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Evaluation of Shallow Geothermal Energy and Study of Problem in High-latitude Regions, China

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ABSTRACT

It is very obvious that shallow geothermal energy resources are developed and utilized for the benefits of energy saving and environmental protection. Due to the low annual average atmospheric temperature in high-latitude regions in China, it has the great potential for the use of shallow geothermal energy. In order to evaluate the applicability of shallow geothermal energy, Harbin and Jiagedaqi were selected in this study to analyze the characteristics of ground thermal properties. The undisturbed ground temperature fields were measured in these two regions, and the temperature ranges and depth of the solar warming, constant temperature, and increasing temperature layers were determined, and the corresponding average initial temperatures are 7.5 °C and 5 °C, respectively. The 26 thermal response tests in 13 boreholes were examined at two heating powers and the analysis of thermal properties was performed in the laboratory. Then, the authors studied the heat exchange capacity of the ground and the characteristic of the thermal physical parameters in each region, and analyzed the correlation obtained in the field and laboratory tests. Since there are existing underground cold sources in high-latitude regions in China, this paper used the numerical method and the laboratory and field tests to determine the effect of cold sources on groundwater source heat pumps. This research offers a reference and practical experience for the use of shallow geothermal energy in high-latitude regions.

1. INTRODUCTION

The global energy crisis and environmental pollution have caused frequent resource shortages, such as oil and electricity shortages. Thus, the development and utilization of renewable energy is an urgent issue.

Shallow geothermal energy refers to the energy at a certain depth (generally 200 m) below the ground surface with a temperature of 25 °C or lower. This energy can be developed and utilized as a valuable energy source by using current technology. On the basis of the statistics of the 2010 World Geothermal Congress, energy using ground source heat pumps (GSHPs) reached 214,782 TJ (10^{12} J) around the world, showing an increase of 2.45 times within five years and an average annual growth rate of 19.7 % compared with the 2005 statistical data. The above data show that GSHP has been attracting increasing attention from countries worldwide (Lund et al. 2011).

The Chinese government began to advocate the scientific use of shallow geothermal energy resources in the 1980s to build an energy-saving society. The engineering specifications for GSHP systems have been published by China's Ministry of Construction since 2006. Currently, the technology is widely used in Beijing, Shenyang, and other regions (Yang et al. 2010). Many researchers also studied some of the problems caused by the use of shallow geothermal energy, including the change in ground temperature field (Hua et al. 2012), the effect of groundwater seepage and heat transfer model (Diao et al. 2004, Zhang et al. 2012), and so on. However, the applicability of shallow geothermal energy has not been sufficiently studied in high-latitude regions. The information on the design of GSHPs available at present is not applicable, which cannot be compared with other regions. In addition, cold sources are distributed in a scattered pattern because of the influence of the climate, which would cause seriously influence to use the shallow geothermal energy in high-latitude regions.

Thus, the characteristics of the thermal properties of the ground in 11 representative areas of Harbin are evaluated in this study based on the data obtained in 22 thermal response tests (TRTs). The shallow geothermal energy of the regions is also evaluated, focusing on the analysis of the initial temperature field of the region and the overall conditions of comprehensive ground thermal conductivity. Furthermore, the characteristics of thermal physical parameters and distribution law in the cold source site of the Jiagedaqi region are studied through laboratory and field tests, and the influence of cold sources was explored on ground water heat pump (GWHP). This study provides a starting point for future development of geothermal energy research and will be favorable for further utilization of geothermal system in high-latitude regions of China.

2. STUDY REGION INTRODUCTION

Harbin City is located in southwest of Heilongjiang Province of China and is the capital of the province. The geographic coordinates of the study region are longitude of 130°42′E-130°10′E and latitude of 44°04′N-46°40′N. The land area is 1006 km^2. Based on exploration data, the ground layer mainly consists of silty clay, silt, fine sand, mudstone, and so on. The groundwater aquifer system mainly consists of quaternary loose pore water system.

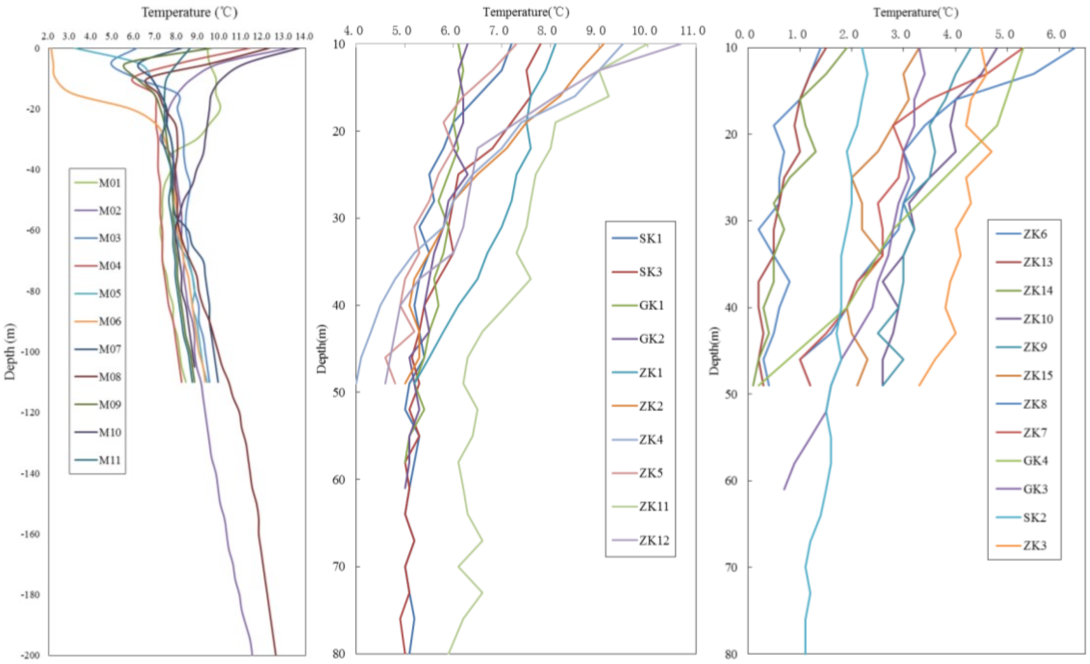
The other study region is in the hinterland of Daxinganling, covering an area of 120 km^2 with Jiagedaqi as its center. The geographic coordinates are longitude of 124°02′E-124°12′E and latitude of 50°22′N-50°28′N. The annual average atmospheric temperature is −2.6 °C, and extreme temperature can be as low as −52.3 °C. Drilling data show that the soil layers in this region are as follows: artificial landfill, miscellaneous fill soil, silty clay, pebbles, grit, sandstone, and granite layers.

3. INITIAL TEMPERATURE FIELD

In this study, the initial ground temperature was measured using the high-precision telephoto deep-water thermometer (HW-3) before conducting TRTs. The recording interval is 1 m. The resulting temperature profiles along boreholes are shown in Fig. 1.

In Harbin region, the initial ground temperature distribution rule in the study area was obtained by analyzing in-situ measurement data, as shown in Fig. 1 (a). The depth of the frozen soil in the Harbin region is 2.1 m. The depth of the solar warming layer is from 0 m to 35 m. The depth of the constant temperature layer is from 35 m to 50 m, and the mean temperature is 7.5 °C. The depth wherein temperature began to increase is from 50 m to 200 m, and the geothermal gradient is approximately 3.3 °C/100 m.

Jiagedaqi region is located in the sporadic island permafrost zone, which easily forms underground cold source because of year-round low temperature, dense vegetation, and mountains blocking direct sunlight. Temperature profiles are shown in Fig. 1 (b). Measuring results show that the constant temperature zone is about 30 m below the surface with a temperature of approximately 5 °C. However, hypothermal anomalies appear in the well loggings around the parking lot of the old development zone. Natural cold sources are estimated to be 40 m to 80 m deep below the surface in this region, and temperature ranges from 0 °C to 1 °C (Fig. 1 (c)).



(a) **(b)** **(c)**

Figure 1: Temperature profiles along different boreholes.

4. THERMAL PROPERTIES AND DISCUSSION

4.1 Laboratory testing results

The analysis of thermal properties was performed in a laboratory. QTM transient thermal conductivity equipment (Zhang et al. 2009) and BRR specific heat capacity equipment were employed in the test.

In Harbin region, 337 representative samples of rock and soil were collected as the 11 boreholes were drilled to better understand the characteristics of ground thermal properties. These samples include silty clay, silt, fine sand, and mudstone. The test data of rock and soil samples show that mass specific heat capacity ranges from 0.7 kJ/(kg K) to 1.5 kJ/(kg K); thermal conductivity ranges from 1.0 W/(m K) to 1.7 W/(m K). Fig. 2 only shows change curves of the thermal conductivity and mass specific heat capacity of M02 and M06 along two boreholes because there are many data.

In Jiagedaqi region, thermal conductivity and specific heat capacity tests were performed for pebbles, grit, sandstone, and granite according to the drilling results for the testing area and the rock and soil samples of each layer. The geotechnical integrated thermal parameters of the exploration hole are calculated within the depth for rock and soil samples by weighted average method. Thermal conductivity is 1.815 W/(m K), and specific heat capacity is 1.5 kJ/(kg K). The thermal conductivity and specific heat capacity of the layers fluctuate because the physical properties of pebble and grit change. Variation of these two parameters is shown in Fig. 3 (a). The physical properties of sandstone and granite are slightly different, and their thermal conductivity and specific heat capacity are relatively stable, as shown in Figs. 3 (b) and (c).

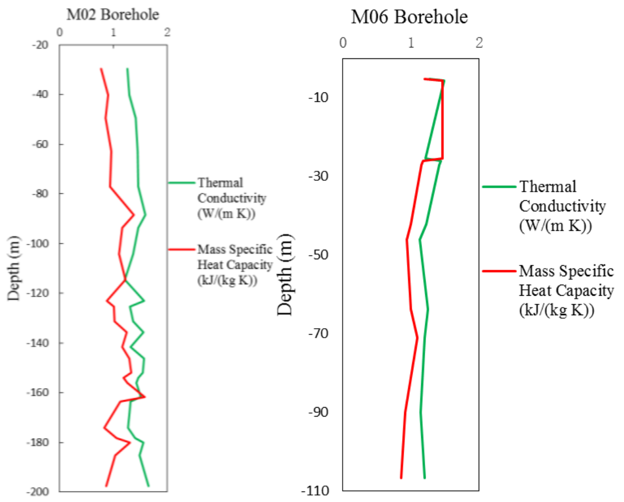
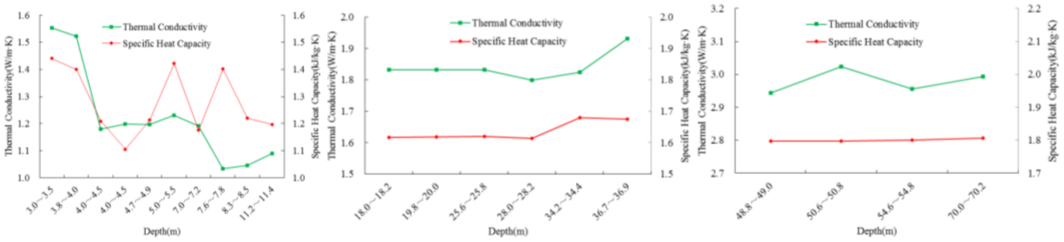


Figure 2: Thermal conductivity and specific heat capacity profiles along the borehole.



(a) **(b)** **(c)**

Figure 3: Variation of thermal conductivity and specific heat capacity with depth: (a) pebbles and grit layers, (b) sandstone layer, (c) granite layer.

Table 1: Results of in-situ TRT.

Region	Borehole NO.	Depth m	Type	Initial Temperature °C	Heat Power kW	Thermal Conductivity W/(m K)	Volumetric Specific Heat Capacity kJ/(m^3 K)
Harbin	M01	110	Double-U	8.21	4.2	1.53	1097.4
					6.5	1.78	1103.7
	M02	150	Single-U	8.99	4.2	1.84	1020.2
					6.5	1.91	1037.4
	M03	110	Single-U	7.83	4.2	1.51	1649.9
					6.5	1.68	1346.5
	M04	110	Single-U	7.55	4.2	1.64	1101.2
					6.5	1.69	1093.5
	M05	110	Double-U	7.30	4.2	1.72	1283.5
					6.5	1.89	1049.3
	M06	110	Single-U	7.77	4.2	1.84	1168.1
					6.5	1.92	1205.1
	M07	110	Single-U	7.92	4.2	1.57	1166.8
					6.5	1.78	1124.0
	M08	150	Double-U	8.61	4.2	1.42	1118.0
					6.5	1.55	1109.8
	M09	110	Double-U	7.46	4.2	1.75	1198.7
					6.5	1.83	1279.9
	M10	110	Single-U	8.38	4.2	1.82	1268.3
					6.5	1.86	1342.9
	M11	110	Double-U	7.81	4.2	1.62	1101.2
					6.5	1.71	968.2
Jiagedaqi	SK1	80	Single-U	5.50	4.2	2.50	3246.0
					6.5	2.51	3187.4
	SK3	80	Double-U	5.77	4.2	2.30	3224.9
					6.5	2.19	3215.7

4.2 TRT results

The operating conditions of summer were simulated in the TRTs according to the design requirement, which is to extract heat from rooms and then discharge it to the underground through BHE.

A total of 22 TRTs were performed in 11 boreholes with two heating powers to examine shallow geothermal energy in Harbin region. We ensured that boreholes were drilled and placed more than 48 h, and verification was conducted to ensure that the ground temperature field has recovered to its initial level prior to the tests. Heating power was constant during testing, and hot water was imported to the pipe at no less than 0.2 m/s from the water pump. Water temperature was continuously recorded for inlet and outlet pipes. The continuous time of each power was more than 48 h. The testing data are shown in Table 1.

Similar to Harbin region, two holes of TRTs are at the depth of 80 m and have the pore diameter of 200 mm in Jiagedaqi region, which are SK1 and SK3, respectively. The backfill is a mixture of bentonite and quartz sand (ratio of 1:4). TRT is performed with the constant heat flow method (Gehlin 2002). Heating power is constant during testing, and hot water is imported to the pipe from the water pump. Water temperature is continuously recorded for both inlet and outlet pipes. Heating power occurred for more than 48 h. The testing data are shown in Table 1.

5. OVERALL DISTRIBUTION OF TRT THERMAL CONDUCTIVITY

Given that TRT considers exhaustive factors and is in accordance with actual conditions, its thermal conductivity can represent the heat transferring capacity of each site and the values mostly range from 1.49 W/(m K) to 1.88 W/(m K), as shown in Table 1. Interpolation was performed to determine the overall distribution of shallow ground thermal conductivity in Harbin. An isogram of thermal conductivity was drawn (Fig. 4). The figure may not be accurate because the number of boreholes is not adequate.

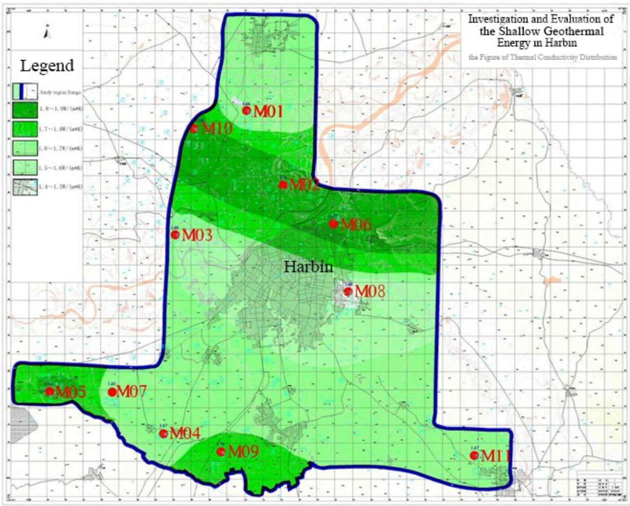


Figure 4: Overall distribution of shallow ground thermal conductivity in Harbin.

As shown in Fig. 4, the value of shallow ground thermal conductivity is small in the central region and large in northern and southern regions. Shallow ground thermal conductivity is basically symmetric in the western and eastern regions where the value around borehole M08 is the lowest, approximately 1.49 W/(m K). The value is high in the areas around Songhua River and in some southwest regions (around boreholes M02, M05, M06, and M10), approximately 1.90 W/(m K). Thermal conductivity in the other regions is approximately 1.7 W/(m K).

Overall, the regions with high thermal conductivity are boreholes M02, M06, and M10 distributed at areas around Songhua River and borehole M05 located near Taiping Lake and Hongqi reservoir. Thus, groundwater seepage has a significant impact on shallow ground thermal conductivity.

6. INFLUENCE OF COLD SOURCE ON THE TEMPERATURE FIELD OF AQUIFER

6.1 Model building

The internationally popular software TOUGHREACT (Xu et al. 2006) is adopted to build a TH-coupled numerical model with the size of 500 m × 200 m and the thickness of 100 m. The aquifer is placed at 20 m to 30 m below the ground. Three injecting and producing wells are designed for the model. The wells are 100 m in depth (Fig. 5). Well 7 is built between the injecting and producing wells to keep the temperature of the injection water approximately at 1.7 °C to simulate cold sources. The influence of cold source on groundwater temperature is simulated in the multiple-well system when the distance between the cold source and the wiring of the first injecting well and producing well is 15, 25, 50, 75, 85, 100, 125, 150, and 200 m, and at infinity (cold source does not exist).

Based on the geology conditions of Jiagedaqi region, the model boundary conditions are as follows: the front, back, and bottom of the model have an impermeable insulation boundary; groundwater direction is along the x axis; water temperature is 5 °C; the boundary conditions at the top border can be adjusted freely. The assumptions regarding the operating conditions of the model are as follows:

1) Simulation time is 365 d; the first 240 d is the heating period, and the succeeding 125 d is the recovery period.

2) The injecting and producing wells operate during the first 240 d. Injection volume is equal to the producing volume, and the total volume of water is 1296 m^3/d. During the recovery period, the injecting and the producing wells stop operating.

3) The difference in the temperature of heat breakthrough between qualified wells is 1 °C, that is, if the producing well reduces the water temperature by more than 1 °C, then heat breakthrough occurs.

4) The initial temperature of the aquifer is 5 °C, and the temperature of the water in the injecting well is 3 °C.

The parameters of the model mainly selected the testing results and the investigation data. Thermal conductivity of rock and soil is 2.5 W/(m K), specific heat capacity is 1.292 kJ/(kg K), mean porosity is 0.2 and mean bulk density is 2700 kg/m^3.

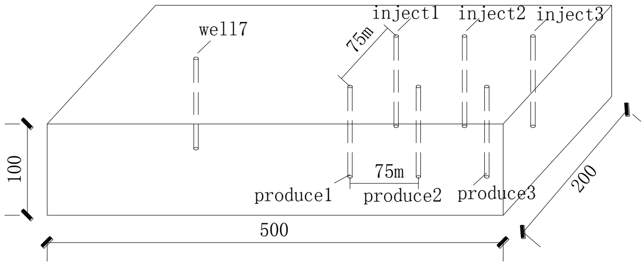


Figure 5: Schematic of the numerical model.

6.2 Simulation result of the model

Producing Well 1 is close to the cold source. Therefore, the cold source has the greatest effect on and is the most representative of the underground temperature field of Producing Well 1. This research focuses on the changes in the underground temperature field of Producing Well 1.

Fig. 6 shows the temperature change over time in Producing Well 1 when the cold source does not exist. After the extraction of groundwater and the recharge of cold water during the heating period, the temperature of Pumping Well 1 decreases gradually. When the heating period ends, the lowest temperature is 4.9984 °C, which increases gradually during the recovery period.

Fig. 7 shows the temperature variations in Pumping Well 1 at different distances from the existing cold source. When the distance of the well from the cold source is below 150 m, the temperature in Pumping Well 1 does not increase even during the recovery period. This finding indicates that the effect of the distance between the cold source and the multi-well system is below 150 m throughout the year. The heat breakthrough occurs at 75 m because of the decrease of temperature more than 1 °C, and the contour of temperature field is shown in Fig. 8 at 75 m cold source distance. The temperature in the pumping well increases during the recovery period when the distance is 150 m or more, and the cold source does not affect the operating efficiency of GWHP. Thus, the effect of the cold source on the temperature field is the greatest when the distance is less than 75 m, and the influence radius of cold source is approximately 150 m.

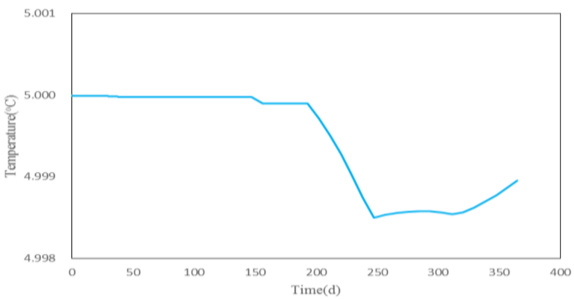


Figure 6: Temperature variation with time under no cold source.

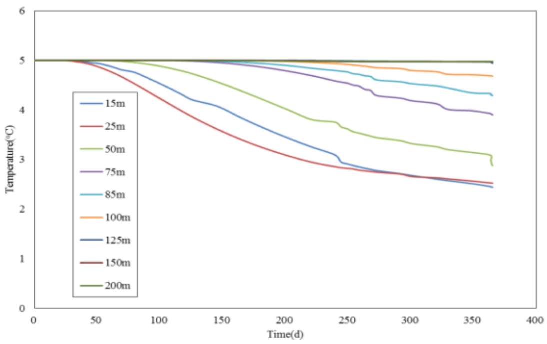


Figure 7: Temperature variation with time under different cold source distance.

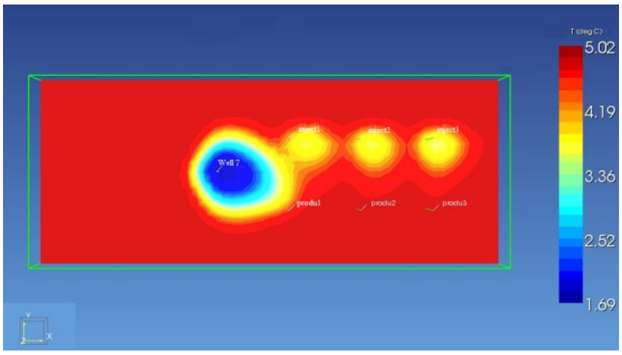


Figure 8: Contour of an underground temperature field at 75 m cold source distance.

7. CONCLUSIONS

The following conclusions can be drawn from the accumulated data and detailed results above.

(a) In Harbin, the depth of frozen soil is 2.1 m. The depth of the solar warming layer is from 0 m to 35 m. The depth of the constant temperature layer is from 35 m to 50 m, and the mean temperature is 7.5 °C. The depth at which temperature increases is from 50 m to 200 m, and the geothermal gradient is approximately 3.3 °C/100 m.

(b) In Jiagedaqi, layers with constant temperature and without a cold source are below 30 m from the ground surface and have a temperature of 5 °C. The underground cold source is distributed below 40 m from the ground surface and is scattered randomly; Cold sources have temperatures ranging from 0 °C to 1 °C.

(c) Laboratory test data indicates that mass specific heat capacity ranges from 0.7 kJ/(kg K) to 1.5 kJ/(kg K), and thermal conductivity ranges from 1.0 W/(m K) to 1.7 W/(m K). A total of 22 TRTs were performed for the 11 boreholes at two heating powers. Overall distribution of ground thermal conductivity is determined in Harbin. The overall characteristic is small in the central region and large in northern and southern regions and basically symmetric in western and eastern regions.

(d) The effect of the natural cold source on the GWHP has a direct relationship with the distance. The cold source whose temperature differs from the constant temperature by 3.3 °C affects the GWHP within a distance of 150 m.

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