Study on the Influential Factors of Heat Transfer of Ground Heat Exchanger with Orthogonal Test

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Abstract. Orthogonal test method could decrease experimental times and obtain better test effect. The Taguchi method, as well as mean value response and analysis of variance, were applied in this paper to study the influence of water flow velocity in pipe, diameter and water temperature of pipe inlet on heat transfer of ground heat exchanger. The optimum design parameters and the estimated values of heat flux per meter of well depth for single U-tubes are obtained. The analysis revealed that diameter is the most influential parameter for heat flux per meter of well depth in single U-tubes while water flow velocity within 0.3m/s to 0.5m/s. And water flow velocity and diameter are important influential parameters for heat flux per meter of well depth in single U-tubes while water flow velocity within 0.5m/s to 0.8m/s. Tubes with big diameters are superior to tubes with small diameters in the design of ground source heat exchanger with single U-tubes.

1. Introduction

Ground source heat pumps are being installed more frequently for cooling and heating because of its high efficiency. Systems with multiple boreholes and ground U-tubes are used to support large heat pumps. But the heat transfer of ground heat exchanger is complicated. There are many factors which influence the heat fluxes per meter of well depth for ground U-tubes, such as soil thermophysical property, heat exchange fluid, dimension of borehole heat exchanger and so on [1-2].

Experiments for measuring heat transfer rate of ground heat exchangers are usually limited by practical conditions. Taguchi method for orthogonal design of experiment is widely used in statistics for analyzing multivariable or multifactor data [3-4]. Taguchi’s orthogonal arrays can be managed to quantify the relationship between variables performing minimum number of experiments [5]. In this paper, the experimental data were analyzed by orthogonal design of experiment method. And the main influential factors of heat transfer of ground heat exchanger were revealed.

2. Experimental Measure of Heat Quantity of Ground Heat Exchanger

The experimental system of ground source heat exchange was established with buried vertical pipes that consist of single U-tubes with diameter 25mm and diameter 32mm. The depth of each borehole is 100 meters. The temperature and velocity of water in the ground source heat exchange system are monitored efficiently. The experimental data were obtained from this system in hot summer.

For the heat transfer of single U-tubes of ground heat exchanger, the considering influential factors in this paper are A water flow velocity in the pipe, B diameter of the pipe and C water temperature of pipe inlet. The experimental measuring results of heat transfer in single U-tubes for different water
flow velocities are shown in Table 1 and Table 2, while the heat flux per meter of well depth \( q \) (W/m) is calculated by

\[
q = \frac{GC_p\rho(t_i - t_o)}{3600H}
\]

where \( G \) is the flow flux of water, m\(^3\)/h; \( C_p \) is the specific heat of water at constant pressure, J/kg°C; \( \rho \) is the density of water, Kg/m\(^3\); \( t_i \) is water temperature of pipe inlet, °C; \( t_o \) is water temperature of pipe outlet, °C; \( H \) is the depth of borehole, m.

### Table 1. Experimental results of heat transfer in single U-tube (1).

| A Velocity of flow (m/s) | B Diameter (mm) | C Inlet temperature (°C) | Heat flux per meter of well depth (W/m) |
|-------------------------|-----------------|--------------------------|----------------------------------------|
| 0.3                     | DN25            | 30                       | 33.865                                 |
| 0.3                     | DN32            | 32                       | 65.293                                 |
| 0.4                     | DN25            | 30                       | 50.813                                 |
| 0.4                     | DN32            | 32                       | 67.460                                 |
| 0.5                     | DN25            | 32                       | 52.925                                 |
| 0.5                     | DN32            | 30                       | 66.420                                 |
| 0.6                     | DN25            | 32                       | 55.660                                 |
| 0.6                     | DN32            | 30                       | 70.374                                 |

### Table 2. Experimental results of heat transfer in single U-tube (2).

| A Velocity of flow (m/s) | B Diameter (mm) | C Inlet temperature (°C) | Heat flux per meter of well depth (W/m) |
|-------------------------|-----------------|--------------------------|----------------------------------------|
| 0.5                     | DN25            | 30                       | 51.384                                 |
| 0.5                     | DN32            | 32                       | 60.476                                 |
| 0.6                     | DN25            | 30                       | 54.925                                 |
| 0.6                     | DN32            | 32                       | 63.02                                  |
| 0.7                     | DN25            | 32                       | 60.27                                  |
| 0.7                     | DN32            | 30                       | 82.203                                 |
| 0.8                     | DN25            | 32                       | 68.812                                 |
| 0.8                     | DN32            | 30                       | 91.332                                 |

### 3. Orthogonal Design of Experiments

Orthogonal design of experiment is a scientific test method which is used to study and analyze experiments with multiple influential factors. With an appropriate design of experiment, factors affecting the heat fluxes per meter of well depth can be properly evaluated, while the number of experiments can be significantly reduced. Taguchi experiment design is one of the widely applied methods for designing parameters for a specific problem, by using the minimal number of test series to represent full practical experiments. And Taguchi method is a high efficiency test design and optimization technology. It uses orthogonal array to arrange experiments.

The \( L_8(4^1 \times 2^2) \) Taguchi hybrid orthogonal array design is shown in Table 3. It was used as the experimental design to conduct 8 experiments. As shown in Table 3, the parameter “A Velocity of flow” is undergoing 4 levels. The parameters “B Diameter” and “C Inlet temperature” are undergoing 2 levels, respectively.
Table 3. Orthogonal array.

| Test | A Velocity of flow | B Diameter | C Inlet temperature |
|------|--------------------|------------|---------------------|
| 1    | 1                  | 1          | 2                   |
| 2    | 1                  | 2          | 1                   |
| 3    | 2                  | 1          | 2                   |
| 4    | 2                  | 2          | 1                   |
| 5    | 3                  | 1          | 1                   |
| 6    | 3                  | 2          | 2                   |
| 7    | 4                  | 1          | 1                   |
| 8    | 4                  | 2          | 2                   |

4. Results and Discussion

According to Table 3, orthogonal tests were conducted using Minitab statistic analysis software. The results for water flow velocity of 0.3m/s to 0.6m/s are shown in Table 4 and Table 5. The results for water flow velocity of 0.5m/s to 0.8m/s are shown in Table 6 to Table 7.

Table 4. Mean value response table (1).

| Level | A Velocity of flow | B Diameter | C Inlet temperature |
|-------|--------------------|------------|---------------------|
| 1     | 49.58              | 48.32      | 55.37               |
| 2     | 59.14              | 67.39      | 60.33               |
| 3     | 59.67              |            |                     |
| 4     | 63.02              |            |                     |
| Delta | 13.44              | 19.07      | 4.97                |
| Order | 2                  | 1          | 3                   |

Table 5. Analysis of variance table (1).

| Source                | Freedom | SS      | Adj SS | Adj MS | F      | P      |
|-----------------------|---------|---------|--------|--------|--------|--------|
| A Velocity of flow    | 3       | 200.17  | 200.17 | 66.72  | 2.43   | 0.305  |
| B Diameter            | 1       | 727.41  | 727.41 | 727.41 | 26.46  | 0.036  |
| C Inlet temperature   | 1       | 49.33   | 49.33  | 49.33  | 1.79   | 0.312  |
| Error                 | 2       | 54.99   | 54.99  | 27.5   |        |        |
| Total                 | 7       | 1031.9  |        |        |        |        |

S = 5.24361   R-Sq = 94.67%   R-Sq(adjust) = 81.35%

The value of “Delta” for parameter “B Diameter” is the biggest in Table 4. So its order of significance is number 1. Analysis of variance approach was used to check the adequacy of the test for heat flux per meter of well depth in single U-tubes. The value of “P” less than 0.05 in Table 5 indicates that parameter “B Diameter” is significant. And the value of “SS” for parameter “B Diameter” is also the biggest.

The above analysis ultimately shows that the main influential factor for heat transfer of single U-tubes of ground heat exchanger, on the condition of water flow velocity within 0.3m/s to 0.6m/s, is diameter of the pipe. And water flow velocity in the pipe is also an important influential factor for the
heat flux per meter of well depth. Tubes with big diameters are superior to tubes with small diameters in the design of ground source heat exchanger with single U-tubes.

By using Taguchi method for design of experiment while water flow velocity is within 0.3m/s to 0.6m/s, the optimum design parameters are diameter of the pipe 32mm, water flow velocity in the pipe 0.6m/s and water temperature of pipe inlet 32°C. The estimated value of heat flux per meter of well depth for single U-tubes is 75.038W/m.

| Level | A Velocity of flow | B Diameter | C Inlet temperature |
|-------|--------------------|------------|---------------------|
| 1     | 55.93              | 58.85      | 69.96               |
| 2     | 58.97              | 74.26      | 63.14               |
| 3     | 71.24              |            |                     |
| 4     | 80.07              |            |                     |
| Delta | 21.14              | 15.41      | 6.82                |
| Order | 1                  | 2          | 3                   |

The value of “Delta” for parameter “A Velocity of flow” is the biggest in Table 6. The order of the significance of parameters is velocity of flow, diameter and inlet temperature. The values of “P” less than 0.05 in Table 7 indicate that all of the three parameters are significant. But the value of “SS” for parameter “A Velocity of flow” is the biggest, and the value of “Adj MS” for parameter “B Diameter” is the biggest.

The above analysis ultimately shows that the main influential factors for heat transfer of single U-tubes of ground heat exchanger, on the condition of water flow velocity within 0.5m/s to 0.8m/s, are water flow velocity in the pipe and diameter of the pipe.

By using Taguchi method for design of experiment while water flow velocity is within 0.5m/s to 0.8m/s, the optimum design parameters are diameter of the pipe 32mm, water flow velocity in the pipe 0.8m/s and water temperature of pipe inlet 30°C. The estimated value of heat flux per meter of well depth for single U-tubes is 91.185W/m.

The value of “Delta” for parameter “A Velocity of flow” is the biggest in Table 6. The order of the significance of parameters is velocity of flow, diameter and inlet temperature. The values of “P” less than 0.05 in Table 7 indicate that all of the three parameters are significant. But the value of “SS” for parameter “A Velocity of flow” is the biggest, and the value of “Adj MS” for parameter “B Diameter” is the biggest.

The above analysis ultimately shows that the main influential factors for heat transfer of single U-tubes of ground heat exchanger, on the condition of water flow velocity within 0.5m/s to 0.8m/s, are water flow velocity in the pipe and diameter of the pipe.

By using Taguchi method for design of experiment while water flow velocity is within 0.5m/s to 0.8m/s, the optimum design parameters are diameter of the pipe 32mm, water flow velocity in the pipe 0.8m/s and water temperature of pipe inlet 30°C. The estimated value of heat flux per meter of well depth for single U-tubes is 91.185W/m.

5. Conclusions
On both conditions of water flow velocity within 0.3m/s to 0.6m/s and within 0.5m/s to 0.8m/s for single U-tubes, the influence of water temperatures of pipe inlet on the heat fluxes per meter of well depth is not very distinct. But diameter of the pipe has significant influence on the heat fluxes per meter of well depth. Therefore, tubes with big diameters are superior to tubes with small diameters in the design of ground source heat exchanger. And water flow velocity has much influence on the heat transfer of ground source heat exchanger with water flowing in higher velocities.

By using Taguchi method for design of experiment while water flow velocities are within 0.3m/s to 0.6m/s and within 0.5m/s to 0.8m/s, the optimum design parameters and the estimated values of heat flux per meter of well depth for single U-tubes are obtained respectively.
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