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Performance of an experimental ground-coupled heat pump system for heating, cooling and domestic hot-water operation

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ABSTRACT

The ground-coupled heat pump (GCHP) system is a type of renewable energy technology providing space heating and cooling as well as domestic hot water. However, experimental studies on GCHP systems are still insufficient. This paper first presents an energy-operational optimisation device for a GCHP system involving insertion of a buffer tank between the heat pump unit and fan coil units and consumer supply using quantitative adjustment with a variable speed circulating pump. Then, the experimental measurements are used to test the performance of the GCHP system in different operating modes. The main performance parameters (energy efficiency and CO_2 emissions) are obtained for one month of operation using both classical and optimised adjustment of the GCHP system, and a comparative analysis of these performances is performed. In addition, using TRNSYS (Transient Systems Simulation) software, two simulation models of thermal energy consumption in heating, cooling and domestic hot-water operation are developed. Finally, the simulations obtained using TRNSYS are analysed and compared to experimental data, resulting in good agreement and thus the simulation models are validated.

1. Introduction

Ground-coupled heat pump (GCHP) system is a type of renewable energy technology and is popular for air-conditioning and domestic hot-water worldwide [1–3]. A number of GCHP systems have been used in residential and commercial buildings worldwide because of their noticeable high efficiency and environmental friendliness. Due to the heat capacity of ground, ambient air temperature variations are directly reflected only on the surface ground temperature, their effect being reduced at deeper layers. According to the reports of the 2010 World Geothermal Congress, the GCHP systems have the largest energy use and installed capacity, accounting for 69.7% and 49.0% of the worldwide capacity and use. The installed capacity is 35,236 MWt and the annual energy use of 214,782 TJ/yr, with a capacity factor of 0.19 (in the heating mode). Almost all of the installations occur in North American, Europe and China, increasing from 26 countries in 2000, to 33 countries in 2005, to the present 43 countries. Sweden, Denmark, Switzerland, Austria, and the United States are the leaders in this field [4]. The number of installed GCHP systems has grown continuously by 10–30% annually in recent decades [5–7]. Extrapolating currently observed growth rates for Europe of 5.4 million heat pump units per year leads to an expectation of 70 million installed units in Europe by 2020 [8]. The use of GCHPs in the achievement of adequate temperatures has been studied by several researchers [9–12]

A GCHP system consists of a heat pump unit coupled with a ground heat exchanger (GHE), usually a vertical borehole heat exchanger (BHE) or, less commonly, horizontal loops [13]. A BHE is commonly drilled to a depth between 20 and 300 m with a diameter of 100–200 mm. A closed single or double *U*-tube is often inserted inside the borehole, and a heat carrier fluid is circulated in the *U*-tube to exchange heat or cold with the surroundings. For safety and stability reasons, a bentonite-cement suspension or an enhanced-cement is used to backfill the space between the *U*-tube and its surrounding soil/rock. A GCHP utilises the ground as a heat source in heating and a heat sink in cooling mode operation. In the heating mode, a GCHP absorbs heat from the ground and uses it to heat the building. In the cooling mode, heat is absorbed from the conditioned spaces and transferred to the earth through its GHE.

Most existing studies of GCHP systems concentrate on theoretical and simulation model research [7,14–16] or in situ monitoring of the heat transfer in BHE [5,6,17–21]. Only a few researchers have investigated the experimental operation

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performance of GCHP systems. Hwang et al. [19] presented the actual cooling performance of a GCHP system installed in Korea for 1 day of operation. Pulat et al. [22] evaluated the performance of a GCHP with a horizontal GHE installed in Turkey under winter climatic conditions. The coefficient of performance (COP) of the entire system and the heat pump unit were found to be 2.46–2.58 and 4.03–4.18, respectively. Yang et al. [23] reported the heat transfer of a two-region vertical *U*-tube GHE after an experiment performed in a solar geothermal multifunctional heat pump experimental system. Lee et al. [24] conducted experiments on the thermal performance of a GCHP integrated into a building foundation in summer. Man et al. [25] performed an in situ operation performance test of a GCHP system for cooling and heating provision in a temperate zone. The experimental results indicate that the performance of the GCHP system is affected by its intermittent or continuous operation modes. Petit and Meyer [26] compared the thermal performances of a GCHP with an air source air conditioner, finding that a horizontal or vertical GCHP was more favourable in terms of economic feasibility. Esen and Inalli [27] proposed using the in situ thermal response test to determine the thermal property of the ground for the GCHP applications in Turkey, and they found that the thermal conductivity and effective thermal resistance of the ground vary slightly with depth.

The present paper is focused on the energy and environmental analysis and modelling of a geothermal experimental plant from a continental temperate climate, located in an institutional building at the Polytechnic University of Timisoara, Romania. The system consists of a reversible GCHP. One the main innovative contribution of this study consists in the achievement and implementation of an energy-operational optimisation device for the GCHP system using quantitative adjustment with a buffer tank and a variable speed circulating pump. The experimental measurements are used to test the performances of the GCHP system at different operating modes. The main performance parameters (energy efficiency and CO_2 emissions) are obtained for 1 month of operation using both classical and optimised adjustment of the GCHP system. A comparative analysis of these performances for both heating and cooling and domestic hot-water (DHW) with different operation modes is performed. The second purpose of this paper is to develop two simulation models of thermal energy consumption in heating/cooling and DHW operation using TRNSYS software. Finally, the simulations obtained using TRNSYS software are analysed and compared to experimental measurements.

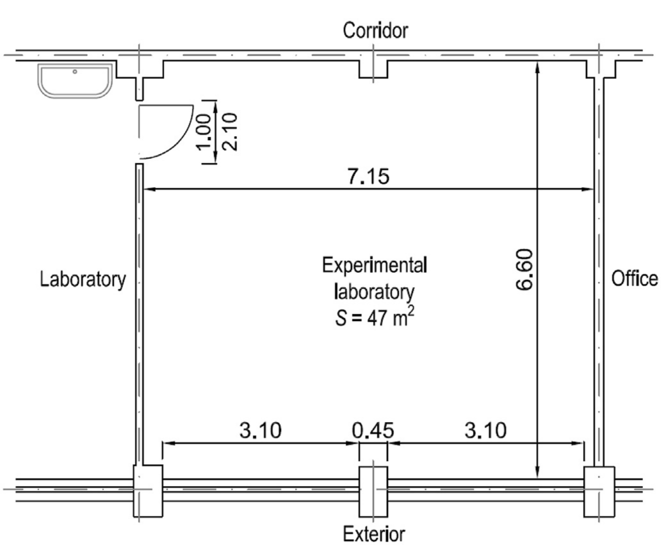

Fig. 1. Experimental laboratory.

2. Description of experimental laboratory

Experimental investigations of GCHP performance were conducted in a laboratory (Fig. 1) at the Polytechnic University of Timisoara, Romania, located at the ground floor of the Civil Engineering Faculty building with six floors and a heated basement. The city has a continental temperature climate with four different seasons. The heating season runs in Timisoara from 1 October to 30 April, and the cooling season runs from 1 May to 30 September. The laboratory room has an area of 47 m^2, and its height is 3.70 m. The envelope (external walls) is made of 200 mm porous brick with a 100 mm thermal insulating layer and 20 mm lime mortar. The thermal transmittances (*U*-values) are as follows: walls 0.345 W/m^2K and double-glazed windows 2.22 W/m^2K. The area of the windows is 16 m^2, and the area of the interior door is 2.1 m^2. The indoor air design temperature is 20 °C for the heating season and 26 °C for the cooling season. The outdoor air design temperature is −15 °C for the heating season and 32.6 °C for the cooling season.

The GCHP installed in this experimental laboratory heated and cooled through a fan coil system. With the mentioned input data, a heating load of 3.11 kW and a cooling load of 2.15 kW were obtained. The laboratory area was assimilated with a three-person apartment area in Timisoara. Considering the DHW daily mean consumption of 50 l/person, a tank hot-water temperature of 45 °C and a cold water temperature of 20 °C, a DHW load of 4.36 kW was determined. Fig. 2 illustrates the monthly energy demand for laboratory heating (positive values) and cooling (negative values).

3. Description of the experimental system

The GCHP experimental system consisted of a BHE, heat pump unit, buffer tank, circulating water pumps, fan coil units, sink, data acquisition instruments and auxiliary parts, as shown in Fig. 3. The heat carrier fluid can be delivered towards two fan coils units in two flow rate adjustment modes:

– direct, by a recirculation pump connected inside of the heat pump unit of the GCHP system (classical solution);
– indirect, by a fixed speed circulating pump connected to a buffer tank. The GCHP automation can control the operation of the circulating pump connected to the buffer tank by on/off switching. This assembly improves the entire system operation. The buffer tank allows decreasing the GCHP on/off switching because

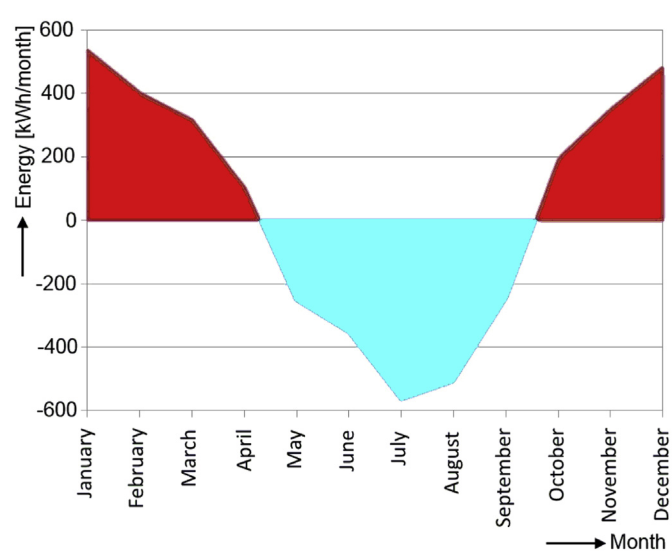

Fig. 2. Monthly energy demand for laboratory heating/cooling.