mistaken estimation of the profitability of the geothermal project. These parameters can be evaluated from semi-empirical relations and/or measured by in situ tests. A comprehensive and recent review about this issue is addressed by Lamarche et al. in Ref. [1]. Moreover, experimental studies of different grouting materials used in vertical geothermal exchangers have been presented by Borinaga-Treviño et al. in Refs. [2,3], by Delaleux et al. in Ref. [4] and by Erol et al. in Ref. [5];

2. The climatic conditions.

The thermal interference of the system with the ground is affected by climate. Morrone et al. in Ref. [6] developed an energy and economic feasibility study for GSHP systems in two different climate locations with different building needs. Their results showed that in mild climates, where the GSHP are mainly used as heat pumps (HP) to satisfy the cooling loads, the annual average temperature of the ground around the energy piles can increase up to about 10 °C after many years of operation, whereas in cold climates the increase is nearly negligible. This can entail a worsening of GSHP performance that needs to be accounted for when designing such systems. Moreover Zarrella and Pasquier in Ref. [7] investigated the effect of weather at ground level on the outlet fluid temperature of the boreholes;

3. The time profile of the heating and cooling loads.

The time operating mode influences the performance of a GSHP system. This issue was experimentally and numerically investigated by Jalaluddin and Miyara in Ref. [8] and by Cui et al. in Ref. [9]. The results show that the discontinuous and alternative operation mode in short time scales effectively improves GSHP performance;

4. The stratigraphic properties of the ground.

In the current design of borehole heat exchangers (BHEs), the ground is commonly considered to be homogenous. Luo et al. in Ref. [10] analyzed the heat transfer problem in a layered subsurface. Their results show that the thermal performance of BHE can deviate drastically with different strata. Thus, the analysis of the heat transfer of a BHE with different geological layers can be important for optimal sizing of BHEs;

5. Soil-pipe interaction under real thermodynamic conditions.

During the running of GSHP systems in cold regions, the interaction between the soil and the ground heat exchanger may cause frost heave. Wang et al. in Ref. [11] presented an experimental study about the interaction between soil and the U-pipe in presence of pipe squeeze or collapse caused by the radial expansion of the ground, as a consequence of freezing during heat extraction. Their results show that GSHP experiences severe performance problems during pipe squeeze due to ground freezing.

The first factor, the length of GHE, concerns the design environment and is usually tackled with long term behavior modeling. The aim of a design tool is to establish a minimum borehole length so that the ability to reject or extract heat over a numbers of years is enough to ensure proper operation of the system. In other words the design goal is to control the temperature rise of the ground and then of the circulating fluid within acceptable minimum and maximum limits tolerated by the heat pump during the life of the system. For systems with severely undersized ground heat exchangers, the entering fluid temperature of the ground side, after a medium or long period, may be so high/low that the heat pump fails because the BHE may not meet the user's long-term heating or cooling needs. Nevertheless, it is possible to avoid this problem either by increasing the total length of the installed ground loop heat exchanger and/or increasing the spacing between the boreholes. However, the initial cost may be significantly higher so that a ground source heat pump system may not be competitive with conventional alternatives and the energy savings may not cover the initial cost.

The authors of the present work did not address the problems concerning the sizing of geothermal exchangers. The length of the ground heat exchanger (GHE) is taken for granted and the one assumed ensures that the fluid loop temperature is held between the minimum and maximum temperature range tolerated by the heat pump during over the life of the system.

The other crucial factor concerns the potential energy savings supplied by the ground with respect to standard air source heat pump equipment, in which heat is extracted from or injected into the atmosphere. This issue is addressed with simulation tools able to perform an evaluation of the energy analysis of GSHP and optimize the economic benefit of such an expensive system in terms of energy consumption and electrical demand as a function of the coefficient of performance (COP) of the system. If all the other parameters are held constant, the efficiency of the GSHP system depends on the temperature of the source from which the heat is extracted, or into which the heat is injected, and on the efficiency with which it is transmitted between the source and the thermal fluid. Even though in its initial conditions the undisturbed ground might represent a more favorable reservoir of heat as a candidate to achieve better heat pumps performance than that achievable by means of atmospheric air. However, the actual efficiency of the system depends on the real-time trends of the temperature gradients in the borehole, since the GSHP disturbs the ground with respect to its initial conditions. In fact heat transfer to and from the ground loop heat exchanger varies continuously owing to changing building energy requirements. These changes occur in short time-step fluctuations in the supply and return temperatures of the ground loop and can typically vary from 5.6 °C to 10 °C over a given day. The resulting variations have a direct impact on the coefficient of performance of the heat pump unit and thus influence overall system performance in a significant way. Thus for a detailed building energy analysis, a ground heat exchanger simulation model is called for that can reliably and efficiently predict the dynamic of short-term fluctuations of the ground heat exchanger return temperature on a given day, in a real-time refinement. This level of refinement is strongly required in simulation of energy analysis applications and in optimization, whenever this is required to estimate the actual COP of the system with a high degree of accuracy.

The literature now provides several models, both numerical and analytical, for the analysis of the thermal behavior of heat exchangers coupled to the ground.

Recent reviews, of the different models have been carried out by Yang and Fang in Ref. [12].