Parameters optimization of ground source heat pump system combined energy consumption and economic analysis using Taguchi method

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ABSTRACT

In order to obtain a high performance and low cost of ground source heat pump (GSHP) system, a methodology based on Taguchi method and analysis of variance (ANOVA) is used to optimize design parameters of GSHP systems. Eight parameters of GSHP system are selected as control factors to investigate effect on the system. Energy efficiency ratio (EER), coefficient of performance (COP), net annual value (NAV) and the average temperature rise (TEM) in soil of GSHP system are chosen as response factors to evaluate the system performance. A GSHP system model software is established by TRNSYS to calculate the EER, COP, NAV and TEM for 36 times repeatedly according to the L36 (2^2, 6^3) mixed level Taguchi orthogonal array. The result showed that the design outlet temperature of heat pump unit is the most important parameter for EER and COP, of which the contribution of significance are 41.88% and 88.12% respectively. While the number of U-Tubes per borehole has the major contribution (84.64%) for NAV and borehole spacing contribute most (45.42%) to TEM. The optimum EER, COP, NAV and TEM for the system with the optimized parameters combination are found to be 3.9355, 3.0339, CNY 106445 yuan and 2.362 ℃ respectively, which have been validated by confirmatory experiment. The utility concept has been used in this paper to find the optimum parameters combination with comprehensive consideration of all response factors (EER, COP, NAV and TEM) and the optimum combination we can get is A2 B1 C3 D1 E1 F3 G1 H3 with the response factors of 3.873, 3.023, 107212 yuan and 2.774 ℃ for EER, COP, NAV and TEM respectively.

INTRODUCTION

GSHP system is widely known for its high performance and low energy consumption despite the relatively high initial investment. Therefore, increasing the system's performance while minimizing initial investment is a major issue to promote GSHP widely. Mensah et al. (2017) carried out a numerical simulation on the optimum design of a closed loop vertical-type ground heat exchanger considering the building load and heat pump performance. Lubisa et al. (2011) considered thermodynamic analysis of a hybrid geothermal heat pump system and concluded that the performance of hybrid geothermal heat pump is superior to air-source heat pumps. Menberg et al. (2017) developed hybrid ground source heat pump system by reducing the power demand of the supply system, altering the temperature level of the supply system and reducing the space energy demand. There are many design parameters

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in GSHP systems and the relationships among them are very complicated. (Li et al. 2014) Some design parameters significantly reduce the energy consumption and improve the financial performance of a GSHP project (Henault, et al 2016; Gabrielli and Bottarelli 2016). But these methods only considered the effect of single variable, which were usually selected according to the experience, to the system. Often several parameters are included in these study and they failed to consider the impact of multiple parameters on the global result. Therefore, a new method based on Taguchi to analyze the effect of multi-parameter is given in this paper. Taguchi method is one of design of experiment methods developed by Dr. Genechi Taguchi in 1940, which is an effective method to deal with the multi-parameter problem. It can conclude the influence of various parameters on the result by a series of designed experiments and estimate the optimal parameter combination at the parameter design stage.

Sholahudin and Hwataik (2016) used Taguchi method to identify significant inputs and reduce number of parameter for dynamic neural network model, which is used to predict the load of building. Song (2017) combined the Taguchi method and CFD simulation to improve the cooling effectiveness and efficiencies of data centers. Numerous studies have applied the Taguchi method to the parameters optimization of the GSHP system. (Sivasakthivel et al. 2014; Verma and Murugesan 2014 and Pandey et al. 2017)

Cervera-Vázquez (2016) optimize the global energy performance of GSHP system by putting forward a new experiment campaign for multistage heat pump units. Another paper of them (2016) make improvements on the basis of the original multistage GSHP system by combining circulation pumps frequency variation and building supply temperature compensation to satisfied the users' comfort while keep energy saving. Ruiz-Calvo (2016) gave an experiment analysis and performance evaluation of GSHPs, which can be used by researchers for model validation. Currently few studies considered the variation of the building load and dynamic energy consumption of the pump and heat pump units simultaneously for the parameters optimization of GSHP system.

This study is mainly to optimize the basic parameters combination of GSHPs with the maximum coefficient of performance (COP) and energy efficient ratio (EER) for heating and cooling mode while minimizing the net annual values (NAV) and the average temperature rise (TEM) in soil after operating for ten years. The dynamic hourly load and the variation of energy consumption for heat pump units and pump under the variation of load and flowrate are taken into consideration. A methodology based on Taguchi technology is proposed to find the optimum parameters combination for the GSHP system with EER, COP and NAV respectively. Then the ANOVA (analysis of variance) is utilized to analyze the influence of each parameter on the evaluation indexes quantitatively. Finally, the optimized evaluation has been made and confirmed by simulation.

MATHEMATICAL MODEL

1. Heat pump

The COP and heat pump capacity (Cap) are used to evaluate the heat pump model. The heat pump's COP in heating and cooling are given by Eq. (1) and Eq. (2).

$$COP_{heating} = \frac{Cap_{heating}}{P_{heating}} \tag{1}$$

$$COP_{cooling} = \frac{Cap_{cooling}}{P_{cooling}} \tag{2}$$

Where $Cap_{heating}$ and $Cap_{cooling}$ are the heat pump heating and cooling capacity at current conditions as shown in Eq. (3) and Eq. (4). $P_{heating}$ and $P_{cooling}$ are the power consumption by the heat pump in heating and cooling mode.

$$Cap_{cooling} = m_{load} \cdot Cp_{load}(T_{load,out} - T_{load,in}) \quad (3)$$

$$Cap_{heating} = m_{load} \cdot Cp_{load}(T_{load,in} - T_{load,out}) \quad (4)$$

Where m_{load} and Cp_{load} are the mass flow rate and the specific heat of the liquid on the load side of the heat pump. The performance of the heat pump model are illustrated as function of EST and ELT, which is entering source temperature and entering load temperature of the heat pump, in Figure 1, Figure 2, Figure 3 and Figure4 according to the manufacturer specification sheets. In this paper, some variables will be chosen as the control factor, such as heat pump outlet temperature and mass flowrate of both load and source side, which would significantly affect the value of EST and ELT when these factors on different levels. Therefore, this transient heat pump model can satisfied the need with the changing of control factors.

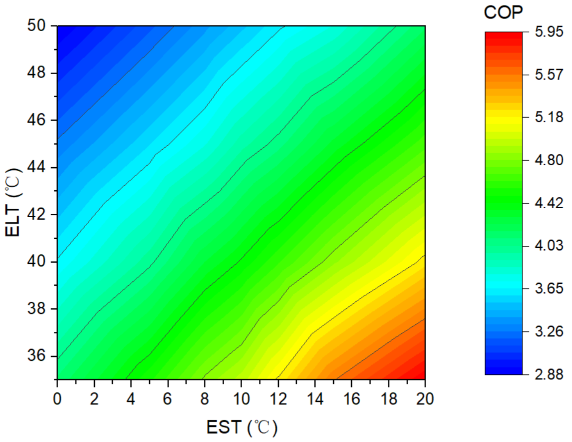


Figure 1 COP contour map in heating mode

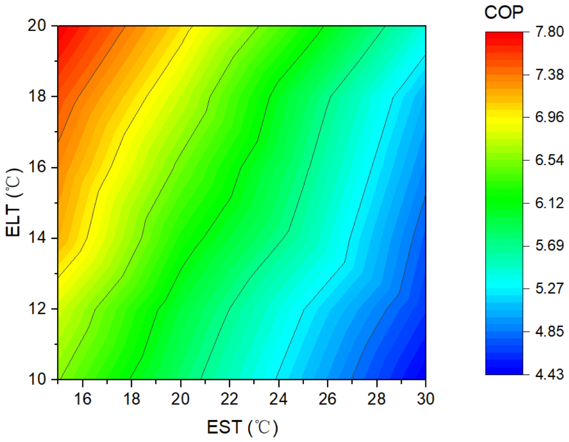


Figure 2 COP contour map in cooling mode

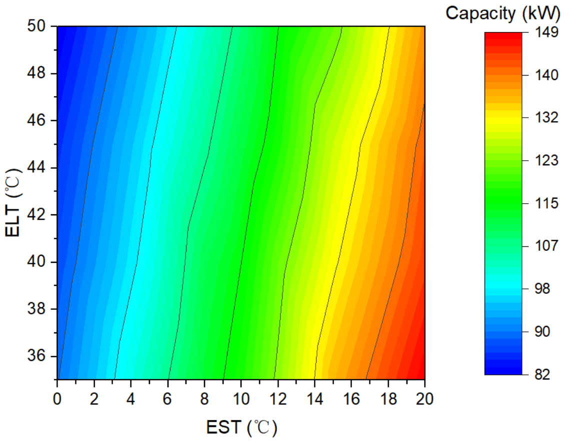


Figure 3 Heating capacity map of heat pump model

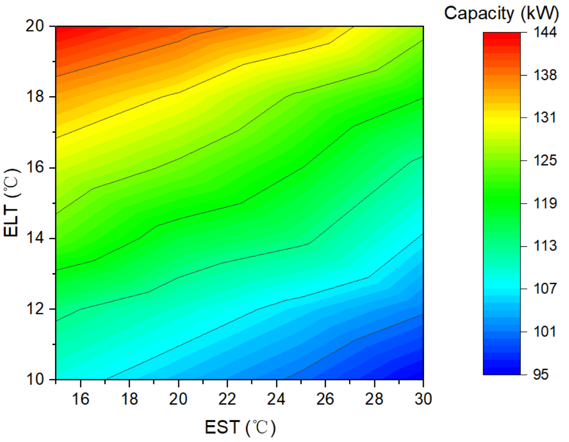


Figure 4 Cooling capacity map of heat pump model

2. Pump

In this article, we also consider the changing of the pump power consumption with the design control factors on different level, such as mass flowrate on both source and load side. The TP65-260/2 pump are chosen with the rated pump head 13.8 m, the rated power 3.75 kW and rated flowrate 55 m^3/h. The polynomial model of the pump are calculated by Eq. (5).

$$\mathrm{P} = a_0 + a_1\left(\frac{m}{m_{rated}}\right) + a_2\left(\frac{m}{m_{rated}}\right)^2 + a_3\left(\frac{m}{m_{rated}}\right)^3 + \cdots \quad (5)$$

Where P is the power consumption of the pump and a_0, a_1, a_2, a_3 are the polynomial coefficients in pump power curve. With m is the design flowrate and m_{rated} is the rated flowrate. Other effects of the pump such as pressure drop, temperature rise etc. are neglected.

3. EER and COP of the system

In the present analysis, the model of this GSHP system has been built in TRNSYS to calculate EER, COP and NAV in Figure 5. The equation of EER and COP are given by Eq. (6) and Eq. (7) respectively.

$$\mathrm{EER_{sys}} = \frac{\mathrm{Q_{SC}}}{\sum \mathrm{N_i} + \sum \mathrm{N_j}} \tag{6}$$

$$COP_{sys} = \frac{Q_{SH}}{\sum N_i + \sum N_j} \tag{7}$$

Where Ni is heat pump units accumulated power consumption and Nj is the pump accumulated power consumption include the source and user pump together during the season and the unit is kWh. Q_{SC} and Q_{SH} are the cumulative cooling and heating capacity of the GSHP system and the unit of it is kWh ,which are presented in Figure 6 with the red line is the heating energy demand and the blue line is the cooling demand.

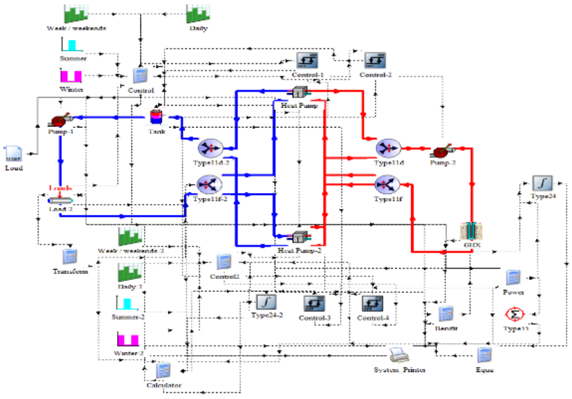


Figure 5 TRNSYS simulation model.

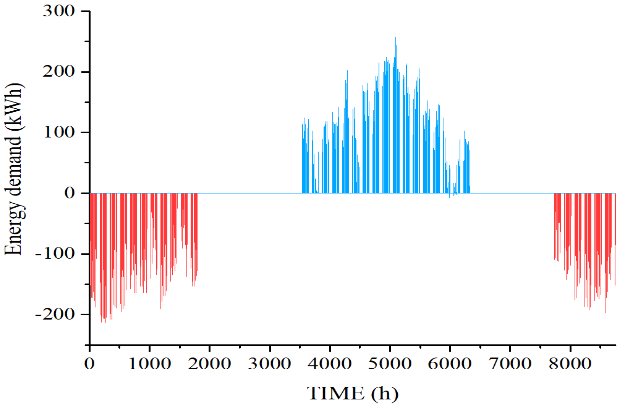


Figure 6 Energy demand of this building throughout year

4. NAV of the system

Net annual value (NAV) of the formula is calculated by Eq. (8).

$$NAV = C_r + C_m + (A/P, i, n) \cdot (C - R) \tag{8}$$

Where C is total initial investment and R is net residual value. R is calculated as $R=\varrho \cdot C$, where ϱ is residual rate chosen as 0.05. Cr is annual operating costs calculated as $C_r=\varepsilon \cdot C$, ε is a coefficient selected as 0.05. Cm is annual maintenance costs, (A/P, i, n) is capital recovery factor, which is calculated as $(A/P, i, n)=\frac{i}{1-(1+i)^{-n}}$. The formula of i is $i=\frac{u-f}{1+f}$ where i is the constant discount rate, u is the current discount rate and f is inflation rate. We consider the life of the pump, heat pump units are 10 and 20 years respectively with the life of GHX is 50 years. Electricity price is CNY 0.94 yuan/kWh. The cost of drilling and grout, the pipe cost are also included, for different type of GHX are summarized in the four columns on the left side of the Table 1. The right three columns of the Table 1 gives the cost of heat pump and pump we selected.

Table 1

Name	DN25	DN32	Unit	Name	Value	Unit
Single-U tube	95	98	yuan/m	**Heat pump**	600	yuan/kW
Double-U tube	100	105	yuan/m	**Pump**	13373	yuan/unit

SYSTEM DESCRIPTION

The schematic office building in Xi'an, China is presented in Figure 7. The area is 2557.8 m^2 and GSHP is used for heating and cooling. Both cooling and heating season are 120 days per year. The weekly operating time is from Monday to Friday and the daily operating time is from 8:00 am to 18:00 pm. The hourly load of this building for one specific years are presented in Figure 8. The blue points mean the hourly load of the building in cooling season and the red points mean the hourly load in heating season, which the maximum cooling load is 287 kW and the maximum heating load is 231 kW. Geothermal properties of soil are obtained from the TRT test. The thermal conductivity of soil is 1.78W/ (m·K) and the volume specific heat capacity of the soil 24820kJ/ (m^3·K). The initial average temperature of the soil 16.0℃. In the TRT test uncertainties are involved in the measurement of temperature, flowrate and power and the uncertainties are calculated by the method (Henk and Witte 2013): error in temperature ±0.2%, flowrate ±0.5%, power ±2%. The error of thermal conductivity and specific heat capacity that are combination error are calculated with the values of ±4.3% and ±14% respectively. Some basic parameters of ground heat exchanger (GHX) are pre-determined. The depth of GHX is 100 m, the diameter of the borehole is 0.14 m, the thermal conductivity of PE pipe is 0.49 W/ (mK) and the center distance of the pipes is 0.08 m.

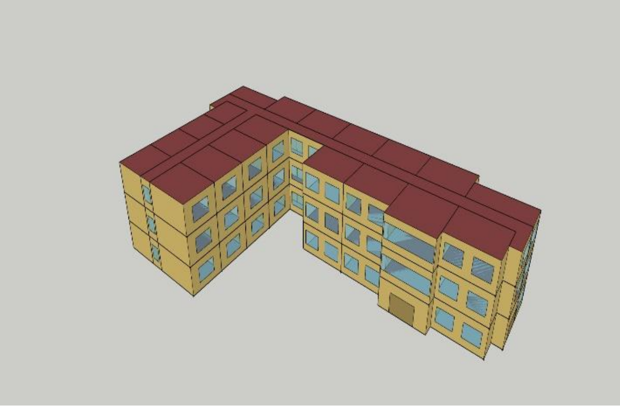


Figure 7 The office building model

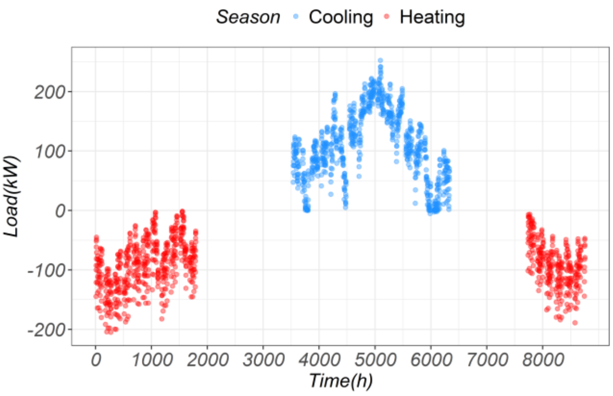


Figure 8 Building hourly load throughout year

METHODOLOGY

1. Taguchi technology

Taguchi optimization is an experimental technology, which uses orthogonal table to arrange fewer levels of combinations for experiments and uses these typical and representative experimental data to make statistical analysis on the role of factors. The main steps of this method are summarized as follows.

1. Definition the number of control parameters and levels. The choice of parameters and its levels are usually based on the previous studies and experiments. Here eight controlled parameters are selected, two of them have two levels and the others have three levels.
2. Design Taguchi orthogonal array (OA) and conduct the experiment. The OA is selected based on the controlled parameters and levels. With the help of this array can get the maximum information by conduction minimum number of experiments. For example, in this study, eight parameters with two parameter having two levels and six parameters having three levels, we need to conduct $2^2\times3^6$=2916 times experiments if we want to get the optimal parameters combination. It is so complex and time consuming to do this. Here only 36 times experiments are needed to conduct to get the maximum

information we need.

3. Analysis the result. In this studies, the signal-to-noise (S/N) ratios are used to analyze the response of the experiment trail and it can conclude the optimal parameters by using three functions: lower the better, higher the better and nominal the better. What's more, ANOVA is used to analyze the contribution of each parameters to the response factors and estimate the values of optimal response factor under the optimal controlled parameter combination.
4. Validation the result. This process is to validate the reliability of the model by comparing whether the error between the experimental value and the estimated value falls into the confidence interval or not. If the errors are outside the confidence the interval, it need return to the step 1 and redesign the parameters, which means the estimated model can't reflect on the optimal values.

2. Utility concept

Utility can be defined as the utilization of a product in response to the expectations of the customers/users which is widely used in manufacturing and quality engineering. (Prasad and Susanta, 2013) The performance parameters of utility are obtained by combining all the individual performance parameters such as EER, COP, NAV and TEM in this paper. Utility function can be expressed as Eq. (9):

$$\mathrm{U}(y_1, y_2, \dots, y_n) = \mathrm{f}(U_1(y_1), U_2(y_2), \dots, U_n(y_n)) \tag{9}$$

Where y is the performance parameters and the 'n' is the number of performance parameters. This article assumes that each factor is independent that means each response factors are not related to other factors, hence the utility function can be expressed as Eq. (10).

$$\mathrm{U}(y_1, y_2, \dots, y_n) = \sum_{j=1}^{n} U_j(y_j) \tag{10}$$

Priority basis can be calculated by defining the weighting coefficients of each response factor and setting weight coefficients in based on the relative importance of each distribution, which are usually obtained according to other studies or experience. The weighting coefficients has to satisfy the sum of them equal to 1. The weight coefficient are assigned equally to each parameters in this study (each response factors share the weighting coefficient of 0.25). The functions are represented as follow Eq. (11) and Eq. (12).

$$\mathrm{U}(y_1, y_2, \dots, y_n) = \sum_{j=1}^{n} w_j \cdot U_j(y_j) \tag{11}$$

$$P_j = A_j \times \log\left(\frac{y_j}{y_j'}\right) \text{ with } A_j = \frac{9}{\log\left(\frac{y_j^*}{y_j'}\right)} \tag{12}$$

Where the preference numbers are assumed to between 0 (representing the lowest performance value that can be accepted) and 9 (representing the highest performance). We can calculate the A value by defining the preference number as 9 so as to obtain a global optimum parameters combination. The y* is the optimum value of y_j that is the performance of the GSHP system (EER, COP, NAV and TEM) and y' is the minimum acceptable performance value. The overall utility is calculated as Eq. (13).

$$\mathrm{U} = \sum_{j=1}^{n} w_j \cdot P_j \tag{13}$$

The main purpose to apply the utility concept is to determine a global optimal parameters combination after considering the impact of various factors (EER, COP, NAV and TEM) of the GSHP system comprehensively. Figure 9 gives a detailed procedure for applying Taguchi technology and utility concept in this study, in which different phases and its logical relationship are listed.

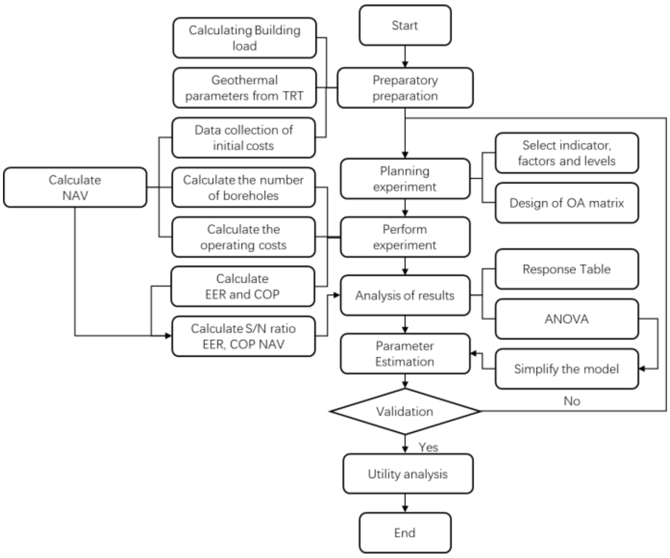


Figure 9 Flow chart for Taguchi procedure in this study

RESULTS AND DISCUSSION

In this study, eight important parameters of GSHPs had been chosen as the controlled factors in Taguchi orthogonal. They are: number of U-Tubes per bore (A), diameter of pipe (B), outlet load temperature in cooling mode (C), load side mass flow rate (D), source side mass flow rate (E), thermal conductivity of fill material (F), outlet load temperature in heating mode (G) and borehole spacing (H). Here the factors A and B have two levels because single-U and double-U are the most common type of boreholes and DN25 and DN32 are the most commonly used buried pipe diameter in China. Other factors are considered at three levels. The outlet load temperature in cooling mode and heating load (C and G) are 7 ℃ and 45 ℃ in the initial system design. We increase and decrease the levels of change by 1 ℃ around this initial design parameter and get the three levels of these parameters. The levels of mass flowrate (D and E) are obtained in same reason, which are around the initial design values with 37.5 m3/h and 42.5 m3/h. The levels of factor G is obtained because we choose three different fill material. The borehole spacing is initially designed in 5 m, which is commonly used in China, and 0.5 m is selected as a gap that the levels are around the 5 m. The values of these controlled factors at different level are presented in Table 2.

Table 2 . Control factors and their levels

Label	Factors	Level		
		1	2	3
A	**Number of U-Tubes per bore**	1	2	
B	**Diameter of pipe (m)**	0.025	0.032	
C	**Outlet load Temperature in cooling mode (℃)**	6	7	8
D	**Load side mass flow rate (m^3/h)**	35	37.5	40
E	**Source side mass flow rate (m^3/h)**	40	42.5	45
F	**Thermal conductivity of fill material (W/mK)**	1.56	1.95	2.27
G	**Outlet load temperature in heating mode (℃)**	44	45	46
H	**Borehole spacing (m)**	4.5	5	5.5

EER, COP, NAV and TEM are chosen as response factors to evaluate the performance of the GSHP system under the optimum parameters combinations. Among those response factors, EER and COP are beneficial in nature where higher values are preferred, and on the other hand, the low value of NAV and TEM are usually desired as it is a non-beneficial criterion. A total of 36 trials need to be implemented and a mixed level L_{36} (2^2, 3^6) orthogonal array has been selected for deciding the experimental layout and the parameters-level matrix trail runs presented in Table 3. It also gives the values of EER, COP, NAV and TEM calculating from TRNSYS and the signal to noise ratio (S/N ratio) for all 36-trail runs. In Taguchi design, signal-to-noise ratio is a measure of robustness used to identify control factors that reduce product or process variability by minimizing the effects of uncontrollable factors (noise factors).The S/N ratio of the EER and COP are calculated using the higher the better concept while the S/N ratio of the NAV and TEM are calculated by using the lower the better. The formulas are given in Eq. (14) and Eq. (15). The last column is the number of boreholes that are calculated according the geothermal parameters from TRT test and the controlled parameters we selected.

$$\text{Higher the better } S/N = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{14}$$

$$\text{Lower the better } S/N = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{15}$$

Attention that the indicators (EER, COP and its S/N ratio) are given with 3 decimals in Table 3. This is because the difference of EER and COP among the experiments is very small. Therefore, these indicators retain three decimal places will reflect on the difference among the experiments better and provide with more accurate results for ANOVA in the next step.

Table 3 . Taguchi L_{36} (2^2, 3^6) orthogonal array

Exn	A	B	C	D	E	F	G	H	EER	COP	NAV	TEM	S/N EER	S/N COP	S/N NAV	S/N TEM	No. B
1	1	1	1	1	1	1	1	1	3.837	3.022	115200	2.898	11.680	9.606	-101.229	-9.241	54
2	1	1	2	2	2	2	2	2	3.839	2.927	114281	2.698	11.683	9.329	-101.160	-8.621	50
3	1	1	3	3	3	3	3	3	3.842	2.865	113107	2.515	11.690	9.143	-101.070	-8.010	47
4	1	1	1	1	1	1	2	2	3.823	2.957	115381	2.653	11.648	9.417	-101.243	-8.476	53
5	1	1	2	2	2	2	3	3	3.807	2.874	113583	2.522	11.611	9.171	-101.106	-8.036	48
6	1	1	3	3	3	3	1	1	3.871	2.993	113691	2.963	11.756	9.523	-101.114	-9.434	49
7	1	1	1	1	2	3	1	2	3.817	3.017	113345	2.779	11.634	9.592	-101.088	-8.879	48
8	1	1	2	2	3	1	2	3	3.780	2.917	114627	2.452	11.550	9.299	-101.186	-7.792	51
9	1	1	3	3	1	2	3	1	3.911	2.883	114716	2.900	11.846	9.197	-101.192	-9.248	51
10	1	2	1	1	3	2	1	3	3.740	2.989	111047	2.646	11.458	9.512	-100.910	-8.452	45
11	1	2	2	2	1	3	2	1	3.825	2.948	110877	3.128	11.654	9.389	-100.897	-9.907	45
12	1	2	3	3	2	1	3	2	3.827	2.866	113991	2.716	11.657	9.146	-101.137	-8.679	49
13	1	2	1	2	3	1	3	2	3.748	2.863	114477	2.776	11.476	9.136	-101.174	-8.868	49
14	1	2	2	3	1	2	1	3	3.789	2.974	110885	2.624	11.570	9.467	-100.897	-8.378	45
15	1	2	3	1	2	3	2	1	3.874	2.951	112232	3.083	11.764	9.399	-101.002	-9.779	45
16	1	2	1	2	3	2	1	1	3.761	2.976	112867	3.113	11.506	9.473	-101.051	-9.863	47
17	1	2	2	3	1	3	2	2	3.816	2.935	112227	2.855	11.632	9.352	-101.002	-9.113	45
18	1	2	3	1	2	1	3	3	3.832	2.885	112452	2.528	11.669	9.203	-101.019	-8.057	47

19	2	1	1	2	1	3	3	3	3.777	2.895	108430	2.828	11.543	9.233	-100.703	-9.030	39
20	2	1	2	3	2	1	1	1	3.781	2.976	110397	3.181	11.552	9.472	-100.859	-10.05	44
21	2	1	3	1	3	2	2	2	3.862	2.949	108994	2.899	11.735	9.393	-100.748	-9.244	42
22	2	1	1	2	2	3	3	1	3.793	2.886	110356	3.284	11.579	9.207	-100.856	-10.33	41
23	2	1	2	3	3	1	1	2	3.765	2.960	110179	2.901	11.515	9.425	-100.842	-9.252	44
24	2	1	3	1	1	2	2	3	3.866	2.956	107491	2.731	11.744	9.415	-100.627	-8.725	40
25	2	1	1	3	2	1	2	3	3.722	2.910	109483	2.754	11.416	9.278	-100.787	-8.800	42
26	2	1	2	1	3	2	3	1	3.806	2.892	110292	3.217	11.609	9.224	-100.851	-10.15	42
27	2	1	3	2	1	3	1	2	3.901	3.024	108059	2.935	11.824	9.612	-100.673	-9.352	41
28	2	2	1	3	2	2	2	1	3.743	2.929	110486	3.353	11.464	9.334	-100.866	-10.508	40
29	2	2	2	1	3	3	3	2	3.787	2.895	110008	3.045	11.566	9.233	-100.828	-9.673	39
30	2	2	3	2	1	1	1	3	3.794	2.984	108366	2.763	11.582	9.496	-100.698	-8.829	40
31	2	2	1	3	3	3	2	3	3.695	2.909	108912	2.930	11.352	9.275	-100.741	-9.336	37
32	2	2	2	1	1	1	3	1	3.799	2.900	111028	3.240	11.593	9.248	-100.909	-10.21	42
33	2	2	3	2	2	2	1	2	3.833	2.988	108937	2.990	11.671	9.508	-100.744	-9.512	40
34	2	2	1	3	1	2	3	2	3.766	2.877	110316	3.058	11.518	9.179	-100.853	-9.710	40
35	2	2	2	1	2	3	1	3	3.764	2.991	107791	2.885	11.513	9.516	-100.652	-9.203	37
36	2	2	3	2	3	1	2	1	3.794	2.915	110890	2.683	11.582	9.293	-100.898	-8.571	38

The average response of S/N ratios for each level of eight parameters for EER, COP and NAV are summarized in Figure 10, Figure 11, Figure 12 and Figure 13. Figure 10 and Figure 11 shows the S/N variation with different levels for EER and COP. Compared with other factors having big change with the variation of the levels, factor G (outlet load temperature in heating mode) in Figure 10 shows little change with different levels, which illustrates this factor has small impact on EER. Low level of the factors A, B, D, E, H and high level of the factor C contribute to the higher S/N ratio of EER for the GSHP system. It is observed that the factor D, E, F have an obvious influence on the S/N ratio of COP for the system and lower the level of these three factors contribute to the higher COP in Figure 11. Figure 12 exhibits the S/N ratio variation for NAV and it is observed that the factor A has the biggest change on the variation of levels compared with other controlled factors. Figure 13 presents the S/N ratio of TEM, in which factor H has the biggest variation on different levels and the factor A followed by.

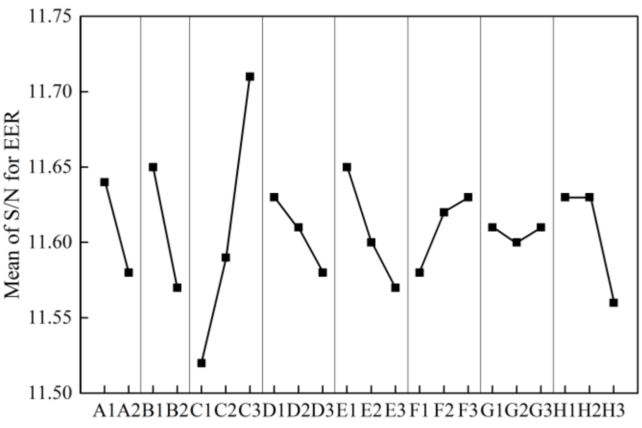


Figure 10 Mean of S/N for EER

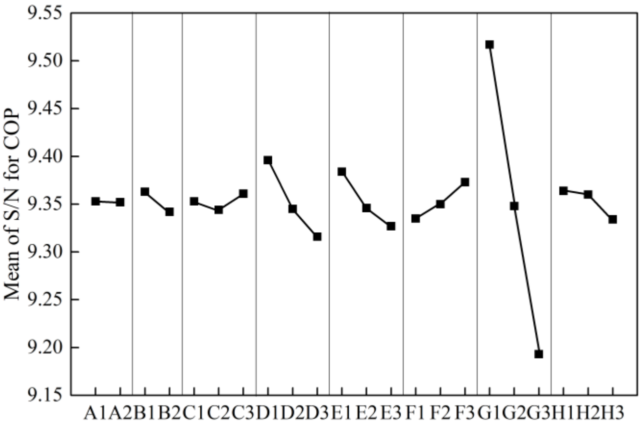
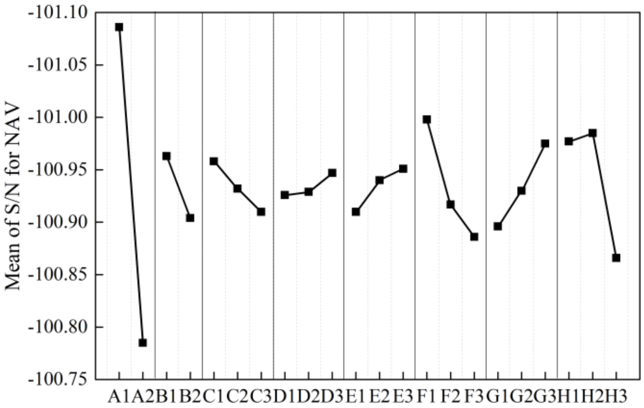


Figure 11 Mean of S/N for COP



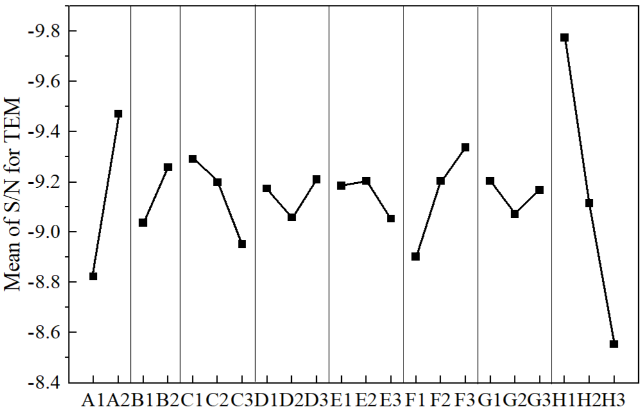


Figure 12 Mean of S/N for NAV **Figure 13** Mean of S/N for TEM

The best parameters combination of GSHPs can be determined by selecting the level with highest S/N ratio for EER and COP and with the lowest absolute value of S/N ratio for NAV. Hence the optimum control parameters levels are A1 (A at level 1), B1 (B at level 1), C3 (C at level 3), D1 (D at level 1), E1 (E at level 1), F3 (F at level 3), G3 (G at level 3), H1 (H at level 1) for EER and A1, B1, C3, D1, E1, F3, G1, H1 for COP. Following the best set of combination parameters for NAV is A2, B2, C3, D1, E1, F3, G1, H3. What's more, A1, B1, C3, D2, E3, F1, G2, H3 is the optimal parameters combination for TEM.

ANOVA ANALYSIS

We use ANOVA to estimate the relative importance of these control factors by calculating the percentage contribution of each parameter in overall response. Degree of freedom, sum of squares, mean of squares, F ratio, P value, percentage contribution and significance by different control factors are included in variance analysis Table 4-7. The aim of ANOVA is to analyze the importance of each factor to the result by verifying whether the testing statistics F ratio falls within the rejection region or not. The p-value is the minimum level of rejection of the null hypothesis. Sum of square (SS), degree of freedom, mean of square (MS) and F ratio have been calculated by using the Eq.(16) and Eq.(17).

$$\text{SS}=\left\{\begin{matrix}\text{(sum of S/N ratio level I)}^2\\ +\text{(sum of S/N ratio level II)}^2\\ +\text{(sum of S/N ratio level III)}^2\text{-C.F}\end{matrix}\right\} \quad (16)$$

$$\text{Correction factor(C.F)}=\frac{\text{(sum of S/N)}^2}{\text{N}} \quad (17)$$

Where N is the total number of experiments and Degree of Freedom=level-1 Mean of square=$\frac{\text{SS}}{\text{DOF}}$ and F ratio=$\frac{\text{Mean of square}}{\text{Mean square error}}$.

Table 4. ANOVA for EER

Factors	Df	SS	MS	F	P	Contribution	Sig
A	1	0.035191	0.035191	197.68	0	13.62%	**
B	1	0.053564	0.053564	300.89	0	20.72%	**
C	2	0.216478	0.108239	608.02	0	41.88%	**
D	2	0.017403	0.008702	48.88	0	3.37%	**

E	2	0.045549	0.022775	127.93	0	8.81%	**
F	2	0.016703	0.008351	46.91	0	3.23%	**
G	2	0.000792	0.000396	2.23	0.133	0.15%	
H	2	0.042484	0.021242	119.32	0	8.22%	**
Error	21	0.003738	0.000178				
Total	35	0.431903				100.00%	

$F_{0.05}$ (1, 21) =4.32, $F_{0.01}$ (1, 21) =8.02, $F_{0.05}$ (2, 21) =3.47, $F_{0.01}$ (2, 21) =5.78

"*" represents the effect is significant, "**" represents the effect is extremely significant.

Table 5. ANOVA for COP

Factors	Df	SS	MS	F	P	Contribution	Sig
A	1	0.000005	0.000005	0.02	0.888	0.00%	
B	1	0.003942	0.003942	15.85	0.001	1.11%	
C	2	0.001689	0.000845	3.4	0.053	0.24%	
D	2	0.039791	0.019896	79.99	0	5.59%	*
E	2	0.020166	0.010083	40.54	0	2.83%	
F	2	0.008756	0.004378	17.6	0	1.23%	
G	2	0.627755	0.313877	1261.9	0	88.12%	**
H	2	0.006316	0.003158	12.7	0	0.89%	
Error	21	0.005223	0.000249				
Total	35	0.713645				100.00%	

Table 6. ANOVA for NAV

Factors	Df	SS	MS	F	P	Contribution	Sig
A	1	0.79342	0.793419	213.84	0	84.46%	**
B	1	0.03091	0.030912	8.33	0.009	3.29%	
C	2	0.01396	0.00698	1.88	0.177	0.74%	
D	2	0.00315	0.001577	0.42	0.659	0.17%	
E	2	0.01069	0.005347	1.44	0.259	0.57%	
F	2	0.08132	0.040658	10.96	0.001	4.33%	*
G	2	0.0372	0.018601	5.01	0.017	1.98%	
H	2	0.0838	0.041902	11.29	0	4.46%	*
Error	21	0.07792	0.00371				
Total	35	1.13238				100.00%	

Table 7. ANOVA for TEM

Factors	Df	SS	MS	F	P	Contribution	Sig
A	1	3.7696	3.7696	50.07	0	38.24%	**
B	1	0.4397	0.43975	5.84	0.025	4.46%	*
C	2	0.7311	0.36557	4.86	0.018	3.71%	*
D	2	0.1486	0.07432	0.99	0.389	0.76%	
E	2	0.1615	0.08075	1.07	0.36	0.82%	
F	2	1.1914	0.59568	7.91	0.003	6.04%	*
G	2	0.11	0.055	0.73	0.493	0.56%	
H	2	8.9549	4.47743	59.47	0	45.42%	**

Error	21	1.5809	0.07528		
Total	35	17.0878			100.00%

It can be observed from Table 4 that almost all the factors except G (outlet load temperature in heating mode) have extremely significant effect on the EER and the higher to lower order percentage contribution of parameters can be arranged as CBAEHDF. The highest contribution comes from the outlet load temperature in cooling mode (C) with 41.88% followed by diameter of pipe (B) with 20.72% and number of U-Tubes per bore (A) with 13.62%. Table 5 shows the ANOVA results for COP of GSHP system, which indicate only load side mass flow rate (D) and outlet load temperature in heating mode (G) have a significant effect on COP. Among them, Factor G contributes the highest percentage of 88.12% and it has an extremely significant effect on the COP. Factor D is followed with the percentage of 5.59%. From this table the COP contributing parameters ranking can be obtain as GDEFBHCA. From the values shown in Table 6 for NAV, the important controlled factor are found to be the number of U-Tubes per bore (A), thermal conductivity of fill material (F) and borehole spacing (H). It can easily notice that the most important factor is the number of U-Tubes per bore (A) for NAV, which contributes 84.64%. Combined the results in previous step that the double U is favorable, we can conclude that the number of borehole in initial investment has a great impact on the NAV because Double U needs less borehole than the Single U when the building load is fixed. Factor H and F is followed with the percentage of 4.46% and 4.33%. The number of U-Tubes per bore (A) and borehole spacing (H) have an extremely significant effect on the average temperature rise of soil (TEM) with the contribution of 38.24% and 45.42% respectively as shown in Table 7. Factor D, E and G are the insignificant variables compared with the others.

It is worthy taking note of that the factors related to GHX having an extremely significant effect on EER become insignificant when considering the COP, such as the factor A, B, F and H. This is because that the design of the GHX is based on the cooling load in summer, which is higher than the heating load in winter when the power of the heat pump and pumps are considered. Therefore, the number of GHX is enough for cooling condition but much for heating condition, which leads to the effect that factors relevant to GHX are insignificant for COP.

CONFIRMATION TEST

1. Parameter Estimation

The first step for confirmation test is to estimate the optimal values of the indicators (EER, COP, NAV and TEM) and the mathematical model is given as Eq. (18).

$$\hat{y}_{opt} = \hat{\mu} + \hat{a}_i + \hat{b}_i + \hat{c}_i + \hat{d}_i + \hat{e}_i + \hat{f}_i + \hat{g}_i \tag{18}$$

With $\hat{\mu}=\bar{y}$, $\hat{a}_i=\bar{A}_i-\bar{y}$, $\hat{b}_i=\bar{B}_i-\bar{y}$, $\hat{c}_i=\bar{C}_i-\bar{y}$, $\hat{d}_i=\bar{D}_i-\bar{y}$, $\hat{e}_i=\bar{E}_i-\bar{y}$, $\hat{f}_i=\bar{F}_i-\bar{y}$, $\hat{g}_i=\bar{G}_i-\bar{y}$. Where $\bar{y}$ is the means of the entire response factor, $\bar{X}_i$ (X=A, B, C, D, E, F, G, H) represents the means of response factors on the different level selected and i is the levels of the factors. According to the ANOVA results from Table 4-7, the optimum response factors for EER, COP and NAV can be estimated under the optimum parameter combination selected previously. The insignificant factors can be neglected during the process of estimation so as to simplify the model. Confirmation test is carried out based on the estimated optimal response factors with the optimum parameter combination coming from Figure 10-13. Simultaneously, an interval estimation with 95% confidence interval is carried out to determine the range of these response factors. The confidence interval is given as Eq. (19):

$$\begin{cases} S_e' = S_e + \sum S_{in} \\ df_e' = df_e + \sum df_{in} \\ n_e = \frac{N}{1+\sum S_{sig}} \end{cases} \text{and} \quad (\hat{y}_{opt} - \sqrt{\frac{F_\alpha(1,df_e')S_e'}{n_e df_e'}}, \hat{y}_{opt} + \sqrt{\frac{F_\alpha(1,df_e')S_e'}{n_e df_e'}} \qquad (19)$$

Where S_{in} is the sum of square (SS) of the insignificant factors, S_e is the mean square error, df_{in} is the degree of freedom of insignificant factors, N is the total number of test and S_{sig} is the sum of square (SS) of the significant factors. The interaction between parameters is not taken into consideration. The optimized EER, COP, NAV and TEM at the optimum parameters combination are estimated to be 3.936, 3.034, 106445 and 2.362 respectively. The confirm values for EER, COP ,NAV and TEM calculated by using TRNSYS software are falling within the region of interval estimates at 95% confidence and the predictive values are all fully close to the confirmed values (see Table 8). Therefore, the optimal response factors obtained from the model have been validated by confirmatory experiment using TRNSYS simulation.

Table 8 Confirmation

Response factors	df'	SSe'	ne'	Predictive value	Confidence interval	Confirmed value
EER	23	0.000894	2.769	3.936	(3.9278, 3.9433)	3.940
COP	31	0.005352	7.2	3.034	(3.0239, 3.0439)	3.031
NAV	30	28848374	6	106445	(105627, 107263)	106054
TEM	27	0.22105	6	2.308	(2.23221,2.384)	2.362

2. Utility analysis

From the result of Taguchi analysis, the optimum parameters combination for response factors are obtained respectively. In order to find out the global optimum parameters combination of this GSHP system from all the parameters combination, the utility concept method are use. The given response factor EER and COP need to be as higher as possible while NAV and TEM are the opposite. We use the parameter estimation model in previous steps to estimate performance (EER, COP, NAV and TEM) of all the parameters combinations for 2916 times and then calculate the U values of each combination. The optimum parameters levels combination for achieving maximum EER and COP while minimum NAV and TEM of this GSHP system are found to be A2 (double U), B1 (pipe diameter with 25mm), C3 (8℃ of the heat pump outlet temperature in cooling mode), D1 (the load side mass flowrate with 35 m^3/h), E1 (the source side mass flowrate with 35 m^3/h), F3 (thermal conductivity with 2.27 W/mK), G1 (44℃ of the heat pump outlet temperature in heating mode), H3 (borehole spacing for 5.5m). The optimum response factor (EER, COP, NAV and TEM) of this combination are 3.873, 3.023, 107212, 2.774 respectively with the utility values are calculated as 7.098.

CONCLUSION

In this study, the performance of the GSHP system has been analyzed using Taguchi method, ANOVA test model and utility concept. Eight parameters at mixed levels of operation for the GSHP system are considered. A TRNSYS model is developed to calculate the system EER, COP, NAV and TEM according to the design of Taguchi method. The optimum combination of parameters are obtained for EER, COP, NAV and TEM respectively. The significant effects of each control factor on the response factors for this GSHP system are quantified according to the result of ANOVA. The main findings are outlined as follows;

The optimum combination of the parameters for the GSHP system are selected by Taguchi method as A1 B1 C3 D1 E1 F3 G3 H1 for EER, A1 B1 C3 D1 E1 F3 G1 H1 for COP , A2 B2 C3 D1 E1 F3 G1 H3 for NAV and A1 B1 C3 D2 E3 F1 G2 H3 for TEM respectively. According to the result of ANOVA, the heat pump outlet temperature (factor C and factor G) are the most influencing (41.88% and 88.12% respectively) control factors of the system for EER and COP respectively while the number of U-Tubes per borehole (factor A) have the major contribution (84.64%) for NAV and borehole spacing (factor H) contribute most (45.42%) to TEM.

The optimum EER, COP, NAV and TEM of the GSHP system have been estimated with the optimized parameters combination, which are found to be 3.9355, 3.0339, CNY 106445 yuan and 2.36 ℃ respectively. The predicted value has been validated by the confirmed value computed from the TRNSYS software.

The utility concept combined the Taguchi method has been used in this paper to find the optimum parameters combination with comprehensive consideration of all response factors (EER, COP, NAV and TEM). After calculating the utility values, the optimum combination can we get is A2 B1 C3 D1 E1 F3 G1 H3 with the response factors of 3.873, 3.023,CNY 107212 yuan and 2.774 ℃ for EER, COP, NAV and TEM respectively.

ACKNOWLEDGMENTS

The authors would like to acknowledge the supports from the National Nature Science Foundation of China (No.51678262)

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