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The post-evaluation of a practical ground source heat pump system based on data mining technology

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Abstract

This paper studies the performance of a practical ground source heat pump (GSHP) system by real-time monitoring data. The GSHP system, which is installed in an office building of Shaoxing (29.42 °N, 120.16 °E), China, is real-time monitored from Nov. 2012 to Mar. 2015. Data Mining (DM) technology is applied to clean the monitoring data. The performance of the GSHP system is evaluated by clean data. The results show that the application effectiveness of this system is unsatisfied because of the persistently low load ratio (LR) and COP (EER, in summer). The condition of indoor temperature and relative humidity (RH) can just basically conform to the uses' requirements both in winter and in summer. The percentage of average LR in each mode over 60% is unsatisfactory. The soil temperature remained relatively constant throughout the monitoring period. And Low LR and irrational energy consumption proportion structure are two main reasons for the relatively low COP (EER).

Keywords - GSHP system; Post-evaluation; Data mining technology; COP (EER).

1. Introduction

Building energy consumption is an important part of the final energy consumption, which accounts for about 35% of the world's total final energy consumption [1]. And more than 50% of the energy consumed in buildings in China and the United States is for space heating and cooling, and domestic water heating [2]. From the viewpoint of sustainable development, it has great significance to apply alternative low-cost energy resources in buildings. Ground source heat pump (GSHP) is one of the promising technologies using shallow geothermal energy for space heating and cooling applications as well as domestic hot-water. The main form utilizing shallow geothermal energy in buildings is GSHP air-conditioning (AC) system. Due to the superiorities of high energy efficiency and environmental friendliness compared to conventional AC systems, it has attracted more and more attention in the past decades [3].

The main disadvantage of GSHP systems compared to conventional ones is higher initial cost. Therefore, it is important to ensure the GSHP systems running with higher efficiency to lower its operation cost. However, the practical performance of GSHP systems in actual project may fail to satisfy design expectation due to improper equipment installation, equipment degradation, sensor failures, or inappropriate control sequences [4]. Therefore, accurate assessment of the effectiveness of the practical GSHP system is very important to find out the undesirable problems.

In previous studies, there were many researches evaluating the performance of practice GSHP system using monitoring data. Montagud et al. [5] collected monitoring data of a GSHP system in Spain which had been monitored for five years and evaluated the system performance and ground thermal response. In Korea, the cooling performance of a GSHP system installed in a school building was evaluated for one summer by Hwang et al. [6]. Naili et al. [7] carried out an experiment in a pilot GSHP system for a few days in Tunisia and evaluated the coefficient of performance of the heat pump and the overall system in continuous operation mode. Based on the accumulated data lasting for four years, Luo et al. [8] analyzed the cooling and heating performance of a GSHP system in Southern Germany. Michopoulos et al. [9] also conducted the evaluation of a GSHP system installed in Northern Greece which had run normally over eight-years and was continuously monitored. Similarly, based on experimental data, operation performances of a GSHP system in China for both cooling and heating provision with different operation modes are evaluated by Man et al. [10]. Zhai et al. [11] presented a GSHP system that was installed in an archives building in Shanghai. And according to experimental results, an increment of about 0.5 °C in soil temperature was observed after one year of operation.

It can be seen that the performance of GSHP systems were experimentally evaluated in long-term or in short-term. It is critical to evaluate the system performance in practical project so that the faults in system design and operation can be found. And operation of the systems would be improved and optimized. However, the accuracy of monitoring data might go through trials in practice projects because of the instrument or sensor failures or other uncontrollable factors. Effective tools need to be used to process the monitoring data, which usually stored in a huge database. DM is an emerging powerful technology with great potential to discover hidden knowledge in large data sets [12], and it has attracted more and more attention in recent years. This study will use DM to clean the monitoring data.

This paper is organized as follows: firstly, we give concise descriptions of the GSHP system and energy consumption monitoring system. Then DM technology will be used to clean the huge database. Follow that, a post-evaluation procedure was conduct on the GSHP system to evaluate the performance of the system. Finally, the results and conclusions were given.

2. Descriptions of the GSHP system and the data sets

2.1 The GSHP system

GSHP project is installed in an office building located in Shaoxing (29.42 °N, 120.16 °E), China, where is a cooling-dominant area with hot summer and cold winter. The cooling and heating load of the building (building area: 7085 m^2; air conditioning area: 4655 m^2) are 618 kW and 403 kW, respectively, and the domestic hot water load is 40.8 kW. Because the cumulative cooling loads are much larger than the heating loads, a hybrid GSHP equipping with a cooling tower which is used as auxiliary heat sink was applied to the building. The schematic diagram of the GSHP system is illustrated in Fig. 1.

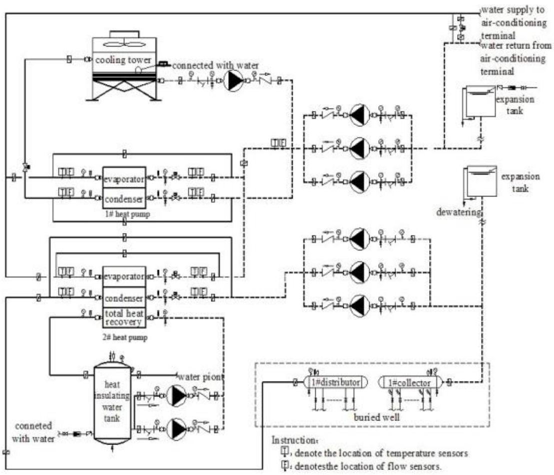

Fig. 1. Schematic diagram of the GSHP system

This system consists of two heat pumps, 1# (ordinary screw-type unit, cooling capacity: 307 kW; heating capacity: 326 kW) and 2# (total heat recovery screw-type unit, cooling capacity: 315 kW; heating capacity: 343.7 kW). 2# heat pump supplies domestic hot water. The system includes three pumps on ground source side, a pump on cooling tower side, three pumps on user side and two hot water pumps. There are 140 boreholes underground with the spacing of 4 m. The depth of the boreholes is 50 m. The type of GHE is mainly double-U pipe and there are also very small amounts of single-U pipe and triple-U pipe. The outer diameter of pipe is 32 mm. The total length of the GHE was 7310 m.

1# heat pump was connected with cooling tower, and 2# heat pump was connected with GHE. In summer mode, only 2# heat pump is running under small partial load ratio (This mode was named S1). With the load ratio increasing in summer, 1# heat pump will be activated and two heat pumps operated simultaneously (This mode was named S2). In winter mode, 1# heat pump is shut down. The heating load and domestic hot water are only provided by 2# heat pump.

2.2 Energy consumption monitoring system

The GSHP system was continuously monitored all the year round. Real-time monitoring data was collected by a data acquisition system from Nov. 2012 to Mar. 2015. The measurements that were regularly recorded every 90 seconds were as follows:

- The supplying and return water temperatures of the ground heat exchangers (GHE) / heat pumps / cooling tower / heat recovery water tank were measured by wire PT500 resistance thermometer sensors.
- The water volume flow rate of GHE / heat pumps / cooling tower / heat recovery water tank were measured by flowmeters.
- The input electrical power of compressors / circulating water pumps / cooling tower fans were measured by electrical energy meters.
- The soil temperatures were measured by PT500 buried at different depths in four thermometry boreholes: A, B, C and D.
- The indoor / outdoor temperatures and relative humidity were measured respectively.

The monitoring data from Nov. 2012 to Mar. 2015 which contained two summers and three winters was collected and a huge number of records of parameters were stored in Structured Query Language (SQL) database.

3. Data clean

Data clean is a critical step in the process of knowledge discovery. The missing values should be given up and outliners should be removed from the database. Many methods can be used for effective removal of the outliers. In this study, the following three rules are firstly used for effective removal of the outliers:

Rule 1: The water flow values in condenser side (winter mode) or evaporator side (summer mode) that are less than 0 are defined as outliners;

Rule 2: The energy consumption values of heat pumps that are less than 0 are defined as outliners;

Rule 3: Load ratio of heat pumps and system that are less than 0 or larger than 1 are defined as outliners.

Secondly, outliers will be simultaneously detected using a simple filter named as the interquartile range rule [13]. It will be performed as following two rules:

Rule 4: Data values that are less than Q_1-$1.5\times(Q_3$-$Q_1)$ are defined as outliners;

Rule 5: Data values that are larger than Q_1+$1.5\times(Q_3$-$Q_1)$ are defined as outliners.

Where Q_1 is the lower quartile and Q_3 is the upper quartile.

Besides that, the data in summer and in winter are also separately processed to facilitate the accuracy of models in different operating conditions. And there are one operating mode in winter and two operating modes in summer mode (S1 and S2) as mentioned in section 2.1. Lastly, in order to compress the amount of data and improve data quality, the original 90 seconds data has been aggregated to 1 h interval by calculating the mean value of each input variable with one hour step of time.

After data clean and preprocessing, the amount of data is 656 in winter and 871 in summer when GHE works alone (S1), and that is 199 when GHE and cooling tower work together (S2).

4. Results and analysis

In this section, a post-evaluation procedure is conducted on the GSHP system. The indoor and outdoor temperature and relative humidity (RH), the load ratio (LR) of heat pumps, soil temperature and COP (EER, in summer) of heat pumps and system were displayed and analyzed.

4.1 Indoor and outdoor temperature and relative humidity

Fig. 2 presents the indoor and outdoor temperature and RH in winter mode. It can be seen that the outdoor average temperature and RH in winter mode were 8.4 ℃ and 59.7% respectively. And the indoor average temperature and RH were 15.7℃ and 40.9% respectively. The highest and lowest indoor temperature were 21.2℃ and 9.3℃ respectively. The indoor temperature, from 16℃ to 22℃, accounted for 55.0% of all data points. It can be drawn that the condition of indoor temperature and RH could basically meet the uses' requirements, but it might be unsatisfactory and be lower than design desire.

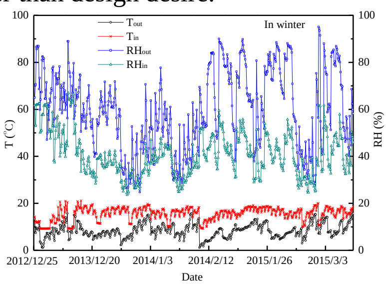

Fig. 2. Outdoor and indoor temperature and relative humidity in winter

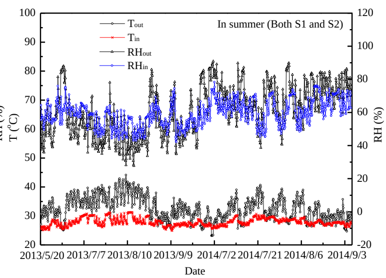

Fig. 3. Outdoor and indoor temperature and relative humidity in summer

Fig. 3 depicts the indoor and outdoor temperature and RH in summer mode (both S1 and S2). The outdoor average temperature and RH in summer mode (both S1 and S2) were 32.6℃ and 60.8% respectively. And the indoor average temperature and RH were 27.9℃ and 59.3% respectively. The highest and lowest indoor temperature were 31.2℃ and 24.9℃ respectively. And the proportion of indoor temperature between 22℃ and 28℃ was 55.9%.

4.2 The LR of heat pumps

Because the changing tendency of LR of system is the same to that of load ratio (LR) of heat pumps, only LR of heat pumps will be analyzed in here. The LR of 2# heat pump in winter mode is as follows:

$$LR_2 = \frac{Q_{c2} + Q_{hr}}{RHL_2} \tag{1}$$

where RHL_2 (rated heating load of 2# heat pump) is 343.7kW, Q_{c2} is the condenser thermal load of 2# heat pump, Q_{hr} is the heat recovery thermal load, Q (thermal load, kW) can be calculated as follows:

$$Q = c\rho F \left| T_p - T_r \right| \tag{2}$$

where c (specific heat capacity of water) is 4.18 kJ/(kg•℃), ρ (water density) is 1×10^3 kg/m^3, F is the flow rate (m^3/h).

The changing curve of LR of 2# heat pump in winter mode is illustrated in Fig. 4. It can be seen that the LR value fluctuated wildly by varying from 12.98% to 77.85%. The average LR of 2# heat pump was 49.35%. Whereas, only about 30 percent of all the LR monitoring points were more than 60%, which meant that the 2# heat pump was persistently operating in low energy efficiency. There might be three reasons for the persistently low LR 2# of heat pump. One might be the unreasonable design of system or/and inappropriate heat pump selection. The other might be the inaccurate building load. The third reason might be problematic operation-control strategies. As confirmed in above section, the indoor thermal environment was lower than design desire, whereas, the LR of heat pump was persistently in low level.

In summer, when the system runs in mode S1, LR of 2# heat pump is calculated by Eq. (3):

$$LR_2 = \frac{Q_{e2}}{RCL_2} \tag{3}$$

where RCL_2 (rated cooling load of heat pump 2#) is 315 kW, Q_{e2} is the evaporator thermal load of 2# heat pump, the computational formula of Q is similar with Eq. (2).

When the system runs in mode S2, LR of heat pump 2# and heat pump 1# can be calculated by formulas which are similar with Eq. (4), RCL_1 (rated cooling load of heat pump 1#) is 307 kW.

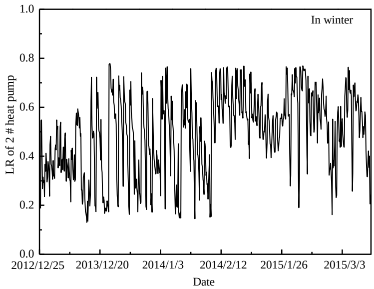

Fig. 4. LR of 2# heat pump in winter mode

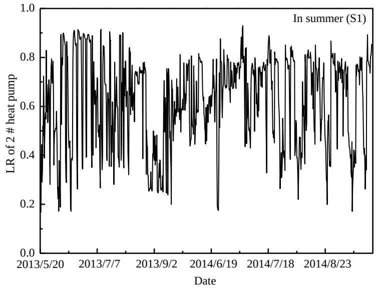

Fig. 5. LR of 2# heat pump in mode S1

Changing curves of LR of heat pumps in mode S1 and S2 are shown in Fig. 5 and Fig. 6, respectively. And the LR comparison of each heat pump in different mode was listed in Table 1. These results showed that the fluctuation range of LR in mode S2 was less than that in mode S1 and winter mode (see Fig. 5 and Fig. 4). This suggested that operation of heat pumps in mode S2 were more stable than that in mode S1 and winter mode. And the average LR of heat pumps in mode S1 and mode S2 were similar, but it was much smaller when the system in winter mode. The percentage of LR over 60% was unsatisfactory in each mode.

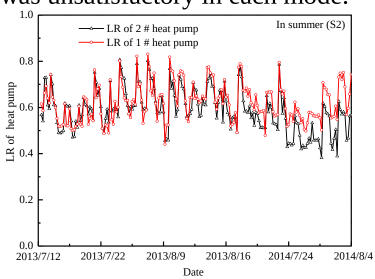

Fig. 6. LR of 1# heat pump and 2# heat pump in mode S2

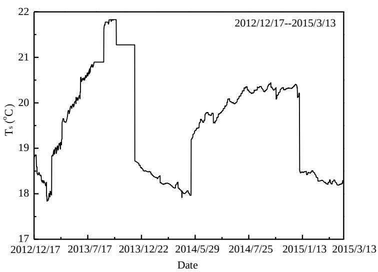

Fig.7. soil temperature in whole monitoring period

Table 1 The LR comparison of each heat pump in different modes

LR value	winter mode	mode S1	mode S2	
	heat pump 2#	heat pump 2#	heat pump 1#	heat pump 2#
range	12.98%-77.85%	16.71%-93.00%	44.09%-83.06%	38.24%-80.67%
average	49.35%	61.89%	62.18%	58.77%
over 60%	29.89%	57.63%	57.29%	41.71%

4. 3 Soil temperature

The soil temperature is a very important factor which influences the efficiency of the GSHP system, i.e., the higher the temperature of soil, the lower efficiency for space cooling, and the higher efficiency for space heating. Three winters and two summers (from Nov. 2012 to Mar. 2015) soil temperature were monitored as shown in Fig. 7. The initial temperature of soil was 19.5℃ which was tested in a thermal response test. The temperature of soil in the three winters, in turn, was starting with 19.5℃, 18.7℃, 18.5℃, and ending with 18.0℃, 18.0℃, 18.2℃. In the two summers, that was starting with 18.8℃, 19.2℃, respectively, and ending with 21.3℃, 20.2℃. The average temperature of soil in whole monitoring period was 19.5℃. It indicated that the soil temperature remained relatively constant. That is significant for both space cooing and space heating.

4. 4 The COP (EER) of heat pumps and system

COP (EER) of heat pumps and system are major indicators to evaluate the performance of the GSHP system. The COP of 2# heat pumps and system in winter mode were as follows:

$$COP_2 = \frac{Q_{c2} + Q_{hr}}{P_2} \tag{4}$$

$$COP_{sys} = \frac{Q_{c2} + Q_{hr}}{P_2 + P_{wp,ter} + P_{wp,hr} + P_{wp,GHE}} \tag{5}$$

In summer, when the system run in mode S1, EER of 2# heat pump and system were calculated by Eq. (6) and Eq. (7):

$$EER_2 = \frac{Q_{e2}}{P_2} \tag{6}$$

$$EER_{sys} = \frac{Q_{e2}}{P_2 + P_{wp,ter} + P_{wp,hr} + P_{wp,GHE}} \tag{7}$$

And in mode S2, EER of 2# heat pump and 1# heat pump can be calculated by formulas which were similar with Eq. (6), whereas, EER of system will be calculated as follows:

$$EER_{sys} = \frac{Q_{e1} + Q_{e2}}{P_1 + P_2 + P_{wp,ter} + P_{wp,GHE} + P_{wp,CT} + P_f} \tag{8}$$

As shown in Fig. 8-10, the average COP_2 was 3.28 (range from 2.81 to 3.78) in winter mode, with the average COP_{sys} was 1.97 (range from 1.03 to 2.45). The average EER_2 was 3.56 (range from 2.37 to 4.73) in mode S1 and the average EER_{sys} was 2.23 (range from 1.55 to 2.92). In mode S2, The average EER_1 and EER_2 were 3.40 (range from 2.55 to 4.01) and 3.68 (range from 3.11 to 4.23), respectively, and the average EER_{sys} was 2.39 (range from 1.94 to 2.81). Compared with some actual GSHP system projects in China in Ref. [14], the COP (EER) of heat pumps and system in this project were under the average level. The poor COP (EER) of heat pumps and system were directly related to the low LR as shown in section 4.2. And the other reason for the low efficiency of system was the irrational energy consumption proportion structure. As shown in Fig. 11, the energy consumption proportions of water pumps were too high. It was 41.52% in winter mode, 38.65% in mode S1 and 32.27% in mode S2.

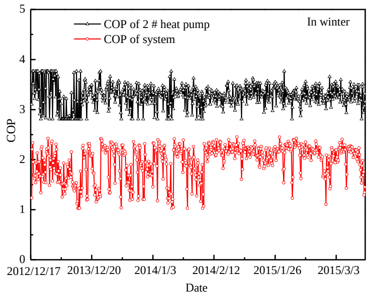

Fig. 8. COP of 2# heat pump and system in winter

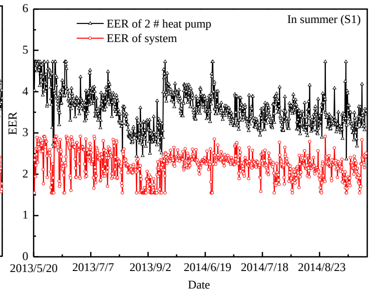

Fig. 9. EER of 2# heat pump and system in mode S1

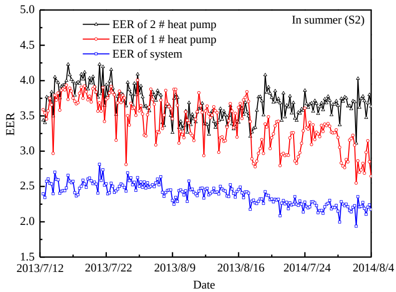

Fig. 10. EER of 1 #heat pump, 2# heat pump and system in mode S2

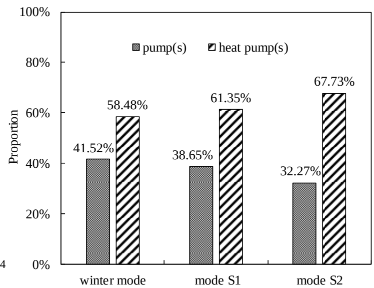

Fig. 11. Energy consumption proportions of pumps and heat pumps

5. Conclusion

The performance of an actual GSHP system, which have been monitored for two summers and three winters, is studied by real-time monitoring data in this paper. And DM technologies are used to clean the monitoring data for the better post-evaluation results.

Based on the study above, it can be know that the condition of indoor temperature and RH can just basically conform to the uses' requirements both in winter and in summer. The practical application effectiveness of the GSHP system is unsatisfied. The average LR in each mode is persistently low and the percentage of average LR over 60% is unsatisfactory. The soil temperature remained relatively constant throughout the monitoring period. The average COP_2 is 3.28 in winter mode, with the average COP_{sys} is 1.97.

And the average EER_2 is 3.56 in mode S1 and the average EER_{sys} is 2.23. In mode S2, The average EER_1 and EER_2 are 3.40 and 3.68, respectively, and the average EER_{sys} is 2.39. Low LR and irrational energy consumption proportion structure are two main reasons for the low COP (EER).

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