Modelling of a Large Vertical Ground Heat Exchanger Integrated with a Heat Pump for Building Energy Simulation in China

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Abstract. Vertical ground coupled heat pump (GCHP) systems used in buildings in China can help to increase the share of renewable energy and improve the energy efficiency. A building energy simulation (BES) tool including a vertical GCHP model is beneficial for analysing the system performance under dynamic building loads. This paper presents a large-scale vertical ground heat exchanger model integrated to a heat pump model in the BES tool COMFIE, in a Matlab-Delphi co-environment. This model was applied to a residential building block with a 26 × 26 borehole field in Wuhan, China. The heat pump performance improvement was investigated for different design parameters. For half-hourly simulation of 1 year, the specific calculation time of the proposed GCHP model is 4 seconds out of 8 minutes for the whole building. The proposed model can be used as a design aid to optimise the system performance.

1. Introduction

Buildings are one of the main energy consumption contributors in China and it is essential to optimise their energy performance. The UN Sustainable Development Goal (SDG) 7: affordable and clean energy targets at increasing the share of renewable energy in the global energy mix and improving the energy efficiency. Buildings can help reach this goal by using renewable energy sources such as geothermal energy. Vertical ground coupled heat pump (GCHP) systems have been used in the building sector at a large scale in China because of not only its energy efficiency and environmental friendliness [1], but also the much smaller land area they required compared to ground heat pumps with horizontal tubes. A typical vertical GCHP system basically consists of three sub-systems: (1) the heat distribution system in the building; (2) the heat pump (HP) system; and (3) the vertical ground heat exchanger (GHE) system embedded in the ground. The ground serves as a heat source to provide heat to the building in winter and a heat sink to receive heat from the building in summer.

As a key component in the GCHP system, the GHE plays an important role in the system performance. A GHE usually consists of one or numerous boreholes, depending on the building loads. The thermal analysis of a GHE is essential for the design of a GCHP system and its performance simulation. The most utilised method to analyse a large-scale borehole field is to firstly use the heat transfer model of a single borehole to analyse one borehole, and secondly employ Duhamel's superposition principle to obtain the ground temperature responses caused by all the boreholes in the field [2].

The energy analysis models for one borehole can be divided into analytical models and numerical models. Compared to numerical models, analytical models are more flexible for various configurations and can be integrated with the heat pump simulation, and furtherly into building energy simulation (BES)
tools. Many analytical models were developed [3], and the finite line source (FLS) model is chosen in this paper for its simple mathematical form and relatively good accuracy in long operation time simulation [4].

A BES tool integrated with a vertical GCHP model can be beneficial for building designers’ decisions making, and interesting for researchers to study the overall performance of a GCHP system. Some BES tools such as TRNSYS and EnergyPlus have implemented simplified ground exchanger models. Residential buildings in China are usually high and population intensive, which leads to large-scale borehole fields. Although several studies [5–7] have been carried out on the modelling of GHEs, HPs and buildings, few focused on integrating the large-scale borehole fields with a BES tool. Besides, a global approach which can model the system as a whole is needed to study the overall performance of GCHP systems in China.

This paper presents an integrated vertical GCHP system with a large-scale borehole field in China. The integration algorithm of the GHE, the heat pump, the distribution system and the building is illustrated. The integrated model is applied to a case study consisting of a $26 \times 26$ borehole field in China with different design parameters. At last, results concerning the performance of the GCHP system are presented and discussed.

2. The theoretical models

The heat transfer process in a GCHP system for heating is shown in figure 1. In this paper, a water-water heat pump is considered. The building model calculates the building heating load $Q_b$. This heating load is fulfilled by the heat flux $Q_{\text{dis}}$ distributed by the distribution model. The water on the condenser side circulates at a mass flow rate $m_{\text{cd}}$. The inlet and outlet temperatures of the distribution unit and the condenser are $T_{\text{in,dis}}$, $T_{\text{out,dis}}$, $T_{\text{in,cd}}$ and $T_{\text{out,cd}}$, respectively. The heat flux exchanged in the condenser is $Q_{\text{cd}}$. On the evaporator side, the fluid is the ethylene glycol water solution at 30% volume at a mass flow rate $m_{\text{ev}}$. Similarly, the inlet and outlet temperatures of the GHE and the evaporator are $T_{\text{in,GHE}}$, $T_{\text{out,GHE}}$, $T_{\text{in,ev}}$ and $T_{\text{out,ev}}$. The heat flux exchanged in the evaporator is $Q_{\text{ev}}$.

![Figure 1. Schematic diagram of the heat transfer in the GCHP system for heating](image-url)
2.1. Building model

The building dynamic energy simulation tool COMFIE is a multizone tool based on the finite volume method and modal analysis [8]. A multizone approach is used in COMFIE to model the building consisting of different elements (zones, walls, material layers...). In this approach, the building is decomposed into small volumes called nodes, assumed to be at a uniform temperature. A heat balance is expressed for each node: the energy stored (temperature change multiplied by heat capacity) equals the heat gains minus energy losses. Each zone model is reduced by modal analysis.

2.2. Heat distribution model

In this model, the flow rate in the condenser is controlled at a constant value, and the varying heating load is fulfilled by adjusting the inlet and outlet temperatures of the heat distribution model. The efficiency of the heat distribution model is set as 1 in this study. Besides, there is no loss between the heat distribution unit and the condenser, which means:

\[ Q_{cd} = Q_{dis} = Q_b \]  
\[ T_{out,cd} = T_{in,dis} \]  
\[ T_{in,cd} = T_{out,dis} \]  

The inlet water temperature of the heat distribution unit \( T_{in,dis} \) is assumed to be 20 °C and 75 °C when the outside air temperature \( T_{air} \) is 15 °C and -5 °C, respectively. \( T_{in,dis} \) is assumed to be linear to \( T_{air} \):

\[ T_{in,dis} = \begin{cases} 
-2.75T_{air} + 61.25 & \text{if } T_{air} \leq 15.7^\circ C \\
18 & \text{if } T_{air} > 15.7^\circ C 
\end{cases} \]  

The outlet water temperature of the heat distribution system can be derived:

\[ T_{out,dis} = T_{in,dis} - \frac{Q_{dis}}{m_{cd} \cdot c_{p,w}} \]  

in which \( c_{p,w} \) is the specific heat capacity of water.

2.3. Heat pump model

A heat pump model was implemented in COMFIE [9]. The model is a steady-state semi-empirical model based on simplified cycle analysis and it considers full load and part load conditions. In this paper, the GHE model is integrated with a HP model containing a rotary compressor with a rolling piston. In order to describe the HP system, 8 parameters concerning the compressor and heat exchangers are necessary to be specified based on the model presented by [10]. The overheat temperature at the outlet of the evaporator is fixed at \( \Delta T_{wb} = 7^\circ C \).

Then the energy exchanged at the condenser and evaporator can be determined by the thermodynamic cycle analysis of the refrigerant (R410a). The coefficient of performance (COP) can be determined by:

\[ \text{COP} = \frac{Q_{cd}}{W} \]  

When the building load is smaller than the full capacity of the HP, the inverter-driven compressor method is used to control the HP heating capacity. The inverter partial load operating model used is based on a corrective factor, the partial load factor (PLF), applied to the COP at full load. PLF is calculated according to the partial load ratio (PLR). The operation below full load is divided into two methods. When \( \text{PLR} > \text{PLR}_{\text{ref}} \), the system performance increases linearly when PLR decreases. When \( \text{PLR} < \text{PLR}_{\text{ref}} \), the system operates in "on-off" mode, which significantly reduces the performance of HP. The PLF can be calculated by PLR with the equation below:

\[ \text{PLF} = \begin{cases} 
\frac{\text{PLR}}{\text{PLR} + \alpha} & \text{if } \text{PLR} < \text{PLR}_{\text{ref}} \\
\frac{\text{PLR}_{\text{ref}} - 1}{\text{PLR}_{\text{ref}} - 1} & \text{if } \text{PLR} \geq \text{PLR}_{\text{ref}} 
\end{cases} \]  

in which, we set \( \text{PLR}_{\text{ref}} = 0.5, \text{PLF}_{\text{ref}} = 1.1, \alpha = 0.01 \) and \( \beta = 1 + \alpha = 1.01 \).
2.4. GHE model
A square borehole field consisting of $N_b$ boreholes with double U-tube in parallel connection is considered in this paper. The spacing between two boreholes is $B$. In COMFIE, the time-varying heating and cooling loads are step-wise constant values. Here we assume that the energy load from the building is uniformly distributed to each borehole, which means the heat load of each borehole at time step $m$ is identical:

$$q_m = \frac{Q_{\text{GHE}}(m)}{N_b \times H} = \frac{Q_{\text{ev}}(m)}{N_b \times H}$$

where $Q_{\text{GHE}}(m)$ and $Q_{\text{ev}}(m)$ are respectively the heat load of the GHE field and the evaporator at timestep $m$, and there is no loss between the GHE and the evaporator; $H$ is the borehole’s depth.

The GHE model focuses on calculating its outlet fluid temperature $T_{\text{out,GHE}}$, which equals to the inlet temperature of evaporator $T_{\text{in,ev}}$. $T_{\text{out,GHE}}$ at time step $m$ can be determined by:

$$T_{\text{out,GHE}}(m) = \sum_{i=1}^{N_b} T_{\text{out},i}(m)$$

where $T_{\text{out},i}(m)$ is the outlet fluid temperature of the $i$th borehole at time step $m$. It can be calculated by

$$T_{\text{out},i}(m) = T_{\text{fl},i}(m) + \frac{N_b q_m H}{2 m_{\text{ev}} C_{p,\text{wg}}}$$

where $C_{p,\text{wg}}$ is the specific heat capacity of water-glycol solution, and $T_{\text{fl},i}(m)$ is the mean fluid temperature of the $i$th borehole at time step $m$. It can be derived by knowing the borehole wall temperature of the $i$th borehole $T_{\text{wb},i}(m)$ at time step $m$ and the thermal resistance $R_{\text{b}}$:

$$T_{\text{fl},i}(m) = T_{\text{wb},i}(m) - q_m \cdot R_{\text{b}}$$

The borehole wall temperature can be determined by the FLS model and represented by the integral mean temperature [2]. The heating load has an effect on both the current time and the future. Considering all boreholes’ effects, the borehole wall temperature of the $i$th borehole at timestep $m$ can be determined by applying the superposition principle:

$$T_{\text{wb},i}(m) - T_0 = \sum_{i=1}^{N_b} \sum_{k=1}^{m} \frac{q_{k-1} - q_k}{2 \pi \lambda_s} \int_0^H \int_0^H \text{erfc} \left( \frac{(r_{ij})^2 + (z-h)^2}{2 z \alpha_s (t_m - t_{k-1})} \right) \text{erfc} \left( \frac{(r_{ij})^2 + (z+h)^2}{2 z \alpha_s (t_m - t_{k-1})} \right) dh dz$$

where $i$ is the $i$th borehole in the borehole field (interacting with the $j$th borehole under consideration); $k$ is the $k$th timestep; $t_m$ is the time at timestep $m$; $r_{ij}$ is the distance between the $i$th borehole and the $j$th borehole, and $r_{ij} = r_{ji}$ when $i = j$; $h$ and $z$ are the integration variables; $\lambda_s$ and $\alpha_s$ are the thermal conductivity and thermal diffusivity of the ground, respectively; $G$ is the thermal response factor ($G$-function) of one borehole under the effect of another borehole; $T_0$ is the initial ground temperature; and $\text{erfc}$ denotes the complementary error function. Combining equations (9) to (12), $T_{\text{out,GHE}}(m)$ can be expressed by a $G$-function of the whole GHE, $G_{\text{GHE}}$:

$$T_{\text{out,GHE}}(m) = \sum_{i=1}^{N_b} \sum_{k=1}^{m} \frac{q_{k-1} - q_k}{2 \pi \lambda_s} G_{\text{GHE}}(r_{ij}, t_m - t_{k-1}) - q_m \cdot R_{\text{b}} + \frac{N_b q_m H}{2 m_{\text{ev}} C_{p,\text{wg}}} + T_0$$

For a large borehole field, the calculation of $G_{\text{GHE}}$ can be complex and time costing. The authors developed a fast calculation method, which was implemented in Matlab. The calculation of $G_{\text{GHE}}$ is offline and a txt file containing the results of $G_{\text{GHE}}$ is generated. This txt file is input when integrating the GHE model and the heat pump model in COMFIE.
2.5. Backup resistance
The studied heat pump is equipped with two electric backup resistances of 1 500 kW. They are used when the heat pump capacity is too low to fulfill the building heating load. In this case, a first backup is turned on, and if it is not sufficient, both are used.

2.6. Integration of the different components
The algorithmic diagram of integrating the GHE model with the HP model to COMFIE in the Delphi-Matlab co-environment is shown in figure 2. With the heating load calculated by the building model, the heat distribution model determines the inlet and outlet fluid temperatures of the distribution system, which correspond to the outlet and inlet fluid temperatures of the condenser. The outlet fluid temperature and the heat flow of the condenser are then transferred to the HP model as inputs. The HP model calculates the energy exchanged in the evaporator and the inlet and outlet fluid temperatures of the evaporator, as well as the compressor work and COP of the heat pump. The energy exchanged in the evaporator is equal to the heat extracted from the ground, which is an input for the GHE model. By using $G_{GHE}$ calculated by Matlab, the GHE model calculates its outlet fluid temperature which is compared to the inlet fluid temperature of the evaporator calculated by HP model. An iterative process is performed here for these temperatures to converge. At each timestep of the simulation, a balance point between different systems is achieved to describe the overall system performance.

![Figure 2. Algorithmic diagram of integrating GHE with HP to building simulation tool](image-url)

**Figure 2.** Algorithmic diagram of integrating GHE with HP to building simulation tool
3. Case study
The GCHP model was applied to a 150 000 m² residential block in Wuhan, China (30°32’ N, 114°20’ E). The residential block consists of one office building and four residential buildings. The heating set point is 18 °C according to Chinese standard. The heating is supplied by a vertical GCHP system. The information of the GCHP is show in table 1.

| Component | Parameters | Description | Value | Unit |
|-----------|------------|-------------|-------|------|
| GHE       | \(N_b\)    | Number of borehole | 26 × 26 |      |
|           | \(B\)      | Borehole spacing | 4     | m    |
|           | \(H\)      | Borehole length  | 133   | m    |
|           | \(R_h\)    | Borehole radius  | 0.110 | m    |
|           | \(R_t\)    | Borehole thermal resistance | 0.147 | m.K/W |
| Ground    | \(\lambda_s\) | Ground thermal conductivity | 2.635 | W/m.K |
|           | \(\alpha_s\) | Ground thermal diffusivity | 1.23 × 10^{-6} | m²/s |
|           | \(T_0\)    | Initial ground temperature | 19 | °C |
| Heat pump | \(m_{cd}\) | Mass flow rate at condenser | 200 | kg/s |
|           | \(m_{ev}\) | Mass flow rate at evaporator | 200 | kg/s |
|           | \(C_{p,w}\) | Specific heat capacity of water | 4 180 | J/kg.K |
|           | \(C_{p,wg}\) | Specific heat capacity of water-glycol solution | 3 590 | J/kg.K |

4. Results and discussion
The calculation of \(G_{GHE}\) for 1 year operation in Matlab using a computer with an Intel i7-6700 CPU and 16 GB RAM cost 4 seconds. The half-hourly dynamic energy simulation of the building with and without the proposed GHE model in COMFIE both cost 8 minutes. For a 1 year simulation, the calculation time of a large 26 × 26 borehole field is almost negligible. The heating load is shown in figure 3 (a). The peak heating load is 4 755 kW. The COP of the heat pump system is illustrated in figure 3 (b). It can be inferred that the heat pump system operates at a COP of over 3.5 for 91 % of the whole year, which shows a good efficiency. The maximal COP is 8.71 and the average COP of the heating period is 4.56. \(T_{\text{out,GHE}}\) varies between 7.22 °C and 16.84 °C.

Figure 3. (a) The heating load and (b) COP and \(T_{\text{out,GHE}}\) of the case study
The proposed model was applied for different boreholes’ spacings, \(B\) (from 3 m to 8 m, \(H = 133\) m), and various depths, \(H\) (90 m, 110 m, 133 m, 150 m and 170 m, \(B = 8\) m) to study the heat pump’s energy efficiency. The COP differences are shown in figure 4. On the whole, COP increases with \(B\). The average COP increases from 4.46 \((B = 3\) m) to 4.65 \((B = 8\) m). The influence of \(B\) on COP decreases with \(B\). Larger \(H\) shows a better heat pump performance. The average COP is 4.77 for \(H = 170\) m, improving the performance of the heat pump by 8 %, compared to 4.40 for \(H = 90\) m.
The electricity consumptions of the heat pump and the backup resistance are shown in figure 5. For $H = 133$ m, the electricity consumption of the heat pump decreases with $B$. The decrease becomes smaller when $B$ gets larger. The same trend is found in the backup resistance as well. The total electricity consumption of $B = 8$ m is 1.491 MWh, which is 94% of $B = 3$ m. For $B = 8$ m, larger $H$ values show better performances. The total electricity consumption of $H = 90$ m is 1.611 MWh; the heat pump and the backup resistance consume 1.415 MWh and 196 MWh, respectively. The electricity consumption decreases with $H$, and similarly, a larger reduction is observed for small $H$ values. For $H = 170$ m, the total electricity consumption is reduced by 10% compared to $H = 90$ m. Although larger $B$ and $H$ values show a better performance, larger land area and higher initial investment costs are required to install the GHE. The proposed model can help the designers to achieve a balance between performance and cost.

**Figure 5.** Electricity consumptions of the heat pump and the backup resistance for (a) different $B$ and (b) different $H$.

5. Conclusion
The building sector is a main energy consumption sector, and it is essential to improve its energy performance. The use of geothermal in the buildings is one promising solution, which also corresponds to the US SDG 7. A BES tool providing a fast simulation of the building integrated with a geothermal heat pump is beneficial for the building design and comprehensive performance analysis. This paper presents the modelling of a large-scale boreholes GHE integrated with a heat pump. This GCHP system was integrated in the BES tool COMFIE. The finite line source model and the superposition model were used in the GHE model and its $G$-function was calculated off-line in Matlab. Then the $G$-function was input and used by the GHE model integrated with an existing heat pump model in COMFIE in Delphi environment. A case study containing a large 26 × 26 borehole field in China allowed to test its usability and simulation speed. The off-line calculation of the $G$-function only cost 4 seconds. The GHE model
did not bring noticeable extra calculation time for this case study. The heat pump system performance was analysed under different $B$ and $H$ values. The results show that the average COP increased with both $B$ and $H$. The total electricity consumption of $B = 8\, \text{m}$, $H = 133\, \text{m}$ was reduced by 6% compared to $B = 3\, \text{m}$, $H = 133\, \text{m}$. The main contributions of this study are: (1) the modelling of a large GHE with fast calculation speed, which is an efficient model can also be applied to other BES tools. (2) The integration of GCHP model into COMFIE, which is helpful to the building designers to improve building efficiency. (3) A system performance optimisation, which is beneficial for the design of GHE.

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