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Hybrid ground-source heat pump system with active air source regeneration

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ABSTRACT

Ground-source heat pump systems (GSHP) offer great advantages over traditional heating and cooling installations. However, their applications are limited due to the high initial costs of borehole drilling. One way to avoid these costs is by reducing the size of the borefield, e.g. by combining the system with other renewable energy sources or by using active regeneration to increase the system efficiency. In this paper a hybrid ground-source heat pump system (HGSHP) is analyzed. The borefield is split into a warm part and a cold part, which allows for seasonal thermal-energy storage. Additionally, supplementary drycoolers capture heat during summer and cold during winter. The relationship between the underground storage size and temperature and the drycooler capacity is described, using an office building in Flanders (Belgium) as reference case. Results show that with a HGSHP system a significant borefield size reduction can be achieved without compromising system performance; i.e. for the reference case a reduction of 47% was achieved in the cost-optimal configuration. It is also shown that the cooling seasonal performance factor decreases significantly with underground storage capacity. In addition, the HGSHP can be used to maintain or restore thermal balance in the geothermal source when heating and cooling loads do not match.

1. Introduction

Ground-source heat pump systems (GSHP) are used in many residential and commercial buildings for heating and cooling. Over the last decade, partially under the incentive of European energy efficiency measures, the energy efficiency of new buildings has increased rapidly. Measures to improve the thermal insulation have resulted in a reduced heating load of these newly constructed or renovated buildings. However, in many cases these improvements have an adverse effect on cooling load, especially when the building has to deal with high internal energy gains (e.g. office buildings and hospitals).

When using a regular GSHP system, the annual imbalance between heating and cooling load may lead to a long term rise in ground temperature, resulting in a less efficient free cooling operation [1,2]. One way to reduce this effect is to install more or longer ground heat exchangers (GHE). However, the increased drilling costs for a larger GSHP system can ultimately render the project economically unviable.

A possible solution to this problem is to use a hybrid ground-source heat pump system (HGSHP), which uses an additional heat exchanger to reject or capture seasonal energy.

The main advantage of the hybrid solution is that the storage temperature is more controllable and thermal depletion of the underground can be avoided. In climates with a distinct thermal imbalance between the heating and cooling season, HGSHP systems can provide a solution. In certain environments space limitations may prohibit a full geothermal installation [3] or in countries with complex subsurfaces where drilling costs restrict the application of geothermal systems, hybrid systems may be preferred. However, the added complexity of a HGSHP system poses technical challenges that have slowed the growth of hybrid systems [4].

To the authors knowledge, only HGSHP systems with a single borefield have been discussed in literature. These configurations use an additional heat rejecter to balance the thermal energy injection and extraction into and from the borefield. In most cases the additional heat exchanger is coupled in series with the ground heat exchangers.

Several references have addressed hybrid heat pumps and their operations strategies. Yavuzturk and Spitler [5] described different operating and control strategies for hybrid ground-source heat pump systems and assessed their impact on the system operation. It was found that the supplemental heat rejecter (in this case a

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cooling tower) performed best under advantageous weather conditions, i.e. the temperature difference between the heat pump fluid temperature and the ambient air exceeds a threshold value.

Lubis et al. [6] performed a thermodynamic analysis of a hybrid ground-source heat pump system. The results indicate that hybrid GSHP systems operate at higher COP and exergy efficiencies compared to typical air-source heat pump systems. Ramamoorthy et al. [7] presented a system simulation approach for determining the optimal size of a hybrid GSHP system that uses a cooling pond as a supplemental heat rejecter. Yi et al. [8] reported a simulation model of a hybrid ground-source heat pump system. Based on the results, the optimal HGSHP system for a cooling-dominated building can save 35% on initial costs and 20% on operating costs in first year of operation compared with the common GSHP system. Hackel et al. [9] carried out parametric studies using a HGSHP model. The conclusions suggested that the GHE in cooling dominated hybrid systems should be sized to meet the peak heating load while the supplemental cooling device should be sized to meet the remaining cooling load.

This paper presents an alternative way of operating HGSHP systems. Seasonal energy is stored into two separate borefields: a warm and a cold borefield. This allows for independent and simultaneous use of the heat pump and a drycooler (functioning as an additional heat rejecter). In the heating season (winter), when ambient temperatures are relatively low, the heat pump extracts thermal energy from the warm borefield while the drycooler extracts heat from the cold borefield, regenerating its cooling capacity. In the cooling season (summer), when ambient temperatures are relatively high, the drycooler injects ambient heat into the warm borefield while the cold borefield is used to provide free-cooling to the building.

It is common practice to size the ground heat exchangers proportional to the buildings heating and cooling load. However, in this alternate hybrid configuration, the amount of heat injected or extracted to and from the separated borefields is also determined by the specifications of the additional heat exchanger, its operation strategy and the ambient temperature. This hybrid setup can result in smaller borefield configuration when compared to a regular GSHP system, since both heat or cold can be stored more efficiently.

Different types of additional heat exchangers can be used in a HGSHP configuration, e.g. drycoolers or cooling towers. In this study a drycooler was used, as the heat exchanger has to be able to deliver both heat and cold to the incoming fluid. It should be noted that the use of an additional drycooler can result in higher operating costs when compared to a regular GSHP system. This is due to higher electricity consumption by additional pumps, valves and fans. Nevertheless, the savings on drilling costs are expected to result in an overall economical benefit.

Another advantage of the hybrid configuration is that the drycooler can be used for grid-balancing or to maximise self-consumption of locally produced electricity from renewable energy sources (e.g. wind, solar). Excess electricity can be converted into heat or cold and stored locally in the borefields in order to balance supply and demand on the electricity grid. In this paper however, the drycooler operation strategy and related business cases will not be investigated.

A Belgian office building with a HGSHP system has been modelled in Trnsys, a dynamic building simulation platform [10]. In order to analyse the system performance, a regular GSHP system was simulated over a 20 year period and used as reference case. In this setup, the ground heat exchangers were sized to cover the cooling load of the building when only using free cooling, resulting in a borefield containing 66 heat exchangers. A series of simulations were carried out with the HGSHP configuration to optimize installation costs and to determine the possible size reduction of the cold borefield.

The general configuration of the Hybrid installation and the operation strategy are presented in Section 2, while the model and simulation environment are discussed in Section 3. Finally, the interpretation of the simulation results is summarized in Section 4.

2. Hybrid ground-source heat pump system

2.1. Description

A general configuration diagram of the HGSHP is presented in Fig. 1 (cooling mode) and Fig. 2 (heating mode). Three-way valves are used to connect either the warm or cold borefield to the building heat exchanger. A bypass over the heat pump allows the system to operate in free-cooling mode. Both the warm and cold borefields are connected to the drycooler by two controllable valves. In order to ensure parallel operation of the drycooler with the heat pump, the drycooler has its own circulation pump.

The initial dimensions of the warm and cold borefield are based on the size of the single borefield of the GSHP reference case, which is determined by the simulated load profile of a Belgian office building. The output temperature of the GSHP borefield must be kept below 15 °C over a period of 20 years to ensure free-cooling operation in summer. Based on the local geological conditions, a borefield of 66 ground heat exchangers (each with a length of 130 m) is necessary in order to provide the necessary free cooling capacity.

2.2. Control strategy

The heat pump and free cooling bypass control strategy is similar to regular ground source heat pump systems and is based on the heat and cooling demand of the office building.

The drycooler control strategy is based on the availability of warm and cold storage capacity and the temperature difference between the borefield and the ambient air (as suggested by Yavuzturk and Spitler [5]).

In winter, when there is no cooling demand and the ambient temperature drops at least 3 degrees below the cold borefield temperature, the three-way valves disconnect the cold borefield (and connect the warm borefield) with the heat exchanger while the two-way valves between the cold borefield and the drycooler are opened (Fig. 2). The two-way valves between the warm borefield and the drycooler are closed. The drycooler is activated and uses the cool ambient to reject thermal energy from the cold borefield, hence lowering the storage temperature. When the temperature difference between the cold borefield and the ambient air decreases below 3 °C, the drycooler is deactivated. In spring and summer, when the temperature difference between the ambient air and the warm borefield exceeds 3 °C and when there is no heat demand, the three-way valves disconnect the warm borefield (and connect the cold borefield) with the heat exchanger while the two-way valves between the warm borefield and the drycooler are opened (Fig. 1). The two-way valves between the cold borefield and the drycooler are closed. The drycooler is activated and uses the warm outside environment to inject thermal energy into the warm borefield, hence increasing the storage temperature. When the temperature difference between the ambient air and the warm borefield decreases below 3 °C, the drycooler is deactivated. This control strategy does not try to balance the yearly injection and extraction of thermal energy, as it would be the case in many HGSHP systems which operate with a single borefield, but attempts to maximize seasonal energy storage.

When the output temperature of the warm borefield drops below 5 °C (during the winter heating season), the heat pump is allowed to extract thermal energy from the cold borefield to