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Optimization of ground heat exchanger parameters of ground source heat pump system for space heating applications

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ABSTRACT

In this paper Taguchi and utility methods have been employed to optimize eight important parameters (i.e. radius of U tube, borehole radius, heating load, grout conductivity, entering water temperature, distance between U tubes, U tube thermal conductivity and mass flow rate) of GHX (ground heat exchanger) used for space heating applications. Length of GHX, COP (coefficient of performance) and thermal resistance of GHX are considered as the objective functions. In Taguchi method lower the better concept is applied to obtain optimum values for the length of the GHX and its thermal resistance and for COP higher the better concept is used. In utility concept higher the better method has been employed. Based on the results obtained using Taguchi optimization, the optimum parameters and levels for GHX length, COP and GHX thermal resistances are found to be, A2B1C1D1E3F3G1I3, A2B2C1D3E3F3G1I2 and A1B2C1D2E1F1G3I1 respectively. Results obtained using the above optimized set of parameters show 15.17% reduction in the length of GHX, 2.5% increase in COP and 17.1% reduction in thermal resistance of GHX. The implementation of utility concept to obtain a single set of optimum parameters and levels resulted in 3.2% increase in GHX length, about 1.2% decrease in COP and 13.23% decrease in thermal resistance.

1. Introduction

GSHP (Ground source heat pump) is one of the promising technologies for space heating and cooling applications [1,2]. A GSHP system extracts heat energy stored below the ground during the winter for heating applications. As the ground temperature at which heat is absorbed is higher than the ambient temperature, the coefficient of performance of GSHP becomes higher than the system that would operate directly taking heat from the ambient which is very low during winter [3]. The efficiency of GSHP system depends on the ground heat exchanger loop that provides thermal connection between the heat pump and the ground. The ground loop used for GSHP applications can be either open loop or closed loop [4]. In an open loop system generally water bodies are used as a source for heating. In a closed loop system a GHX (ground heat exchanger) is used as a linking medium between the ground and heat pump. A GHX can be either a horizontal or a vertical loop system. In horizontal loop system HDPE (high density polyethylene) pipes are buried under the ground at a depth of 2–3 m. In vertical systems boreholes are drilled at a depth of 30–300 m. Selection of loop for heat pump applications depends on the availability of water bodies, land etc. The horizontal loop system requires a vast area of land, whereas borehole systems require only a piece of land [5]. In general, there is a mindset among GSHP users that vertical borehole systems are more efficient than the horizontal loop system because the variation in ambient temperature will have more influence on the horizontal loop system that is buried at shallow depth compared to the deep vertical boreholes. Nevertheless, in both the cases the performance of a GSHP system depends on many other parameters such as geological condition, heat exchanger material, carrier fluid, diameter of the pipe, mass flow rate of heat exchanger fluid, distance between the pipes, trench type and borehole diameters [6]. Hence optimization of these parameters is important to reduce the initial cost and running cost of the GSHP system [7].

Bazkiaei et al. [8] proposed a method to optimize a horizontal GHX system by using homogenous and non-homogenous soil profiles. Based on their study, they concluded that the performance of GHX installed in soil with non-homogenous profile has better extraction and dissipation rates compared to the soil with homogenous profile. Zogou and Stamatelos [9] studied the design optimization of heat pump systems to examine the effect of

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Nomenclature

GSHP	ground source heat pump
ASHP	air source heat pump
HDPE	high density polyethylene
RSM	response surface methodology
TRNSYS	transient system simulation
ANN	artificial neural network
S/N	single to noise ratio
GHX	ground heat exchanger
HP	heat pump
COP	coefficient of performance
U	utility value
L	levels
CI	confidence interval
DOF	degree of freedom
ANOVA	analysis of variance
T_{DOF}	total degree of freedom
NV	number of variables
P_i	preference number
sys	system
H	center to center distance between the two pipes
N	total number of experiments
R	number of repetitions
V_e	error in variance
r_{bore}	borehole radius
h_{conv}	convection coefficient
k	ground thermal conductivity
$r_{p,in}$	inner radius of the U pipe
$r_{p,ext}$	outer radius of the U pipe
k_{pipe}	thermal conductivity of the pipe
f_e	error in degree of freedom
k_{grout}	thermal conductivity of the grout
P_{pump}	pump power consumption
P_{comp}	compressor power consumption
P_{fan}	fan power consumption
p	fluid density
q	flow Rate
h	pump head
g	acceleration due to gravity

climatic conditions. They considered northern and southern parts of Europe for their analysis. Their study reveals that milder climates of the Mediterranean and subtropical climates are found to be favorable for a heat pump system. Spitler et al. [10] performed simulation and optimization for different components of a GSHP system. They considered the effect of heating and cooling loads of the buildings on the optimization of heat exchanger length when the GSHP system was operated for 20 years. Their optimization results enabled them to maintain the entering water temperature to the heat pump at the design value. Kjellsson et al. [11] optimized a solar assisted GSHP system with a vertical GHX installed in a dwelling. Their results reveal that using solar collector for hot water production in summer and recharging the ground in winter is the optimal combination. Park et al. [12,13] performed optimization of a hybrid GSHP with parallel configuration of a GHX and compared with a non-hybrid GSHP system. They found that hybrid GSHP system was 21% more efficient than the conventional GSHP system and also they optimized the hybrid GSHP using RSM (response surface methodology). Hackel et al. [14] investigated the optimization of a hybrid GSHP system using TRNSYS (transient system simulation) simulation studio and concluded that for cooling dominated buildings the hybrid system should be sized to meet the heating demand. Some researchers [15–17] carried out thermo-economic optimization of horizontal and vertical ground coupled heat pump systems to reduce the cost of the system. Esen et al. [18] studied the performance of GSHP system and its economic benefits compared to other conventional systems like electric heater, fuel oil, natural gas, liquid petrol gas, coal and oil. They found that during heating operation, the average COP (coefficient of performance) of heat pump was 3.2 and GSHP is economically a good option compared to electric heater, fuel oil, coal, liquid petrol gas and oil but not as a good option compared to natural gas, because of plenty of availability of natural gas in Turkey. Gang and Wang [19] applied ANN (artificial neural network) to predict the exit temperature of GHX. Esen et al. [20–25] applied ANN, neuro-fuzzy and fuzzy logic methods to evaluate the performance of GSHP systems. Esen and Yuksel [26] studied the possibility of using various renewable energy sources for green house heating and they concluded that GSHP also can be used for green house heating. Park et al. [27] compared the cooling performance of an optimized hybrid GSHP system with conventional GSHP system. It was found that hybrid GSHP system was 2–6.5% more efficient than the conventional GSHP system.

Balbay and Esen [28,29] studied GSHP based bridge and pavements heating to clear snow during winter in Turkey by using three different types of heat exchangers. It was found that the GSHP system was able to successfully remove the snow from the bridges and pavements. Pardo et al. [30] optimized the combination of GSHP, HVAC (heating, ventilating, and air conditioning) and ASHP (air source heat pump) to get better performance by studying different groupings of these systems. Luo et al. [31] carried out thermal performance study of a BHX (borehole heat exchanger) with three different borehole diameters. They concluded that boreholes with larger diameter are well suited to achieve better thermal performance. Esen et al. [32] carried out experimental study on a GSHP system coupled with horizontal ground heat exchanger. They evaluated the performance by calculating COP of the system and also created a numerical model to predict the temperature distribution in the vicinity of the heat exchanger and their numerical results compared close to their experimental data. Zhai et al. [33] optimized the required indoor temperature to reduce thermal imbalance in the ground. They concluded that indoor temperature in the range of 22–24 °C is the best temperature for optimum performance of the system. Li and Lai [34] proposed a method to minimize entropy generation with an aim to optimize a single U tube heat exchanger. They concluded that the empirical value proposed for fluid velocity was high compared to the optimum value. Alavy et al. [35] proposed an approach to optimize the design of a hybrid GSHP system. They applied the optimized design to ten different projects to reduce the initial investment cost, payback period and operating cost. Their optimized design was able to meet more than 80% of total annual load. Ramamoorthy et al. [36] proposed a procedure to optimize a GLHE (ground loop heat exchanger) that used cooling pond as heat rejection sink. The main objective of their study was to select an optimum GLHE length along with other supplemental heat rejection units. Khalajzadeh et al. [37] optimized various parameters of a vertical GHX by RSM. They considered depth of borehole, pipe diameter, inlet fluid temperature and Reynolds number as parameters and studied their effect on the efficiency of heat transfer and effectiveness of heat exchanger. They concluded that the inlet fluid temperature and pipe diameter were the most influential parameters. Fujii et al.

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