Field test and modeling analysis on unbalance of heat extraction and rejection of GSHP systems with different AC terminal units

Mingyang Qian¹, Da Yan¹,*, Jingjing An¹

¹ School of Architecture, Tsinghua University, China, Beijing, China

* Corresponding author email: yanda@tsinghua.edu.cn

Abstract. Ground source heat pump, as renewable energy technologies, are increasingly appearing to provide the indoor thermal environment for residential buildings in Hot Summer and Cold Winter zone. However, it needs to be tested whether GSHP is proper to the Hot Summer and Cold Winter zone? From 2012-2017, comprehensive field test was carried for 8 GSHP systems of residential buildings in Hot Summer and Cold Winter zone. The field test focused on performance of GSHP and the heat balance of ground source, which is an important factor for the application of ground source heat pump systems. In this paper, the analysis results of the balance of ground source of the systems with different AC terminal units are different from each other. The main influence factors for the heat balance of ground source are performance of heat pump and heating/cooling demand of buildings. The results of field test reveal that there is little difference for COP of heat pump. The heating/cooling demand is different for different systems. The further investigation reveal that the occupant behavior of different AC terminal units may determine heating/cooling demand of system, which resulted in the difference of the heat balance for ground source. The paper proposed an integration model of building load simulation considering the occupant behavior and GSHP systems. A case study will be conducted to quantitative analyze for the influence of the occupant behavior of different AC terminal units on the balance of ground source.

KEYWORDS. GSHP, Unbalance of Heat Extraction and Rejection, Occupant Behavior, Residential Buildings, Field Test

NOMENCLATURE

| Nomenclature | Description                  |
|--------------|------------------------------|
| Q            | heating or cooling load      |
| τ            | operation time               |
| ρ            | water density                |
| cp           | constant-pressure specific heat |
| G            | volume flow rate             |
| t            | temperature of water         |
| COP          | Energy efficiency            |
1. **Introduction**

Ground source heat pump, as renewable energy technologies, are increasingly appearing to provide the indoor thermal environment for residential buildings in Hot Summer and Cold Winter zone. GSHP system is the system using electricity to enhance the heat from ground source through heat exchange pipe to cool or heat the buildings and so could play a significant role in reducing CO2 emissions (Sarbu I et al. 2014). Under the supporting policy of government, GSHP are increasingly appearing to provide the indoor thermal environment for buildings in the Hot Summer and Cold Winter zone (Liu X et al. 2018). However, it needs to be tested whether GSHP is proper to the Hot Summer and Cold Winter zone? An important factor for the application of ground source heat pump systems is heat balance for ground source. Heat rejection and extraction unbalance would make the temperature of ground source rise or drop continuously and GSHP systems could not work anymore. Some has proposed integrated methods which can solve the problem of unbalanced cooling and heating loads during warm or cold climate (X.Q. Zhai. 2011). Some field test in Hot Summer and Cold Winter zone has found that the temperature of ground source continues to decrease. It suggested to alter the operating mode to partial recovery mode to reduce the yearly heat extraction from the soil(Zhang S et al. 2016). However, it still lacks the quantitative analysis of the reason for the unbalance of heat extraction and rejection. From 2012-2017, comprehensive field test was carried for 8 GSHP systems of residential buildings in Hot Summer and Cold Winter zone. The main AC terminal units of these systems are FCU, radiant floor and radiant ceiling. The field test focused on performance of GSHP and the heat balance of ground source. In this paper, the analysis results of the balance of ground source of the systems with different AC terminal units are different from each other. The main influence factors for the heat balance of ground source are performance of heat pump and heating/cooling demand of buildings. The results of field test reveal that there is little difference for COP of heat pump. The heating/cooling demand is different for different systems. The further investigation reveal that the occupant behavior of different AC terminal units may determine heating/cooling demand of system, which resulted in the difference of the heat balance for ground source. The paper proposed an integration model of building load simulation considering the occupant behavior and GSHP systems to do quantitative analyze for the influence of the occupant behavior of different AC terminal units on the balance of ground source.

2. **Methodology**

The methodology of the paper is shown in **Figure 1**. Firstly, the paper conducted the field investigation on 8 residential community cases with GSHP heating and cooling systems to show the unbalance of heat extraction and rejection and find the key influence factors. Secondly, the paper proposed an integration model of building load simulation considering the occupant behavior based and GSHP systems. Finally, according to the simulated results, the paper conducted the quantitative analyze for the influence of the occupant behavior of different AC terminal units on the balance of ground source.
2.1. Case selection
8 residential community cases with GSHP heating and cooling systems were selected for measurement and comparative analysis for the following reasons: (1) these cases are all located in the Hot Summer and Cold Winter zone of China, (2) they contained detailed measured data for at least a cooling season or heating season and sub-metered heat consumption data, and (3) their terminal air conditioning units are either FCU or radiant terminal units for the purpose of comparison. The detailed information of 8 cases is shown in Table.1.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
AC terminal units & Case Number & Charge form & Location \\
\hline
Heating: radiant floor & Case1 & According to Heat consumption & Yangzhou \\
Cooling: FCU & Case2 & According to Heat consumption & Yangzhou \\
& Case3 & According to Heat consumption & Yangzhou \\
Heating: radiant ceiling & Case4 & According to air conditioning area & Nanjing \\
Cooling: radiant ceiling & & & \\
Heating: FCU & Case5 & According to Heat consumption & Nantong \\
Cooling: FCU & Case6 & According to Heat consumption & Yangzhou \\
& Case7 & According to Heat consumption & Yangzhou \\
& Case8 & According to Heat consumption & Zhengzhou \\
\hline
\end{tabular}
\caption{The information of selected cases}
\end{table}

2.2. Field measurements and long-term monitoring data
The object of field measurements is to get the key performance indicators. The key performance indicators of systems are heating/cooling electricity consumption $E_{\text{system}}$, heating/cooling demand $Q_{\text{heating/cooling season}}$, and coefficient of performance of GSHP system ($COP_{\text{system}}$). The heating/cooling demand can be calculated by the temperature and flow of heating/chilled water of the user-side. The calculation equation is shown as equation (1).

\begin{equation}
Q_{\text{heating/cooling season}} = \int_{t_{\text{start}}}^{t_{\text{end}}} \rho \cdot c_{p} \cdot |t_{\text{supply}}(\tau) - t_{\text{return}}(\tau)| \cdot G(\tau)
\end{equation}

Field measurement can only get the short-term data. The heating/cooling electricity consumption $E_{\text{heating/cooling season}}$ can be get from long-term monitoring data. The $COP_{\text{system}}$ is calculated by the equation (2).
\[ \text{COP}_{\text{system}} = \frac{Q_{\text{heating/cooling season}}}{E_{\text{heating/cooling season}}} \]  

In order to get the use mode of these two terminal AC units, the indoor air temperature and the usage rate of FCUs are also measured in part of these cases.

2.3. Simulation for quantification

This paper establishes the residential buildings model by DeST (Designer’s Simulation Toolkits) software (D. Yan et al. 2008) as shown in Figure 2. This residential building is set in Nanjing with the building envelop according to Design Standard for Energy Efficiency of residential building in Hot Summer and Cold Winter Zone (MOHURD A. 2010). There are three bedrooms, one dining room, one living room, two bathrooms and one kitchen in one household. The designed room temperature is 18 °C for heating season and 26 °C for cooling season.

As to consider the occupant behavior of different AC terminal units, the paper using the AC CP model of the previous research to describe the AC usage quantitatively. (Ren et al. 2014). There are three parts for the AC CP model: the AC turning on model, the AC turning off model, and the AC setting temperature model. The curve fitting results of a typical family is from the data of previous research (Ren et al. 2014).

In order to calculate heat extraction and rejection, the system COP was measured from 8 cases. The simulated heat extraction and rejection are calculated by the equation (3).

\[ Q_{\text{simulated extraction}} = Q_{\text{simulated heating season}} \frac{Q_{\text{simulated heating season}}}{\text{COP}_{\text{system}}} \]
\[ Q_{\text{simulated rejection}} = Q_{\text{simulated cooling season}} + \frac{Q_{\text{simulated cooling season}}}{\text{COP}_{\text{system}}} \]  

3. Results of field investigation

3.1. Field test results

The heat extraction and heat rejection by field test are shown in Figure 3. It reveals that heat extraction is larger than heat rejection of the systems with both radiant floor and FCU. The heat extraction is almost three times of heat rejection of the worst one. For the system with only radiant ceiling, the heat rejection is larger than heat extraction. For the system with only FCU, it cannot find the same conclusion for different cases.
The influence factors for the heat balance of ground source may be performance of heat pump and heating/cooling demand of buildings. The results of field test reveal that there is little difference for COP of different systems with different AC terminal units. System COP for heating is larger than system COP for cooling. The average System COP for heating is 3.7. The average System COP for cooling is 3.0.

For the heating/cooling demand, it is really different for different systems with different AC terminal units. The heating demand is larger than cooling demand according to the results of field test. For the system with both radiant floor and FCU, heating demand is 2.2-4.8 times of cooling demand. For the system with only radiant ceiling, the heating demand is similar to cooling demand. For the systems with only FCU, heating demand is 1.4-2.8 times of cooling demand.

3.2. Influence factors for heating/cooling demand

The results of measurement and long-term monitoring data demonstrate that there is big difference on the heating/cooling demand of two kinds of terminal AC units. All the cases analyzed are located in Hot Summer and Cold Winter Zone. The meteorological parameters of all the cases are similar. The building envelopes of all cases are similar to each other as all the cases are built according to Design Standard for Energy Efficiency of Residential buildings in Hot Summer and Cold Winter Zone. The indoor air temperature of different households in heating season is shown in Figure 6, where $T_{\text{max}}$ is the highest indoor air temperature and $T_{\text{min}}$ is the lowest indoor air temperature. $T_{\text{max}}$ of two kinds AC units is higher than 18 centigrade according to the thermal comfort, which represents that heating capacity of both two types is enough.
The significant differences between two kinds systems is operation and controls of residents. FCU is more controllable than the radiant terminal unit, which reflects both in the time and space aspects. In the time aspect, little possibility is that the residents are at home for all the time of one day. As the charge of heating/cooling fee is according to heat consumption, the residents tend to need the heating and cooling only when they are in the room. In the space aspect, little possibility is that all the room of household occupied by residents for the same time. Considering the heating/cooling fee, the residents tend to switch off the AC unit when they leave the room. For the cases with radiant terminal units, residents cannot switch off part of rooms in one household with the radiant floor or radiant panel as there is only one main valve to control all the rooms in one household. For the cases with FCUs, residents can easily switch on and off the FCU to their need. The proportion of the rooms with the used AC units is the key point for designing the heating and cooling load of residential district.

Figure 6 Quartile graphs of indoor air temperature of different households in heating season

Figure 7 and Figure 8 provide the proportions of households with different amount of used heating or cooling AC units on the coldest day or on the hottest day from the survey in Case 9 community in Henan. It revealed that more than 85% of households use not more than three AC units for both heating and cooling season. As a result, the cases with radiant terminal units will keep heating or cooling for all space and the cases with FCUs will heat or cool part space in one household.

4. Results of simulation

In order to quantitative to analyze the different occupant behavior for different AC terminal units, it established the model considering the occupant behavior. The occupant behavior for radiant terminal unit is to heating or cooling for all the time and all the rooms. The occupant behavior for FCU is heating or cooling for part time and part rooms describing by AC CP model. The simulated heating
demand and cooling demand calculated by model considering occupant behavior are shown in Figure 9. It reveals that the heating demand is 4.2 times of cooling demand for the systems with both radiant floor and FCU. For the system with only radiant ceiling, the heating demand is 0.9 times of cooling demand. For the systems with only FCU, the heating demand is 1.3 times of cooling demand.

5. Discussion
According to the results of field test and simulation, it indicates that the unbalance of heat extraction and rejection for the systems with both radiant floor and FCU is worst. It is recommended to using FCU both for heating and cooling for the consideration for heat balance of ground source. The further research for dealing with the unbalance for the system with both radiant floor and FCU is necessary. However, comparing the simulated results and field test results, it can find that the simulated heat extraction and rejection are really different for different cases with only FCU. The diversity of occupant behavior contributed to such difference for different systems. It still need more research for the occupant behavior of using FCU in residential buildings. In addition, the system performance, such as system COP is also an important factor for the heat balance of ground source. It still needs further research for system performance and operation for the problem of unbalance of heat extraction and rejection.

6. Conclusion and implications
In this paper, comprehensive field test was carried for 8 GSHP systems of residential buildings in Hot Summer and Cold Winter zone. The paper proposed an integration model of building load simulation considering the occupant behavior and GSHP systems to do quantitative analyze for the influence of the occupant behavior of different AC terminal units on the balance of ground source.

1. The analysis results of the balance of ground source of the systems with different AC terminal units are different from each other. The problem of unbalance for heat extraction and rejection is common in Hot Summer and Cold Winter Zone.
2. The results of field test reveal that there is little difference for COP of different AC terminal units.
3. The occupant behavior of different AC terminal units determines heating/cooling demand of system, which resulted in the difference of the heat balance for ground source.
4. Through the simulation, it indicated that the heat extraction is 2.3 times of heat rejection for the systems with both radiant floor and FCU. For the system with only radiant ceiling, the heat extraction is 0.4 times of heat rejection. For the systems with only FCU, the heat extraction is 0.7 times of heat rejection.

5. It is recommended to using FCU both for heating and cooling for the consideration for heat balance of ground source. The further research for dealing with the unbalance for the system with both radiant floor and FCU is necessary.

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