A new analytical model for the underground temperature profile under the intermittent operation for Ground-Coupled Heat Pump systems

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Abstract

Ground-Coupled Heat Pump (GCHP) systems used in commercial buildings are conventionally controlled by some time schedule strategies. So, a reliable method of modeling underground temperature profiles is of great importance for the operation of GCHP systems. Underground temperature profiles are usually predicted by commercial numerical software. This approach is time consuming and lack the flexibility of modeling various cases of GCHP systems. In this paper, a new analytical model based on a composite-medium line-source model is proposed. The new analytical model agrees well with in situ experimental data. An exhaustive simulation is conducted to explore influencing factors on the ground temperature profile, such as operating time, on-off ratio, heat fluxes and thermal conductivity of back-filled grout. These results indicate that a proper operating schedule and heat fluxes are helpful for maintaining the balance of ground temperature, which may offer an opportunity to develop a control strategy based on the heat flux prediction with the help of GCHP system intermittent operation.

Introduction

The Ground-Coupled Heat Pump (GCHP) systems have attracted global attention for its high energy efficiency and low maintenance cost. According to the reports of World Geothermal Congress 2010 (WGC2010), 33,134 MWt GCHP systems installations have been reported in 43 countries by 2010, and both the numbers of GCHP systems and the installed capacity are doubled from 2005 to 2010\cite{1}. In China, the total building area served by GCHP systems has reached 240,000,000 m\(^2\) by the end of 2012, and it will be expanding much more rapidly in the coming future \cite{2}.

For a typical GCHP system, the ground is used as a heat source for space heating or cooling through Ground Heat Exchangers (GHEs). Compared with the conventional space air conditioning system, the ground temperature keeps nearly constant all over the year, which leads a higher Coefficient of Performance (COP). However, the heat will be built up with extended operation, and it calls for a temperature recovery to improve the performance of the system.

Due to the heat capacity inside the borehole, the heat transfer model around the GHEs is divided into

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short-time response model and long-time response model by Eskilson[3]. Most of existing investigations on the intermittent operation for GCHP system is focus on seasonal geo-temperature variation, and it is based on the long-time response heat transfer model. Several researchers investigate the short time intermitted operation of GCHP systems. It was first concerned by Fang et al. and Stevens[4, 5], and they provide an solution to simulate the temperature recovery process base on the line source model and numerical models, respectively. However, the line source model is not capable to simulate the heat transfer process during intermittent operation which is limited to a few hours. Followed by this study, Cui et al [6] verified that the intermittent operation and the alternative cooling/heating operation will alleviate the heat buildup around the borehole with the finite element numerical model. Jalaluddin[7] and Man Yi[8] operated an experiment in intermittent operation and continuous operation for both heating mode and cooling mode, respectively. Both of them indicate that the performance of GCHP system will improve a lot with numerical model and experimental method, respectively. Yan Shang and JACED S.[9-11] investigate the recovery time and its influencing factor for the geo-temperature recovery under intermittent operation of GCHP system. Gao[12] pointed out that the number of GHEs and the initial investment will be reduced with intermittent control strategy.

From above literature reviews, most of the current studies concern on intermittent operation are calculated with numerical models. However, the numerical models are time consuming and lack of the flexibility to model various cases of GCHP system. In this paper, a new analytical model to simulate the intermittent operation process of GCHP system was proposed, and it was validated by an in-situ experiment operated in Hebei, China. Besides this, the influencing factor on the ground temperature profile was calculated. And it offers an opportunity for the future study about intermittent operation control strategy.

Methodology

In order to simulate the intermittent operation of GCHP system, the transient short-time response heat transfer model should be proposed, both the numerical model and the analytical model are available for the study. However, the analytical model have shown its advantage for heat transfer simulation for previous study, and the analytical heat transfer model for GHEs simulation is seldom reported in the previous studies. In this paper, a compositied-medium line-source solution developed by Jaeger and Li is employed [13] [14]. The time-varying heat flux is replaced by step-wised constant heat flux. The heat flux and the temperature response for the inlet pipe and the outlet pipe are calculated, respectively. The U-pipe wall temperature is selected to respect the temperature rise for the GHEs.

![Fig 1 Step-wised time-varying heat flux with assumption](image)

1.1. Modeling assumption

In order to simplify the simulation process and reduce the computation time, some assumption was made as follows:

- Only four angles which are 0, π/2, π, 3π/2 are taken into consider for the U-pipe wall temperature calculation.
- The heat flux was constant during the heat pump operation process, and the heat flux is set as zero when the heat pump shuts off, which is illustrated in fig. 1
The system is operated for 4 days.

1.2. Modeling description

The dimensionless expression of the temperature profile around U-pipes proposed by Li is [14, 15]

\[
\begin{align*}
\Theta_1(Fo, R, \theta) &= \sum_{n=-\infty}^{\infty} \cos[n(\theta - \theta')] \left[ 1 - \exp(-v^2 Fo) \right] \frac{J_n(vR)J_n(v' \theta/R)(\varphi g - \psi f)}{v(\varphi^2 + \psi^2)} \, dv \\
\Theta_2(Fo, R, \theta) &= \sum_{n=-\infty}^{\infty} \cos[n(\theta - \theta')] \left[ 1 - \exp(-v^2 Fo) \right] \frac{J_n(vR')(\varphi J_n(\alpha vR) - \psi Y_n(\alpha vR))}{v^2(\varphi^2 + \psi^2)} \, dv
\end{align*}
\]

(1)

Where \( \Theta_n(Fo, R, \theta) = 2\pi k_b T / q, a = \sqrt{a_b / a_s}, k = k_b / k_s, Fo = a_t / r_b^2, R = r / r_b, R' = r' / r_b, v = ur_b \)

\[
\begin{align*}
\varphi &= akJ_n(v)J_n'(av) - J_n'(v)J_n(av) \\
\psi &= akJ_n(v)Y_n'(av) - Y_n'(v)J_n(av) \\
f &= akY_n(v)J_n'(av) - Y_n'(v)J_n(av) \\
g &= akY_n(v)Y_n'(av) - Y_n'(v)Y_n(av)
\end{align*}
\]

(2)

In this equation, subscript 1 and 2 is defined as the regions inside the borehole and outside the borehole, respectively. As we know, if the heat fluxes in all line sources are equal, \( n \) is the numbers of the line sources, the temperature profile around the line source can be easily calculated with Eq (1). However, the heat flux in the inlet pipe and the outlet pipe is not symmetric, and the heat flux difference between the inlet pipe and the outlet pipe on the top is greater than the button [16]. Take the average heat flux into consider, Cui and Yavuzturk [6, 17] assigned 60% of the total heat flux for the inside pipe and 40% for the outside pipe, the whole temperature profile around the U-tube can be be obtained with the principle of superposition for two separated pipes.

\[
\Theta = 0.6\Theta_{in} + 0.4\Theta_{out}
\]

(3)

For the intermittent operation process of the GCHP system, the time-varying heat flux is considered as a sequence of step-wise constant value, the temperature distribution around the U-tube can be calculated with Duhamel’s theorem as

\[
T(t, R, \theta) - T_0 = \sum_{n=0}^{\infty} (q_{n+1} - q_n)G(t_n + 1, t, R, \theta)
\]

(4)

Compared with Eq. (2), the G function can be written as

\[
\begin{align*}
G_1(Fo, R, \theta) &= \frac{\Theta_1(Fo, R, \theta)}{2\pi k_b} \\
G_2(Fo, R, \theta) &= \frac{\Theta_2(Fo, R, \theta)}{2\pi k_b}
\end{align*}
\]

(5)

To simplify the analysis for the influencing factor, the U-pipe wall temperature which can be easily measured in an experiment was selected to represent the underground temperature profile. The U-pipe wall temperature was calculated as the integral mean temperature for both inlet and outlet pipe wall, the formula is written as

\[
T_p(t) = \frac{1}{2} \left[ \frac{1}{2\pi} \int_0^{2\pi} T(t, r_{p, in}, \theta) d\theta + \frac{1}{2\pi} \int_0^{2\pi} T(t, r_{p, out}, \theta) d\theta \right]
\]

(6)

Results and discussion

1.3. Model validation

In order to evaluate the goodness of the proposed simulation model, an experiment operated by Man in Hebei, China was employed, and the experiment parameters and system description can be found in the paper [8] in details. The temperature profile calculated by Eq. (4) is a mean temperature profile along the
borehole, so the temperature at the midpoint of the borehole was selected as a benchmark for comparison. The temperature profile inside the borehole with 10h operation is illustrated in Fig. 2. Besides that, the temperature recorded in the experiment is the pipe wall temperature, so the U-pipe wall temperature was calculated by Eq. (6). Fig.3 compares the simulation results and the experimental results recorded at H=63m, it indicates that the simulation method gives a good agreement with the experimental measurement, and the pairwise correlation coefficients between the two results is 0.9116, the coefficients will be much better if the operation schedule is not delay for the first day.

1.4. Influencing factor

Based on Eq. (4-5), it is obvious that the temperature profile around the U-pipe is a function of operation time, heat flux as well as thermal conductivity of back-filled grout. In order to simplify the evaluation process for the influencing factor, only the U-pipe wall temperature is analyzed in this paper.

1.4.1. Operation Time

For an intermittent operation system, the U-pipe wall temperature, especially the recovery temperature, is greatly affected by the operation time. The longer the system operates, the harder for the pipe wall temperature restores, and it is shown in Fig. 4. The figure also illustrates that the pipe wall temperature cannot be restored in a short time. Take 10% of the temperature rise as the criterion for perfect restore process, the on-off ratio for the system operation should be smaller than 1/2 according to the simulation, and it will be much better for smaller on-off ratio which is indicated by Fig.5. 90% and 95% of the heat will be restored with 1/2 on-off ratio operation and 1/3 on-off ratio operation, respectively. However, the
on-off ratio for the system operation is not the most important, too frequently on-off control is not suitable for the temperature recovery with the same on-off ratio for the system operation, and it is illustrated in Fig. 6.

1.4.2. Back-filled grout thermal conductivity and heat flux

According to the Eq.(4) and Eq.(5), the underground temperature profile is determined by \( q/(2\pi kb) \). Fig. 7 illustrates the various temperature at the U-pipe wall under various back-filled grout thermal conductivity. It indicates that the back-filled grout thermal conductivity only results in the temperature rise of the U-pipe wall, the temperature restore process is remained the same under various back-filled grout thermal conductivities.

For the various heat fluxes of the borehole, it is important for both the temperature rise process and temperature recovery process when the system is on and off, respectively. Fig. 8 illustrates that the heat buildup in the ground is lighter with a lower heat flux. With a limited heat flux, the heat buildup will keep in an acceptable degree with proper intermittent operation control strategy.

Conclusion

In this paper, a new analytical short time response model to simulate the temperature profile under the intermittent operation for GCHP system is proposed. This method is based on composite-medium line-source solution. The analytical model is validated by an experiment operated in Hebei. Some comparison was taken to find the influencing factor which affects the temperature rise process and temperature

![Fig 5 U-pipe temperature comparison under various operation times with same on-off ratio](image)

![Fig 6 U-pipe wall Temperature comparison under various back-filled grout thermal conductivity](image)

![Fig 7 U-pipe wall temperature comparison under various heat flux](image)
recovery process under the system is operated and stopped, respectively. Based on these comparisons, some results are obtained as follows.

1) The proposed short time response model based on composite-medium line-source solution is the most effective analytical method to simulate the underground temperature profile around the U-pipe.

2) Both of the operation time and the on-off ratio for an operation system are important for the temperature recovery process of the ground, and the most efficiency on-off ratio is 1/2 or 1/3.

3) The back-filled grout thermal conductivity only affects the temperature rise process when the system is operating, and the temperature will restored with the same degree.

4) With a suitable heat flux, the temperature undergound will keep balance and the heat buildup will keep in a relatively low degree, and it provides the possibility to propose control strategy based on the heat flux prediction for the hybrid GCHP system operation.

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Reference

Biography
Prof. Zhang Quan is a full professor in Hunan University, China, his research is focus on the renewable energy and the energy storage.