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Study on Cold and Heat Response Characteristics of Geothermal Field Based on Shallow Geothermal Energy Development

Yuan Yu [1]*, Wanshun Wei[2], Ke Wang[2,3], Xiaohua Diao[1], Jingjing Qiao[1]

Institute of Resources and Environment, Beijing Academy of Science and Technology, Beijing 100089, China [1]*, Beijing Academy of Science and Technology, Beijing 100089, China [2], Institute of New Materials and Advanced Manufacturing, Beijing Academy of Science and Technology, Beijing 100089, China [3]

Yuan Yu[1]* mintyuan@hotmail.com

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ABSTRACT

The distribution law and thermal response characteristics of shallow geothermal energy are one of the key geological issues affecting its efficiency in the process of shallow geothermal energy development. When the scale of a single ground source heat pump system is large, the supply capacity of shallow geothermal resources will directly restrict the overall energy efficiency ratio of the system. Therefore, it is necessary to carry out research on the heat exchange mechanism of shallow geothermal energy to determine the magnitude and evolution trend of the heat exchange of individual systems. This paper selects typical ground source heat pump projects with buried pipes in Beijing. By studying the dynamic response mechanism of the temperature field of the rock and soil mass under the influencing factors such as groundwater flow rate, stratification of rock and soil mass, and seasonal changes in cold and heat, the spatio-temporal distribution law of heat exchange in shallow geothermal energy is analyzed. The results show that during the exploitation of shallow geothermal energy, the heat exchange capabilities of different holes and different layers present significant differences. Laying underground pipes at a certain mesh size, equal spacing and equal depth is unscientific. It is recommended to carry out refined exploration and evaluation of shallow geothermal energy mainly based on the evaluation of heat exchange capabilities to find target areas with good heat exchange effects of underground pipes. The laying of underground pipes should be determined differently based on the size of the heat exchange contribution capacity.

1 INTRODUCTION

Beijing has an enormous winter heating demand, currently relying on coal-fired boilers, gas-fired boilers and combined heat and power generation. These traditional methods cause severe energy supply pressure and air pollution, conflicting with the goal of building a green low-carbon city, while the growing heating demand driven by urban development makes efficient and sustainable heating an urgent task.

As an eco-friendly renewable energy technology, GSHP uses shallow geothermal resources for heating and cooling, with remarkable energy-saving and environmental benefits, and has become an important direction for the green transformation of Beijing's heating industry. However, large-scale GSHP application is restricted by the strong heterogeneity of shallow geothermal resources in underground rock-soil mass. Uneven thermal response leads to low energy efficiency, poor operational stability and resource waste, hindering the scientific development of shallow geothermal energy.Against this background, this study takes three typical GSHP projects in Beijing with different hydrogeological conditions as research objects, analyzes the initial rock-soil temperature characteristics, temperature response during exploitation and the influence of hydrogeological conditions on heat exchange efficiency, aiming to provide scientific support for the efficient, sustainable and large-scale development of shallow geothermal energy.

2 RESEARCH METHODS AND TYPICAL PROJECTS

2.1 Research methods

GSHP operation causes thermal disturbance to the geothermal field, and geological heterogeneity leads to distinct temperature responses in different underground zones, which are ultimately reflected in the heat exchange efficiency of buried pipes. This study focuses on response temperature (T_r) and defines response temperature difference (ΔT_r) as the difference between T_r and the initial stratum temperature (T_0).The calculation formula for ø in different rock-soil strata is **Eq.1**.

$$\phi_{Q_n} = \frac{Q_{sn}}{Q_g} = \frac{\int K_s \Delta T_r dL}{V \rho c \Delta T_g} = \frac{K_{sn}(T_m - T_{on})L_n}{V \rho c (T_{g1} - T_{g2})} \quad (1)$$

The heat exchange contribution rate (øQ)—the ratio of the heat exchange quantity of buried pipes in different strata (Q_{sn}) to that on the ground source side (Qg)—is proposed to characterize the heat exchange capacity of different strata, based on the linear heat source hypothesis of buried pipes. øQ is positively correlated with ΔT_r, heat transfer coefficient (K_s) and rock-soil thickness (L); K_s, L, density (ρ) and specific heat capacity (c) are constant parameters, while ΔT_r, groundwater velocity (V) and geothermal temperature difference (ΔTg) are monitored variables that directly affect the value of øQ. Calculating øQ through field monitoring data is the core method of this study, which is used to identify high-efficiency heat exchange strata and borehole areas under heating and cooling scenarios.

2.2 Selection and Overview of Typical Projects

Three GSHP projects with distinct hydrogeological conditions in Beijing were selected, covering Quaternary fine-grained strata, coarse-grained strata and bedrock strata, and their basic information is as follows:

Automobile Industry Base: Total building area 174,310 m², hybrid GSHP system (integrated with cold/thermal storage and gas boilers), 1020 heat exchange boreholes (150m deep, 5m×5m spacing); located in the Wenyu River alluvial plain, Quaternary fine-grained strata (clay, silty fine sand, medium-coarse sand), Quaternary system thickness about 1000m.

Liaogongzhuang Base: Building area 951 m² (3-floor staff dormitory), closed-loop GSHP system, 18 buried pipe heat exchangers (120m deep, 150mm diameter, 5m×5m spacing); located in the Yongding River alluvial plain, Quaternary coarse-grained sandy pebble strata, groundwater level buried about 26m, good groundwater runoff condition.

Tuoli Base: Building area 259 m² (1-floor scientific research building), closed-loop GSHP system, 8 buried pipe heat exchangers (120m deep, 150mm diameter, 5m×5m spacing); located in Fangshan District, Cretaceous bedrock strata (clastic rock fracture-pore water), poor stratum drillability, with pebble, silty sandstone and breccia layers within 120m depth.

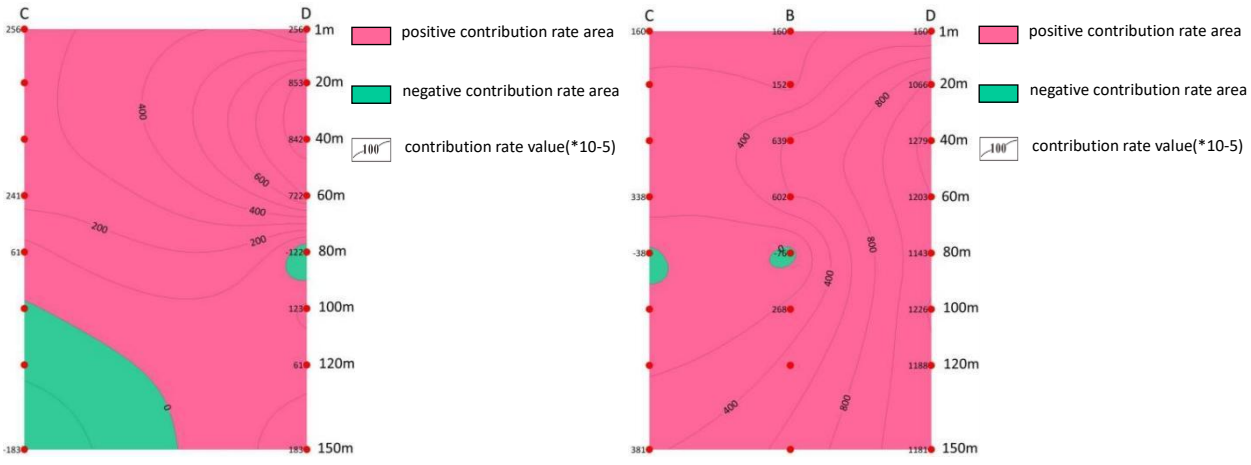
3 ANALYSIS RESULTS

3.1 Automobile Industry Base (Quaternary Fine-grained Strata)

Initial Geothermal Field: The field has large temperature variation (14.2℃~>15.4℃) and complex irregular distribution, contradicting the "homogeneous plate" hypothesis. Low-temperature zones are mainly distributed in shallow layers, while high-temperature and heat island zones exist in both shallow and deep layers, with distinct characteristics among different boreholes.

Stratum Response Temperature: Heating (Nov 17, 2023): most stratum temperatures decrease, distribution becomes more uniform with obvious shallow cold-deep hot stratification, and structural heat transfer connected zones remain. Cooling (Jul 17, 2024): most temperatures increase, distribution differs significantly from the initial state (e.g., the middle of borehole C changes from heat island zone to low-temperature zone), and rock-soil mass shows positive/negative responses with significant differences in response magnitude.

Heat Exchange Contribution Rate: Most areas show positive contribution (heating for heat supply, cooling for heat absorption) under both scenarios, but the middle of boreholes B and C has negative contribution, which is consistent with the change direction of ΔT_r(**Figure 1)**.



(a) during heating days **(b) during cooling days**

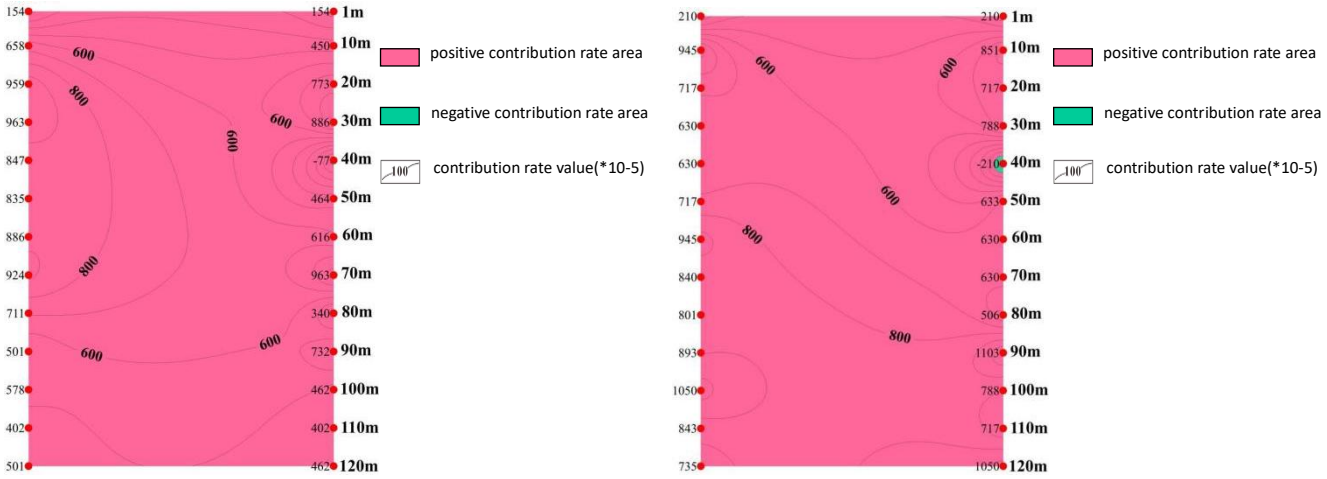
Figure 1. Heat exchange contribution rate at Automobile Industry Base

3.2 Liaogongzhuang Base (Quaternary Coarse-grained Strata)

Initial Geothermal Field: Temperature variation range is 13℃~>14.6℃, with irregular distribution controlled by multiple factors. After long-term operation, low-temperature zones are in deep layers, high-temperature and heat island zones are concentrated in shallow layers (maximum temperature 16.4℃ at 30~50m of monitoring borehole 3), with obvious differences among boreholes.

Stratum Response Temperature: Heating (Jan 17, 2024): most temperatures decrease, the initial distribution pattern and structural connected zones remain, with individual abnormal temperature increases in boreholes 3 and 4. Cooling (Jul 1, 2024): most temperatures increase, maintaining shallow hot-deep cold characteristics; boreholes 1 and 2 have stable temperature distribution, while the shallow high-temperature/heat island zone connectivity of boreholes 3 and 4 is significantly enhanced.

Heat Exchange Contribution Rate: Most areas have positive contribution under heating and cooling scenarios, only the middle of heat exchange borehole 2 has negative contribution, which is consistent with the change trend(ΔT_r change trend(**Figure 2)**.



(a) during heating days **(b) during cooling days**

Figure 2. Heat exchange contribution rate during heating (upper) and cooling (lower) days at Liaogongzhuang

As shown in Figure 3-6, under the heating scenario, the heat exchange contribution rate in most areas is positive, i.e., providing heat to the system. However, the heat exchange contribution rate in the middle area of Heat Exchange Borehole 2 is negative, which is consistent with the change direction of the response temperature. Under the cooling scenario, the heat exchange contribution rate in most areas is positive, i.e., absorbing the heat discharged by the system. However, the heat exchange contribution rate in the middle area of Heat Exchange Borehole 2 is negative, which is consistent with the change direction of the response temperature.

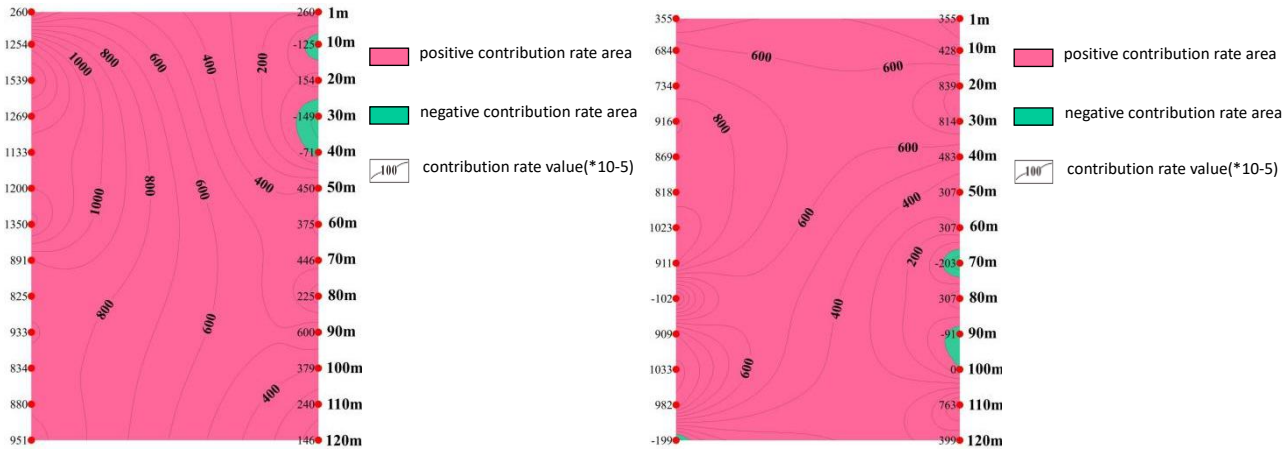
3.3 Tuoli Base (Bedrock Strata)

Initial Geothermal Field: Low-temperature zones are distributed in deep layers, high-temperature and heat island zones are concentrated in shallow layers; the temperature of monitoring boreholes within the layout area is relatively high, while that outside is low, with obvious spatial differences.

Stratum Response Temperature: Heating (Nov 17, 2023): most temperatures decrease, the initial distribution pattern and structural heat transfer zones remain, with individual abnormal temperature increases in partial boreholes. Cooling (Jul 17, 2024): most temperatures increase, distribution is more uniform with shallow hot-deep cold stratification, and only a few areas have abnormal changes (e.g., 90m depth of borehole 2 temperature decreases).

Heat Exchange Contribution Rate: Most areas show positive contribution under both scenarios; heating scenario has negative contribution in individual shallow areas of borehole 2 (heat absorption instead of supply), and cooling scenario has negative contribution in individual deep areas of borehole 2 (heat release instead of absorption)(**Figure 3)**.

heat exchange hole 1 heat exchange hole 2 heat exchange hole 1 heat exchange hole 2



(a) during heating days **(b) during cooling days**

Figure 3. Heat exchange contribution rate during heating and cooling days at Tuoli Base

4 COMPARISON OF TYPICAL GSHP PROJECTS IN BEIJING

Combined with hydrogeological conditions, the cold-heat response and heat exchange efficiency of the three projects were compared, and the correlation between hydrogeological characteristics and heat exchange contribution rate was clarified **(Table 1)**.

Table 1 Relation analysis between hydrogeological conditions and ground-source heat pump projects

Project Name	Stratum Particle Size	Groundwater Seepage	Heat Exchange Contribution Rate	Correlation Analysis
Automobile Industry Base	Fine	Poor	Heterogeneous, with large negative values; general heat exchange effect	Both stratum conductive heat exchange and convective heat exchange are general
Liaogongzhuang Base	Coarse	Good	Homogeneous, basically positive values; good heat exchange effect	Good groundwater occurrence and seepage conditions
Tuoli Base	Bedrock	Poor	Relatively homogeneous, few negative values; good heat exchange effect	Good stratum thermal conductivity

5 CONCLUSIONS

This study collected hydrogeological, system design and long-term operation monitoring data of three typical GSHP projects in Beijing, calculated and analyzed their cold-heat response characteristics and heat exchange contribution rate distribution, and drew the following key conclusions:

The initial geothermal temperature field in the shallow geothermal energy exploitation area has obvious differentiation characteristics, which is not a simple plate-like "homogeneous body", and the distribution of low/high-temperature and heat island zones is irregular and controlled by multiple geological factors.

During GSHP operation, the underground rock-soil mass shows diverse cold and heat responses to the water temperature change on the ground source side, including both positive and negative responses, and the response magnitude varies significantly even for the same response type, which is closely related to the hydrogeological conditions of the stratum.

Hydrogeological conditions determine the heat exchange efficiency of GSHP: coarse strata with good groundwater mobility and bedrock strata with high thermal conductivity have good heat exchange effects, while fine strata with poor groundwater seepage have general heat exchange effects due to the coexistence of low conductive and convective heat exchange efficiency.

The traditional uniform mesh, equal spacing and equal depth of underground pipe laying is not suitable for shallow geothermal energy development, as it fails to adapt to the heterogeneity of stratum heat exchange

capacity. Refined exploration and evaluation based on heat exchange capacity is the key to improving the overall efficiency of GSHP systems, and pipe laying schemes should be differentiated according to the heat exchange contribution rate of different strata and boreholes.

This study reveals the cold and heat response mechanism of shallow geothermal fields under different hydrogeological conditions, providing important theoretical support for the large-scale, efficient and sustainable exploitation of shallow geothermal energy, and can promote the high-quality development of the GSHP industry in Beijing and similar regions.

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