ANALYSIS AND DISCUSSION ON VARIATION PATTERNS OF SOIL TEMPERATURE FIELD OF GROUND-COUPLED HEAT PUMP SYSTEM[1]

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Abstract: In this paper, according to the climatic conditions in Beijing, a single low-density building was selected as the typical building which was equipped with the ground-coupled heat pump system for heating and air-conditioning. Because of the imbalance of heat extraction and injection of underground heat exchanger, the solar energy was used as the auxiliary heat source for heating in winter. And then, the variation patterns of soil temperature field of the systems with and without the auxiliary heat source was studied. The results indicated that for these two systems, the average soil temperature of heat storage bed was decreased to some extent in the first year. Furthermore, the decreased rate of unbalanced system was much greater than that of the balanced one, and it was not obvious in other years. On the other hand, the heat storage bed lost heat through the ground surface toward outside every year, the proportion of heat loss was much greater in the first year, and as well as the thermal effects on the whole storage bed.

Key Words: single low-density building, ground-coupled heat pump, average soil temperature

1 INTRODUCTION

The ambient temperature conditions of soil refers to soil temperature changes over time and space (Zuiliang Ma 2007). It is the reaction of the soil heat balance and soil thermal conditions. The changes in soil temperature is mainly affected by solar radiation and atmospheric

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temperature. Specifically, the main factors that affect the soil temperature are the solar radiation balance, the soil heat balance and soil thermal properties. Different regions, different time and different soil composition, nature and utilization, will have different effect on the distribution of soil temperature. For ground source heat pump system, the temperature difference between the soil and the circulating fluid is the driving force of heat transfer. When soil temperature is higher, it is beneficial for the system operation under the working condition of the heating season. However, when soil temperature is lower, it is beneficial for the system operation under the working condition of the air-conditioning season.

In this paper, a single low-density building was selected as the benchmark building. The simulation program TRNSYS (Transient Systems Simulation Program) has been used modeling the building to get hourly load. It can be seen that the difference between the cumulative heat load in heating season and the cumulative cold load in air-conditioning season is large. Then, the difference between the annual heat extraction and injection of underground heat exchanger is relatively larger. If no measures are taken, there will be a larger degree of decline of soil average temperature, affecting the operation of the system in winter conditions. So make use of solar heat in winter as the auxiliary heat source, the annual heat extraction and injection can be basically balanced (Yuliang Pan 2011). Analysis and research on the system with or without solar thermal system, some conclusions can be get that can provide references for practical engineering.

2 THE SYSTEM DESIGN PROCESS

2.1 Benchmark building and load calculation

The building is three layers on the ground, 1 floor underground, and the gross area is about 330 square meters. The Heat transfer coefficient of building envelop is shown in Table 1.

Table 1 Heat transfer coefficient of building envelop **W/(㎡·K)**

Building envelop	Heat transfer coefficient
Roof	0.38
Wall	0.362
Reinforced concrete walls of the negative layer	0.489
Door	2.0
Windows	2.79
Floor of the negative layer	0.482
Floor	0.509

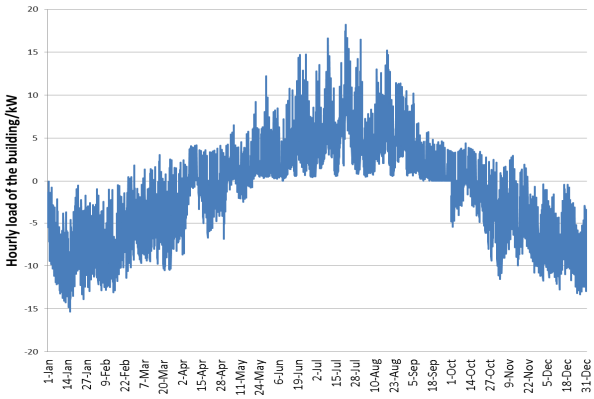


Figure 1: The whole year hourly dynamic load simulation

Set heating season is from November 15 to March 15 and air-conditioning season is from June 1 to September 30. According to coefficient of performance (COP) is 3.5 and energy efficiency ratio (EER) is 4, the cumulative heat extraction from the underground is 14,607.8 kWh, and the cumulative heat injection to the underground is 10,420.2 kWh. Thus the heat imbalance value is 4,187.6 kWh (Yuliang Pan 2010).

2.2 The design of underground heat exchanger

The temperature of deep underground soil is related with location and depth from the ground (Nairen Diao 2006). Generally, the soil temperature about 15 meters deep underground is approximately equal to the local average annual air temperature. In practical engineering calculations, an average temperature in the direction of depth is usually taken in order to simplify the calculations. In this paper, the original soil temperature in Beijing is selected as 15 ℃.

Select vertical borehole heat exchangers, and set double U-shaped tube within each drill hole. The pipe is high-density polyethylene pipe, and the thermal conductivity is 0.46 W/(m•K). The drilling diameter is taken as 0.15 m, and the distance is 5 m. Select dense clay as the soil materials, the thermal conductivity is 2.0 W/(m•K), and the heat capacity is 2 016 kJ/(m^3•K)(CABR 2009). Using the original soil as backfill material, assuming its thermal parameters are unchanged. The number of drill holes is two, and the depth of each drilling is 100 m deep.

3 THE ANALYSIS OF SOIL TEMPERATURE FIELD VARIATION

3.1 Annual heat extraction and injection balanced system

For ground-coupled heat pump system with solar thermal system, it can be seen that the

heat extraction and injection of the ground heat exchanger can be basically balanced with the supply of solar heat. The heat imbalance rate is very small, within ± 2%. As shown in Figure 2, a negative value indicates that the heat injection is more than heat extraction. The changes of average temperature of the soil within 20 years are shown in Figure 3.

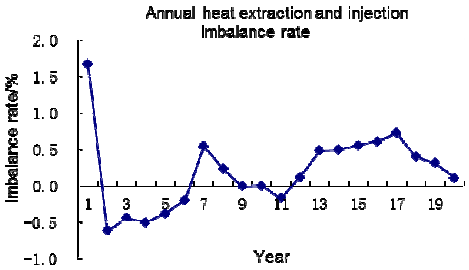


Figure 2: Annual heat extraction and injection imbalance rate of underground heat exchanger

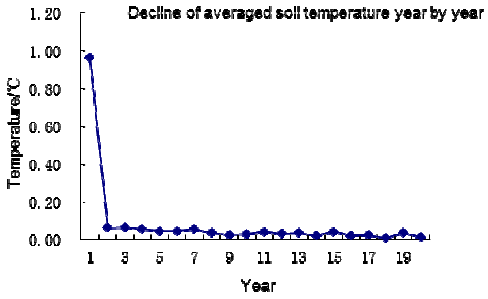


Figure 3: Changes of average soil temperature within 20 years

According to the calculation results, the decline of average soil temperature in the first year reached a maximum of 0.96 ℃. However, the heat imbalance rate in the first year were 1.67% and -0.62% in the second year, showing that the decline of average soil temperature in the first year was quite large relative to its heat imbalance rate. For the Duct Ground Heat Storage Model used in TRNSYS, it is underground heat storage system that stores heat directly into the soil. Not only the heat exchanges between the heat storage bed and the underground heat exchanger, but also between the heat storage bed and the surrounding rock mass and the atmospheric environment.

The heat exchange values consists of three parts, namely, the bottom, the top and the surrounding heat transfer. The heat transfer data of the first five years are detailed in table 2-4. It can be seen that the top and surrounding heat exchanges between the heat storage bed and the surrounding environment are much more than the bottom. The heat loss in the first year was the greatest and the average soil temperature had the most dramatic decline. However the heat loss in other years was small, the average soil temperature did not change significantly.

Table 2 Heat transfer data of the first five years kWh

Year	Top			Surrounding			Bottom			Total
	Heat gain	Heat loss	Total	Heat gain	Heat loss	Total	Heat gain	Heat loss	Total	
1	816.63	-1 289.62	-472.99	4 518.72	-6 156.71	-1 637.99	70.39	-92.50	-22.11	-2 133.09
2	897.64	-1 170.08	-272.44	6 208.08	-6 088.90	119.18	95.65	-90.71	4.95	-148.31
3	914.46	-1 152.25	-237.78	6 164.98	-6 092.69	72.29	96.30	-90.02	6.28	-159.22
4	923.48	-1 125.65	-202.18	6 160.08	-6 084.10	75.98	97.00	-89.20	7.80	-118.40
5	929.32	-1 135.86	-206.54	6 194.54	-6 082.20	112.34	98.63	-88.62	10.01	-84.19

Table 3 Annual heat extraction and injection of underground heat exchanger kWh

Year	Heat extraction	Heat injection	Amount of imbalance
1	-12 213.50	12 013.19	-200.30
2	-11 961.91	12 035.99	74.08
3	-11 896.69	11 949.48	52.80
4	-11 837.11	11 896.67	59.56
5	-11 807.12	11 852.15	45.03

Table 4 Annual heat changes in the soil kWh

Year	1	2	3	4	5
Heat changes	-2 333.39	-74.23	-106.42	-58.84	-39.16

Analyzed from the perspective of their reasons, the original soil was undisturbed. When the heating system began to operate in the heating season, the temperature difference between soil and the surrounding environment was small, and because of the presence of heat transfer delay and phase difference, the heat extraction of underground heat exchanger from soil had little effect on the surrounding environment, resulting in less heat extraction from the surrounding environment. When the system began to operate in the air conditioning season, the average soil temperature was relatively higher than other years. When underground heat exchanger dissipated heat to the soil, the ground temperature rise faster, and the temperature difference between the soil and surrounding environment increased, so the heat injection of the heat storage bed was a little more than other years. On the whole, the heat injection of the heat storage bed was more than the heat extraction, the soil temperature would fall.

After one year of operation, the heat storage bed temperature would fall. There would be a temperature gradient between the heat storage bed and surrounding environment. The system reached a more stable running state, and the heat extraction and injection of underground heat exchanger was almost equal, so the heat storage bed temperature changed little year by year. Analyze the data in table 1, the heat storage bed lost heat at the top every year. The heat loss at the top accountd for 22.2% of the total heat loss of the heat storage bed in the first year. While in other years, the heat loss at the top was the only source of heat loss of the heat storage bed. By calculation, the heat loss at the top in the

heating season accounted for 80% of the total heat loss at the top in the first year, namely most of the heat loss at the top occured in the heating season. So the heat loss at the top was not good for the system operation in the heating season. Corresponding measures should be taken to reduce the heat loss through the top surface.

3.2 Annual heat extraction and injection unbalanced system

In this paper, the variation patterns of soil temperature field of the ground-coupled heat pump system without auxiliary heat source was studied too. In this operating condition, the heat transfer imbalance rate is relatively large, between 37% to 40%. The data of heat transfer imbalance rate and yearly average soil temperature decreased value are shown in figures 4 and 5. It can be seen that the average soil temperature downward trend is similar to the heat balanced system. But because of no supplement heat, the average soil temperature dropped large in the first year, reaching 1.57 ℃. In other years, the average soil temperature had a certain degree of decline, changing slightly between 0.02~0.18 ℃.

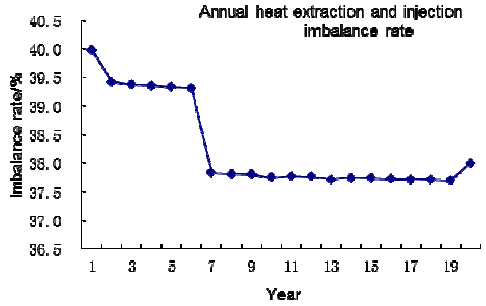


Figure 4: Annual heat extraction and injection imbalance rate of underground heat exchanger

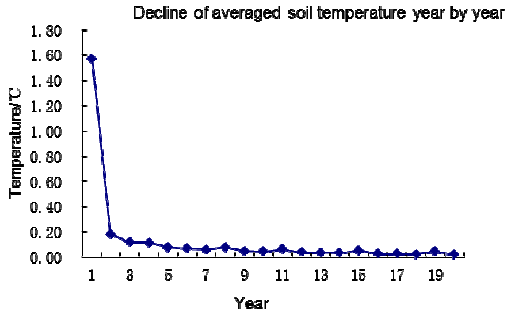


Figure 5: Changes of average soil temperature within 20 years

The heat transfer data of the first five years are detailed in table 5-7. In the first year, the heat storage bed lost most heat, the value was 3 809.04 kWh, so the average soil temperature dropped largest. While in other years, the heat loss was small, and the average soil temperature fell slightly.

Overall, the heat storage bed got heat from the surrounding environment each year, and the

heat gain in the first year was the least. While the heat gain in other years were much more than the first year. It was this part of the heat gain to a certain extent that make up heat imbalance of the ground heat exchanger. Similar to the analysis of section 3.1, the average soil temperature was relatively higher in the first year. And when the heating system began to operate in the heating season, the temperature difference between soil and the surrounding environment was small, and the heat extraction of underground heat exchanger from the surrounding environment was little. So the average soil temperature dropped significantly. Even though the heat storage bed could get some heat from the surrounding environment, but due to the insufficient heat gain, the average soil temperature still had a downward trend.

Table 5 Heat transfer data of the first five years kWh

Year	Top			Surrounding			Bottom			Total
	Heat gain	Heat loss	Total	Heat gain	Heat loss	Total	Heat gain	Heat loss	Total	
1	836.03	-1 263.37	-427.34	7 142.36	-6 393.51	748.86	110.76	-95.52	15.24	336.76
2	932.21	-1 129.23	-197.02	9 950.35	-6 181.46	3 768.90	153.41	-90.55	62.86	3634.74
3	953.34	-1 107.56	-154.22	10 013.43	-6 143.49	3869.94	156.85	-88.64	68.21	3 783.94
4	964.33	-1 079.75	-115.42	9 955.87	-6 125.74	3 830.13	157.60	-87.24	70.35	3 785.06
5	972.01	-1 087.92	-115.90	10 029.13	-6 117.78	3 911.35	160.41	-86.19	74.23	3 869.67

Table 6 Annual heat extraction and injection of underground heat exchanger kWh

Year	Heat extraction	Heat injection	Amount of imbalance
1	-14 515.76	10 369.96	-4 145.80
2	-14 431.94	10 351.08	-4 080.86
3	-14 414.50	10 341.84	-4 072.66
4	-14 401.92	10 334.67	-4 067.24
5	-14 391.58	10 328.57	-4 063.01

Table 7 Annual heat changes in the soil kWh

Year	1	2	3	4	5
Heat changes	-3 809.04	-446.12	-288.72	-282.18	-193.34

The heat storage bed lost heat at the top every year. The total heat loss at the top in the first year was the most, accounting for 55.9% of the total heat gain of the surrounding and bottom of the heat storage bed. While in other years, the top heat loss decreased, the impact on the overall heat changes transfered within 3% to 5%.

3.3 Comparison of two kinds of working conditions

From the analysis in Section 3.2 and 3.1, for the two kinds of working conditions, the average soil temperature in the first year would have a certain degree of decline. And for the two kinds of conditions, the average soil temperature decline was not exactly for the same reasons. The soil temperature decline of heat balanced system was due to that the heat gain from the surrounding environment was less than the heat loss in the first year. While the soil temperature decline of heat unbalanced system was due to that the heat loss of the heat storage bed was mainly from the inside. Therefore, for the two kinds of working conditions, the temperature of heat storage bed would all decline because of the heat loss. In other years, the temperature of heat storage bed changed little, but the causes were different. For the heat balanced system, the heat transfer between the heat storage bed and the surrounding environment was almost balanced; while for the heat unbalanced system, the heat storage bed got a certain amount of heat supply from the surrounding environment, but due to the insufficient heat, the average soil temperature still had a downward trend.

Besides the underground heat exchanger, there would also be a heat transfer between the surrounding environment and the heat storage bed. Especially for the heat unbalanced system, a large part of the heat loss needed to be supply by the surrounding environment. So measures should be taken to enhance the heat transfer between the heat storage bed and the surrounding environment. Of course, the surrounding environment could not completely balance the differential value of heat extraction and injection of underground heat exchanger. The average soil temperatures would continue to fall. Therefore, in the actual design, maintain the annual heat extraction and injection of underground heat exchanger basically balanced is necessary.

Overall, the heat storage bed lost heat at the top surface every year. The heat loss at the top of the heat balanced system was more than the unbalanced system. From the perspective of the years of data, the heat transfer of the heat storage bed in the first year accounted for a large proportion of all the heat transfer. And the thermal equilibrium impact on the heat storage bed was larger as well. Therefore, in the actual design, for the system that the annual heat extraction is more than heat injection, some measures could be taken to reduce the heat loss at the top of the heat storage bed, such as putting thermal insulation material on the ground surface or arranging underground heat exchanger under the building.

4 Conclusions

For the heat balanced system or unbalanced system, the temperature of the heat storage bed in the first year would all have a certain degree of decline. The temperature decline degree of heat storage bed of the heat unbalanced system in the first year is much larger than the heat balanced system. While in other years, the temperature of the heat storage bed

changes slightly.

Overall, the heat storage bed lost heat at the top surface every year. Especially in the first year the heat transfer of the heat storage bed accounted for a large proportion of all the heat transfer. And the thermal impact on the heat storage bed was larger as well.

Take soil as heat storage bed in the heat storage design especially in seasonal heat storage design, the heat transfer between the heat storage bed and the surrounding environment should be calculated to ensure that the heat or cold loss is within the range of requirements.

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