Evaluation of the performance of a hybrid cooling/heating system combining groundwater direct cooling with groundwater heat pump for rural buildings

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Abstract. With the remarkable improvement of villagers' living standard and the requirement of building energy efficiency, it becomes imperative to rely on renewable sources of energy and make a more efficient use of energy to solve the problem of cooling/heating for the rural buildings. This paper presents a new hybrid cooling/heating system, which combines groundwater direct cooling system (GWDCs) with groundwater heat pump system (GWHPs). The system is installed in an office building in Youhao Street, Duliu town, Jinghacounty, Tianjin, China. The feasibility of the system is verified and the performance of the system is experimentally evaluated both in cooling and heating modes. It is found that the average GWDCs COPS is approximately 3.85 in the cooling season, while the average heat pump COP and the overall system's COPS of GWHPs are about 5.05 and 2.8 respectively. The results obtained from the experiment show that these systems could be used safely, reliably and efficiently at the lowest cost for the rural buildings in Tianjin, China.

1. Introduction

Energy and environmental issues have been more and more important all over the world. At present, energy structures in countryside of China lag behind, with coal and biomass being the major energy sources, accounting for more than 70% of the total rural energy consumption in 2014 [1]. Studies also indicate that the proportion of straw, firewood, and coal consumption in total energy consumption remains at a ratio of about 90% in northern China, whereas the proportion of high-quality commercial energy and modern renewable energy is still very low [2]. Meanwhile, with the improvement of living standards of rural residents, the thermal comfort in the rural buildings is more demanding. In order to establish comfortable indoor environment for rural buildings, renewable energy sources should be utilized as much as possible [3].

Ground-source heat pumps, including ground-coupled heat pumps, groundwater heat pumps (GWHPs) and surface water heat pumps [4], have become important energy-saving and environmental protection technology for space cooling/heating of residential buildings all over the world. The report on Chinese groundsource heat pump points out that the application area of groundsource heat pump has exceeded 110 million m2 [5]. The wide applications also motivate the research on heat pump, and a great deal of theoretical and experimental work has been accomplished on the design, modeling and testing [6-8]. Among these systems, the groundwater heat pump
system becomes more popular, especially in cities full of high-density buildings in China [9], but its application in rural areas is not taken seriously [5]. Actually, compared with cities, some characteristics of rural areas make them more suitable for heat pumps’ application. For example, there are more groundwater resources as the heat/cold sources, and there are more open spaces around buildings for digging wells, or there are even pre-existing wells which can be used for heat pump system. At the same time, requirements of thermal comfort of rural buildings are not as demanding as that of city buildings. Therefore, the use of groundwater for direct cooling could be taken into consideration in summer, especially in areas where the groundwater temperature is relatively low [10].

In this study, a new hybrid cooling/heating system combining groundwater direct cooling with groundwater heat pump is constructed in a town in Tianjin. The feasibility of the system is verified and the performance of the system is experimentally evaluated both in cooling and heating modes.

2. Description of the system

The project presented here uses a pre-existing well as a source which is not only for groundwater direct cooling system (GWDCs) in summer, but also for the groundwater heat pump system (GWHPs) in winter. While the building cooling load is relatively low in summer or transitional seasons, the groundwater is directly supplied to the air handling units for direct cooling. When the cooling load increases, heat pump is added as a supplement. In winter, the groundwater is used as the heat source of the heat pump and water supplied to air handling units is from the condenser of GWHPs. The pipeline connection diagram of the system is showed in Figure 1 and Table 1 gives the status of valves in different modes of the system.

![Figure 1](image1.png)

![Figure 2](image2.png)

Table 1. The status of valves in different modes.

| Mode                        | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------------------------|---|---|---|---|---|---|---|---|---|
| Direct cooling              | open | open | open | closed | closed | closed | open | open | open |
| Heat pump for cooling       | open | open | closed | closed | closed | closed | open | open | open |
| Heat pump for heating       | open | closed | open | closed | open | closed | open | closed | open |

The experiment is conducted in a three-story office building, in Youhao Street, Duliu town, Jinghaicounty, Tianjin, China. The air conditioning system consists of indoor air conditioning system and machine room system. The indoor air conditioning system is designed as all-air system to reduce initial cost. Two air handling units are designed every floor to process return air into designate state and then the processed air is distributed among all rooms. The floor plan and the indoor air conditioning system on half of the typical floor are showed in Figure 2. It should be noted that in the actual project, the withdrawing well for the system is a pre-existing well which is used for irrigating in the village, so the water through heat exchange is discharged to irrigating system directly and water
recharging is finished through osmosis. By this means, the air conditioning system and the rural production are combined together, and the omission of the recharge well largely reduces the initial cost of the system.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| COPS  | coefficient of performance of the whole system, dimensionless |
| COP   | coefficient of performance of heat pump, dimensionless |
| $C_{p,\text{air}}$ | specific heat of air (kJ/kgK) |
| $T_{\text{in,air}}$ | average temperature of air entering air handling unit (°C) |
| $C_{p,\text{wa}}$ | specific heat of water (kJ/kgK) |
| $T_{\text{out,air}}$ | average temperature of air leaving air handling unit (°C) |
| $W_{\text{divp}}$ | power input of diving pump (kW) |
| $T_{\text{in,wa}}$ | average temperature of water entering air handling unit (°C) |
| $W_{\text{air–wa}}$ | power input of air handling unit (kW) |
| $T_{\text{out,wa}}$ | average temperature of water leaving air handling unit (°C) |
| $W_{\text{cipp}}$ | power input of circulating pump (kW) |
| $T_{\text{cwi}}$ | average temperature of water entering condenser (°C) |
| $W_{\text{comp}}$ | power input of compressor (kW) |
| $T_{\text{cwo}}$ | average temperature of water leaving condenser (°C) |
| $T_a$ | outdoor air temperature (°C) |
| $T_{\text{ewi}}$ | average temperature of water entering evaporator (°C) |
| $T_{\text{i105}}$ | indoor air temperature of Room 105 (°C) |
| $T_{\text{i106}}$ | indoor air temperature of Room 106 (°C) |
| $Q_{\text{air}}$ | heat extraction rate from the indoor air (kW) |
| $Q_{\text{con}}$ | heat extraction rate from condenser (kW) |
| $m_{\text{air}}$ | mass flow rate of air (kg/s) |
| $m_{\text{conv}}$ | mass flow rate of water through condenser (kg/s) |
| $m_{\text{evaw}}$ | mass flow rate of water through evaporator (kg/s) |
| $I$ | current (A) |
| $U$ | voltage (V) |
| $\phi$ | power factor, dimensionless |

The total floor area of the tested building is 2300 m², with the utilization ratio of 60%. It is required that the indoor temperature should be below 30 °C in summer and above 16 °C in winter. The cooling/heating load is 100/90 W/m² at design conditions. A pumping test of the well was carried out for successive 12 hours before the experiment. The results showed that the well could keep the systems operating normally and continuously.

**3. Experimental analysis**

All the above-mentioned measured values are used to determine the performance of the system. The performance of the system is evaluated in terms of the COP, which defined as the ratio of cooling/heating energy output to the electrical energy input [11].

**3.1. Energy performance analysis of the GWDCs in summer**

The cooling capacity of GWDCs equals to the heat extracted from the indoor air stream $Q_{\text{air}}$, which is calculated as:

$$Q_{\text{air}} = m_{\text{air}} C_{p,\text{air}} (T_{\text{in,air}} - T_{\text{out,air}})$$  \hspace{1cm} (1)

For a GWDCs, the temperature difference between the groundwater and the indoor air is a direct driving power of the system [11]. The diving pump and the air handling units are the only
components consuming energy in it. The power input to the diving pump $W_{\text{div}}$ and the air handling unit $W_{\text{air-hu}}$ are calculated by the Eq. (2).

$$W = IU \cos \phi$$

(2)

The overall system’s COPS is calculated as:

$$COPS_{GWDCs} = \sum Q_{\text{air}} / \sum W = (Q_{\text{air1}} + Q_{\text{air2}} + Q_{\text{air3}}) / (W_{\text{div}} + W_{\text{air-hu}})$$

(3)

3.2. Energy performance analysis of the GWHPs in winter

The useful heat obtained from the condenser $Q_{\text{con}}$ is calculated as:

$$Q_{\text{con}} = m_{\text{cons}} C_{p,wa} (T_{\text{cwo}} - T_{\text{cwi}})$$

(4)

The extracted heat from the underground water is given by the following equation:

$$Q_{\text{eva}} = m_{\text{eva}} C_{p,wa} (T_{\text{ewi}} - T_{\text{ewo}})$$

(5)

The COP of the heat pump is calculated as:

$$\text{COP} = Q_{\text{con}} / W_{\text{com}}$$

(6)

The overall system’s COPS is calculated as:

$$COPS_{GWHPs} = Q_{\text{con}} / (W_{\text{com}} + W_{\text{sum}})$$

(7)

Where $W_{\text{sum}} = W_{\text{div}} + W_{\text{cir}} + W_{\text{air-hu}}$. The power input to the circulating pump $W_{\text{cir}}$ and the compressor $W_{\text{com}}$ are computed in the same way as Eq. (2).

4. Results and discussions

4.1. Result and discussion of the GWDCs in summer

The tests were conducted on the GWDCs in the cooling mode during the period from June to September in 2017. The test results on the first floor are chosen for analysis. The testing methods and discussions of the second floor and the third floor are the same as the first floor, thus those details are not included for the sake of brevity.

Room 105 and Room 106 are chosen as the typical rooms for the indoor environment analysis. Figure 3 shows the daily variation of $T_{\text{in,105}}, T_{\text{in,106}}, T_{\text{a}}, T_{\text{in,air}}, T_{\text{out,air}}, T_{\text{in,w}}, T_{\text{out,w}}$ on July 11, 2017. As seen from this figure, the indoor temperatures hover around 25°C when the ambient temperatures change. Temperature in Room 105 ($T_{\text{105}}$) is about 1°C higher than that in Room 106 ($T_{\text{106}}$), because Room 105 orients towards the south and accepts more solar radiation. Figure 3 also indicates that the average value of the temperatures of the air entering and leaving the air handling unit ($T_{\text{in,air}}, T_{\text{out,air}}$) are about 25°C and 20°C, respectively. The difference between the two is about 5°C, the effective temperature difference could meet the demand of comfortable air condition. The mean value of the temperatures of the water entering and leaving ($T_{\text{in,w}}, T_{\text{out,w}}$) the air handling unit is about 18°C and 21.8°C, respectively.

The variation of $T_{\text{in,105}}, T_{\text{in,106}}, T_{\text{a}}, T_{\text{in,air}}, T_{\text{out,air}}, T_{\text{in,w}}, T_{\text{out,w}}$ during 3-day period is given in Figure 4. The GWDCs has been run between 8:00 and 18:00 each of the three days. When the system runs (8:00), the indoor air temperature ($T_{\text{a}}$) typically occurs between
14:00 p.m. and 16:00 p.m. When the system stops at the end of the day (18:00), the room air temperature \( T_{105}, T_{106} \) is drastically increased. The mean value of \( T_{105} \) and \( T_{106} \) are 26.0\(^\circ\)C and 25.2\(^\circ\)C, respectively. Figure 4 also shows that when the system runs during the three days, the temperature of the water entering the air handling units \( T_{in,w} \) is smooth, which indicates that the GWDCs could supply a relatively stable cold source.

The monthly variation of \( T_a, T_{in,w}, T_{out,w} \) and COPs during the cooling season is given in Figure 5. The maximum value of \( T_{in,w} \) over 4-month period is approximately 17.9\(^\circ\)C, the average being 17\(^\circ\)C, while the minimum value is approximately 16.5\(^\circ\)C. The mean value of outdoor air is found as 25.35\(^\circ\)C. The difference between the average values of \( T_{in,w} \) and \( T_{out,w} \) is found as 3.82\(^\circ\)C. The monthly mean value of COPs is obtained to be 3.85. The highest cooling coefficient of the system is found as 4.1 in September, while the lowest cooling coefficient of the system is found as 3.54 in July.

### 4.2. Result and discussion of the GWHPs in winter

The tests were conducted on the GWHPs in the heating mode during the period from November 2017 to February 2018. The data were averaged from 6:00 a.m. to 18:00 p.m. The testing rooms and measurement points are chosen the same as the experiment in summer for better comparison.

Figure 6 shows the daily variation of \( T_a, T_{105}, T_{106}, T_{cw1}, T_{cw2}, T_{cw1} \) and \( T_{cw2} \) on January 19, 2018. The lowest indoor temperature appears in the morning and it gradually rises with the heat pump unit running. The indoor temperature reaches 16\(^\circ\)C an hour later and then becomes relatively steady. \( T_{105} \)
is 1-2°C higher than $T_{106}^\uparrow$, it is also because that Room 105 orients towards the south and accepts more solar radiation. Additionally, the heat loss by infiltration of southward room is smaller, which also results in higher indoor temperature. Figure 6 also indicates that the temperatures of water entering the condenser ($T_{\text{cw}i}$) are between 38-40°C and the temperatures of the water leaving the condenser ($T_{\text{cw}o}$) are between 42-44°C, both regularly change as wave every half an hour, which agrees with the fact that the compressor runs with the start and stop cycle of half an hour. Figure 6 shows a little difference between the temperatures of the water entering and leaving the condenser when the heat pump unit is just driven on at 6:00, because the compressor is just driven on and the temperature of the water through the condenser just starts rising. The temperatures of water entering the evaporator ($T_{\text{ew}i}$) and the temperatures of the water leaving the evaporator ($T_{\text{ew}o}$) are between almost 17-18°C and 11-12°C, respectively.

The variation of $T_a$, $T_{105}$, $T_{106}$, $T_{\text{cw}i}$, $T_{\text{cw}o}$, $T_{\text{ew}i}$ and $T_{\text{ew}o}$ during 3-day period is given in Figure 7. The GWHPs has been run between 6:00 and 18:00 each of the three days. When the system stops during the nights, the mean indoor air temperatures ($T_{105}^\uparrow$, $T_{106}^\uparrow$) of the two rooms are 8.1°C and 6.8°C, respectively. When the system runs during the 3 days, the mean value of $T_{105}^\uparrow$ and $T_{106}^\uparrow$ are 16.4°C and 18.2°C, respectively, which satisfy the thermal comfort requirement of rural buildings. Figure 7 also shows the temperatures of the water entering the evaporator ($T_{\text{ew}i}$) stabilize at around 15.5-16.3°C, which indicates that groundwater could be a stable heat source for GWHPs in winter.

![Figure 7. The 3-day variation of various temperatures from January 18 to 20, 2018.](image7)

Figure 8 depicts the monthly variation of $T_a$, $T_{\text{ew}i}$, $T_{\text{ew}o}$, COP and COPS during the heating season. The maximum value of $T_{\text{ew}i}$ over 4-month period is approximately 16.4°C, the average being 15.7°C, while the minimum value is approximately 15°C. The mean value of outdoor air is found as 1.3°C. The heating coefficient of the performance of the heat pump unit, the COP, and the performance of the whole system, the COPS are calculated from Eq. (6) and (7), and found to be in average 5.05 and 2.8. The highest heating coefficient of the heat pump unit is found as 5.22 in February, while the lowest heating coefficient of the heat pump unit is found as 4.86 in January. The highest COPs of the system is found as 3 in February, while the lowest COPs of the system is found as 2.6 in January.

The mean values of all the measured data and calculated results during the whole cooling and heating seasons are calculated. It is found that the average GWDCs COPS is approximately 3.85 in the cooling season, while the average heat pump COP and the GWHPs COPS are about 5.05 and 2.8. Since the results are largely exceed the minimum allowable value of energy efficiency for room air
conditioners [12], they are not very high when compared to other heat pumps operating under conditions at near design values. The primary reason is over-sizing some system parts. However, it is seen that the performance values obtained here are moderate.

5. Conclusions
This research project aims to develop a highly efficient cooling/heating system which is suitable for rural buildings. A hybrid cooling/heating system combining groundwater direct cooling and groundwater heat pumps developed and tested both in cooling and heating modes. The result obtained from the experiment shows that these systems could be used safely, reliably and efficiently at the lowest cost for the rural buildings in Tianjin, China. The following conclusions can also be drawn from this study:

(1) This developed system offers one of the most energy-efficient ways to provide heating and cooling in villages, because it uses renewable energy sources in our surroundings.

(2) The running modes (direct cooling, heat pump for cooling, heat pump for heating) of the system mainly depend on the ambient temperatures, geological conditions and air-conditioning requirements. In this particular project, direct cooling and heat pump were used and the results of experiments indicated that they could completely meet the cooling and heating demand in Tianjin district.

(3) This developed system presents tremendous environmental benefits when compared to the conventional systems. In addition to nearly no consumption of natural resources, the main advantage is the absence of almost any air emissions or waste products in most cases. Therefore, this system can minimize environmental impacts and air emissions.

(4) In the design of a system, all parts of the system should be checked in terms of energy efficiency. Thus, it will be necessary to conduct a pre-design analysis to determine the optimal system parameters that will ensure minimum energy consumption and favorable costs. New financing mechanisms are needed to promote investment in energy efficiency and renewable energy.

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