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Optimization of operating parameters of a ground coupled heat pump system by Taguchi method

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ABSTRACT

This paper focuses on optimization of vertical ground coupled heat pump (VGCHP) system. This optimization is realized by examining effects of parameters on the system. Thus, experimental studies have been conducted under varying depth of boreholes and temperatures of condenser and evaporator. Then, the Taguchi method is applied to these parameters to optimize coefficient of performance (COP) of VGCHP system. Also, analysis of variance (ANOVA) and signal/noise (S/N) ratio are used for evaluation of experiment results. It is found that depth of borehole is the most significant parameter, affecting the COP by 67.77%.

1. Introduction

Usage of ground coupled heat pumps (GCHPs) increases day by day. Temperature of soil at a certain depth remains constant and that is the most important property, making this system attractive. The GCHPs gather heat from the soil, using a ground heat exchanger (GHE) whose pipes are installed in soil by different geometries. Heat, drawn through the soil, is transferred into a water-antifreeze solution inside a loop of pipe. Refrigerant passes through a compressor, raising it to a higher temperature, then heat water or air for heating system. The cooled GHE fluid returns to the soil where it gathers further energy from, in a continuous cycle since heating is required. Typically, for a domestic home the loop is laid flat or coiled in trenches about 2 m deep but if there is not enough space in your area, you can install a vertical GHE down into the soil to a depth of up to 100 m. Vertical GHEs are also used where the soil is too shallow for trenching, and they minimize the disturbance to existing landscaping.

In literature, countless numerical, experimental and economical studies related to GCHP system are made [1–24]. In this study, we focus on vertical GHEs. Experimental studies constitute a major part of scientific researches. To reach precise results, experimental design must be well planned [25]. Observation, derivation and interpretation of any variation on the response variable, while acting such changes needed with respect to the input variables of any process, can be defined as experimental design [26]. In engineering area, experimental studies have an important role in new product design and improvement. According to Salmon (1990) and Taguchi (1986), suggested numerous approaches to experimental designs that are sometimes called "Taguchi methods". These methods apply two-, three-, and mixed-level fractional factorial designs. Large screening designs seem to be principally chosen by Taguchi adherents. Since that is a way for guaranteeing better performance in the design period of products or processes, this method refers to experimental design as "off-line quality control". Some experimental designs can be used on-line while the process is running, such as when used in evolutionary operation [27].

With regard to optimization of GCHP operating parameters, few research works have been published. Ramniwas et al. [28] applied Taguchi technique to optimize the operating parameters of a GCHP system for space heating application. They observed that the condenser outlet temperature plays an important role in controlling the value of COP of a GCHP system when operated in heating mode. Verma and Murugesan [29] examined the performance of a solar assisted GCHP system for heating application using Taguchi technique and utility concept. The design parameters are optimized to obtain the optimum solar collector area and ground heat exchanger length for space heating application with optimum COP. Sivasakthivel et al. [30] proposed a methodology to optimize the performance of a GCHP system for space heating and cooling applications using Taguchi method and utility concept.

In the present work, we attempt to determine the most significant parameter, affecting COP of a vertical GCHP system for heating mode. Condenser inlet–outlet, evaporator inlet–outlet

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temperatures and depth of boreholes are considered as influencing parameters of the GCHP system. Detailed discussions, on the Taguchi method implementation for heating mode alone followed by the use of utility concept to determine the final optimum COP of the GCHP system, are made in following sections.

2. Experimental devices and measurements

In this study, vertically drilled boreholes were implemented for three different depths as 30, 60, and 90 m for a room in Elazig, Turkey. The GCHP system overview is given in Fig. 1.

In the experimental study, thermal resistance and conductivity tests of soil were done in selected boreholes (60 m and 90 m). The thermal resistance/conductivity of 60 and 90 m-boreholes were calculated as 0.05 kW^{-1} m^{-1}/1.70 Wm^{-1} K^{-1} and 0.03 kW^{-1} m^{-1}/1.70 Wm^{-1} K^{-1}, respectively [5].

The single U-borehole GHEs were connected to a heat pump unit, sited in room. The heating load of the room was 1.72 kW at design conditions. The main components used in experimental studies can be summarized as follows; pipe distance: 60 mm; pipe diameter: 40 mm; borehole diameter: 150 mm; polyethylene SDR 11; single borehole. Heat exchanger: (air cooled condenser for heating, evaporator for cooling); manufacturer: Friterm; HS 10; 3.77 kW; heat transfer surface: 10 m^2. Water-antifreeze solution heat exchanger; TTE 3; 6.97 kW (with Freon 22). Compressor: Tecumseh Europe; hermetic; FH 5524 F; 7.6 m^3/h; 2900 tr/mn; 2 HP; suction line: 5/8 in, discharge line: 3/8 in. Dryer: Carly; DCY 083; 11.1–18.8 kW. Fan circuit: Friterm; 350 mm; 2350 m^3/h, 145 W. Observe glass: Carly VCYL 13; green and yellow; 3/8 in. In heating mode, the water-antifreeze fluid transfers its heat to refrigerant fluid in the evaporator. R-22 refrigerant, which flows through other closed GHE in the heat pump, evaporates by gathering heat from the brine solution, flowing through the evaporator, then passes through compressor. Ozone Depleting Substances (ODS) are chemicals that can damage the earth's ozone layer if they escape into the upper atmosphere. ODS include chlorofluorocarbons (CFCs) such as R12 and R502, hydro chlorofluorocarbons (HCFCs) such as R22 and drop in blends such as R408A, R123 and R142b. HFCSs are still in use as refrigerants in many buildings in Refrigeration and Air Conditioning (RAC) equipment. A ban on the use of all refrigerants ODS for the maintenance or servicing of existing RAC and heat pump equipment is place since 1st January 2015 [31]. A condenser fan carries warmed air into room. The solution in the GHEs gathers heat from the soil and transfers to room. The horizontal distances between the boreholes are 3.4 (VB3–VB2) and 2 (VB1–VB2) m, respectively (see Fig. 2). The measurement dots of the soil section are also shown in Fig. 2.

In this study, U-pipe GHEs were vertically buried in the marn type ground (λ = 1.70 Wm^{-1} K^{-1}). For all boreholes, as a grout

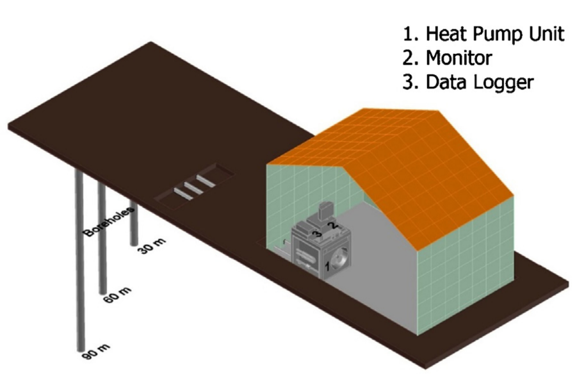

Fig. 1. Vertical GCHP system overview.

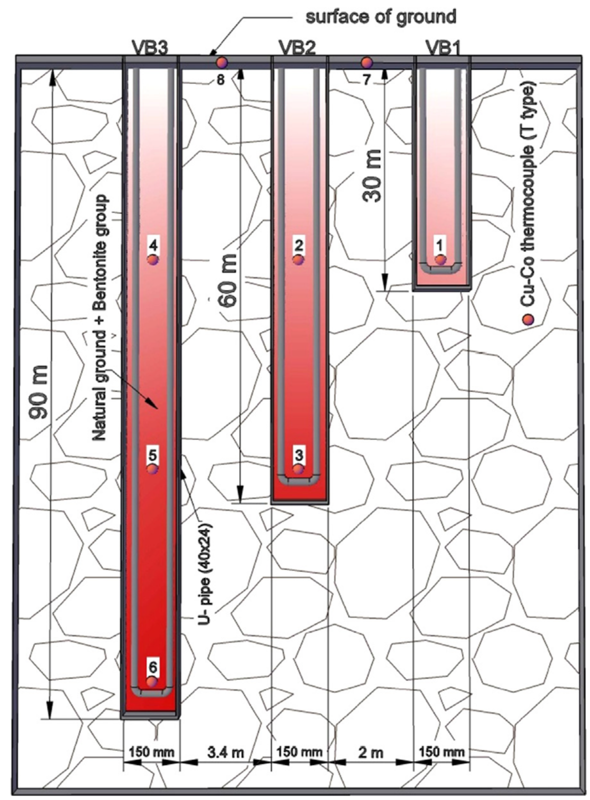

Fig. 2. The sketch of ground section.

material, bentonite is used. A number of T-type thermocouples were installed to measure all the circulating water-antifreeze solution and soil temperature.

T type thermocouples with an accuracy 0.018 °C, a metal vane type anemometer with ±2% accuracy and pressure manometer with ±0.3% (at ±25 °C) accuracy were used to accomplish these experiments. The error analysis of the measurements are calculated ±2.89% for the brine and R-22 temperatures, ±2.75% for pressures, ±4.35% for power inputs to the compressor, condenser fan and circulating pump, and ±3.00% for electric currents. Error value is taken ±0.20% in reading values of the table.

3. Analysis and verification of experimental study

Following equation gives heat ($\dot{Q}_{eva}$), extracted from the soil in heating mode:

$$\dot{Q}_{eva} = \dot{m}_{wa} C_{p,wa} (T_{wa,o} - T_{wa,i}) \tag{1}$$

By Eqs. (2)–(4), power of compressor ($\dot{W}_c$), the water-antifreeze circulating pump ($\dot{W}_p$) and the condenser fan ($\dot{W}_{cf}$) are calculated, respectively.

$$\dot{W}_c = I_c U_c \mathrm{Cos}\,\varphi \tag{2}$$

$$\dot{W}_p = I_p U_p \mathrm{Cos}\,\varphi \tag{3}$$

$$\dot{W}_{cf} = I_{cf} U_{cf} \mathrm{Cos}\,\varphi \tag{4}$$

COP of GCHP system is determined by,

$$\mathrm{COP} = \frac{\dot{Q}_{hl}}{\dot{W}_c + \dot{W}_p + \dot{W}_{cf}} \tag{5}$$

where heating load ($\dot{Q}_{hl}$) is calculated by,

$$\dot{Q}_{hl} = \rho_{air} \dot{V}_{air} C_{p,air} (T_{air,o} - T_{air,i}) \tag{6}$$