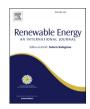
ELSEVIER

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



An hourly simulation method for the energy performance of an office building served by a ground-coupled heat pump system



Linfeng Zhang ^{a, b}, Gongsheng Huang ^{b, *}, Quan Zhang ^{a, **}, Jinggang Wang ^c

- ^a College of Civil Engineering, Hunan University, Changsha, Hunan, 410082, China
- ^b Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong
- ^c College of Energy and Environment Engineering, Hebei University of Engineering, Handan, Hebei, 056038, China

ARTICLE INFO

Article history: Received 13 November 2017 Received in revised form 8 March 2018 Accepted 28 March 2018 Available online 29 March 2018

Keywords:

Ground-coupled heat pump system Hourly simulation method Fluid and ground temperature prediction Mean temperature calculation accuracy

ABSTRACT

Ground heat exchangers are key component of ground-coupled heat pump systems, and their thermal response is therefore very important for ground-coupled heat pump system design and operation. This paper proposes a new hourly simulation method, and uses it to study the performance improvement potential for the ground-coupled heat pump system. First, with an effective U-pipe shank spacing determined by the calculated and measured borehole thermal resistance, a reasonable and accurate fluid temperature prediction method is developed, and the hourly energy performance simulation method is also proposed accordingly with the Fast Fourier Transform superposition algorithm. This hourly simulation method is validated using experimental data collected from a well-designed ground-coupled heat pump experiment platform, which shows that the maximum absolute error for the predicted fluid temperature is smaller than 1.04 °C. Second, using the proposed hourly simulation method, a framework for the energy performance simulation of an office building served by the ground-coupled heat pump system is developed. Impact factors on ground-coupled heat pump system performance are systematically analyzed using this simulation method, and the results show that performance can be improved with shorter operation schedules and lower heat fluxes.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

The energy shortage and environment pollution are two worldwide pressing issues, especially for developing countries. To deal with these problems, renewable energy, which can be generated from sunshine, wind, geothermal and biological sources, etc., is used as a substitute for fossil fuels [1]. One possible renewable energy system, the Ground-Coupled Heat Pump (GCHP) system, has been shown to be a sustainable technology, due to its high energy efficiency and low greenhouse gas emissions [2]. According to the world geothermal congress 2015 [3], the installed capacity of the GCHP system grew 1.51 times at a compound annual rate of 8.65% compared to the capacity in 2010. In 2017, geothermal energy was for the first time included in China's National Development plan (the 13th five-year plan) [4]. According to this plan, the

E-mail addresses: gongsheng.huang@cityu.edu.hk (G. Huang), quanzhang@hnu.edu.cn (Q. Zhang).

building square footage served by GCHP systems at the end of 2020 must reach $1.5\times10^9\,\text{m}^2$, which is 3.75 times the area served by such systems in 2015.

Ground Heat Exchangers (GHEs) are key components in GCHP systems, and thus play an important role in their energy efficiency performance. To analyze this performance, the systems' coefficient of performance (COP), which is dependent on the temporal variation outlet temperature of GHEs, needs to be simulated on a small time scale according to the hourly building thermal load with superposition calculation method and heat transfer model (only the COP in the cooling season is discussed in this paper to simplify the calculation process). The superposition method is based on Duhamel's superposition theorem [5] and has been simplified by Bernier et al. [6] using the Multiple Load Aggregation (MLA) algorithm and by Marcotte and Pasquier [7] with a Fast Fourier Transform (FFT) algorithm. In this paper, the FFT algorithm is used because of its computation speed and accuracy. Two types of the heat transfer model for the GHEs, including numerical models and analytical models, are employed. Although numerical models can offer more accurate simulation results as reported by Lee and Lam [8] and Zarrella et al. [9], the simulation process is very complex and lack of

^{*} Corresponding author.

^{**} Corresponding author.

| Nomenclature Part | | | | |
|---|---------------|---|-----------------------|--|
| List of abbreviations R_b Coefficient of Performance FTP FAST FOURITY Transform FLS R_b State Nourier Transform Report Finite Line Source Cofflee Coround Heat Exchangers GCHB Coround Heat Exchangers GCHB Coround Coupled Heat Pump CMIS Infinite Composite-Medium Line Source ILS Infinite AND AND ADDRESS AND AND ADDRESS A | Nomenclature | | r_{o} | Outside radius of the pipe, m |
| Six of abstractions Rb_steady | | | | |
| Section Se | | | | |
| $ \begin{array}{c ccccccccccccccccccccccccccccccccccc$ | List of abb | reviations | | - |
| FFT Fast Fourier Transform FLS Finite Line Source GHES Ground Heat Exchangers GCHP Ground-Coupled Heat Pump ICMLS Infinite Composite-Medium Line Source ILS Infinite Line Source ILS Infinite Line Source ILS Infinite Composite-Medium Line Source ILS Infinite Composite-Medium Line Source ILS Infinite Composite-Medium Line Source ILS Infinite Line Source ILS Infinite Composite-Medium Line Source ILS Infinite Composite Composi | | | * | • |
| FISE Finite Line Source CHEs Cround Heat Exchangers Crown Ground - Coupled Heat Pump CMLS Infinite Composite-Medium Line Source Its Crown Mac Multiple Load Aggregation Temperature, °C Temperature, °C Undisturbed soil temperature, °C Undisturbed soil temperature, °C Temperature, °C Temperature, °C Undisturbed soil temperature, °C Temperature, °C Temperature, °C Temperature, °C Temperature, °C Undisturbed soil temperature, °C Undisturbed soil temperature, °C Temperature, °C Undisturbed soil temperature, °C Undisturbed soil temperature, °C Te | | | , | • |
| GCHP Cround-Coupled Heat Pump Infinite Composite-Medium Line Source ILS Infinite Composite Actor Infinite Line Source ILS Infinite Line Source ILS Infinite Line Source ILS Infinite Composite Actor Infinite Line Source ILS Infinite Line Source ILS Infinite Composite Actor Infinite Line Source ILS Infinite Condition Infinite Line Source ILS Infinite Condition Infinite Composite Actor Infinite Line Source ILS Infinite Condition Infinite Composite Actor Infinite Line Source ILS Infinite Condition Infinite Composite Actor Infinite Line Source ILS Infinite Condition Infinite Condition Infinite Composite Actor Infinite Line Source ILS Infinite Condition Infinite Conditio | | | $R_{bp}(t)$ | Improved borehole-to-pipe thermal resistance, |
| GCHP Ground-Coupled Heat Pump Kbp.tronsleem Iransient borehole-to-pipe thermal resistance, mr°C/W ICMLS Infinite Composite-Medium Line Source R Pipe-fluid thermal resistance, mr°C/W MAE Mean Absolute Error t Time, s RMSE Root Mean Squared Error T Undisturbed soil temperature, °C RMSE Root Mean Squared Error To Undisturbed soil temperature, °C List of symbols T _{in} Inlet temperature, °C C Fluid heat capacity, J/kg· °C T _{in} Inlet temperature, °C D Distance between center of pipe and center of pope and center of por borehole, m z' Vertical coordinate of borehole, m G G-function response factor List of Greek letters a Thermal diffusivity ratio between the ground and grou | | | | m·°C/W |
| ILS Infinite Composite-Medium Line Source ILS Infinite Conditate of U-pipe, Columbers Infinite Conditate of U-pipe, Columbers ILS Infinite Conditate of Infinite Pipe Infinite Infinite Conditation, Infinite Conditation, In | | <u> </u> | $R_{bp,transient}$ | Transient borehole-to-pipe thermal resistance, |
| Infinite Line Source MAE Mean Absolute Error MIA Multiple Load Aggregation RMSE Root Mean Squared Error If Temperature, "C Infinite Line Source RMSE Root Mean Squared Error RMSE Root Mean Squared Error If Temperature, "C Indisturbed soil temperature, "C Intermal diffusion to brothole, m Intermal diffusion pale Intermal diffus | | | • • | m·°C/W |
| MAE Mean Absolute Error MIA Multiple Load Aggregation RMSE Root Mean Squared Error T Temperature, "C Undisturbed soil temperature, "C Fluid temperature inside the pipe, "C List of symbols C Fluid heat capacity, J/kg. "C D Distance between center of pipe and center of borehole, m The friction factor G G-function response factor for FLS model Gruss G-function response factor for ILS model Grab G-function response factor at borehole wall Grab G-function response factor outside the borehole h Heat transfer coefficient H The depth of the borehole, m Mass flow rate, kg/s N Numbers of borehole N ₁₂ N ₂ Q ₈ Relative sensitive coefficient M ₁₂ N ₁ Dimensionless vertical coordinate of the pipe, m Mass flow rate, kg/s N Numbers of borehole Q ₁₀ Input power, W Q ₂ Input power, W Q ₃ Heat injected into the ground, W Q ₄ Building load, W Q ₇ The radius of U-pipe legs, m r' The radius of the porehole, m The radius of the borehole, m The radius of the borehole, m The radius of the porehole, m The radius of the porehole, m The radius of the borehole, m T | | | R_{p} | Pipe-fluid thermal resistance, m·°C/W |
| MIA Multiple Load Aggregation RMSE Root Mean Squared Error RMSE Root Mean Squared Error RMSE Root Mean Squared Error If I Fluid temperature, "C Itist of symbols C Fluid heat capacity, J/kg. "C D Distance between center of pipe and center of borehole, m Distance between center of pipe and center of borehole, m Inlet temperature, "C Outlet temperature, "C | | | - | = : |
| RMSE Root Mean Squared Error To | | | | · |
| List of symbols c Fluid heat capacity, J/kg.°C D Distance between center of pipe and center of borehole, m The friction factor G-G-G-function response factor for FLS model G-function response factor for ELS model G-function response factor for IS model G-function response factor for IS model G-function response factor at borehole wall G-funside G-function response factor at borehole wall G-funside G-function response factor outside the borehole h Heat transfer coefficient H The depth of the borehole, m H The depth of the borehole, m J-D Sensitive coefficient Vertical coordinate of the pipe, m Mass flow rate, kg/s N Numbers of borehole N ₁₂ , N ₃ , 1 Dimensionless vertical coordinate of the pipe, m Mass flow rate, kg/s N Unimbers of borehole Q-g Heat flux per meter, W/m Q-g Heat injected into the ground, W Q-g Relatives community in the pipe wall P-r T he radius of the pipe legs, m T Radius, m T Radius, m T Radius, of T-pipe legs, m T He radius of the borehole, m T Radius of the borehole, m T Radius of the borehole, m T Radius of the borehole T Radius of the borehole, m T Radius of the borehole T Radius of the borehole T Radius of the borehole, m T Radius of the borehole T Radius of the borehole, m T Radius of the bore | 1 | | | • |
| List of symbols C Fluid heat capacity, J/kg. °C D Distance between center of pipe and center of borehole, m Fin Court overtical coordinate of borehole, m F The friction factor G G-function response factor G-function response factor for FLS model G-function response factor for ICMIS model G-function response factor for ILS model G-function response factor for ILS model G-function response factor for ILS model G-function response factor at borehole wall G-function response factor at borehole wall G-function response factor inside the borehole G-function response factor inside the borehole Heat transfer coefficient H The depth of the borehole, m L The radius of the pipe, m Mass flow rate, kg/s N Numbers of borehole D Dimensionless vertical coordinate of the pipe, m Mass flow rate, kg/s N Numbers of borehole Q-g Heat injected into the ground, W Q-g Heat injected into the ground, W Q-g Heat injected into the ground, W Q-g Building load, W F The radius of the borehole, m F The r | KIVISE | Root Mean Squared Error | | |
| C Fluid heat capacity, J/kg. °C Tout Outlet temperature, °C D Distance between center of pipe and center of borehole, m z' Vertical coordinate of borehole, m borehole, m z' Vertical coordinate of U-pipe, m f The friction factor List of Greek letters G-function response factor for IS model a Thermal diffusivity ratio between the ground and grout G _{ICMLS} G-function response factor for ILS model ap Grout thermal diffusivity, m2/s G _b G-function response factor at borehole wall ap Thermal diffusivity of pipe, m2/s G _{miside} G-function response factor unside the borehole as Ground thermal diffusivity, m2/s G _{miside} G-function response factor unside the borehole as Ground thermal diffusivity, m2/s G _{miside} G-function response factor outside the borehole as Ground thermal diffusivity, m2/s G _{miside} G-function response factor outside the borehole as Ground thermal diffusivity, m2/s G-function response factor outside the borehole kp Ground thermal diffusivity, m2/s G-function response factor outside the borehole kp Ground thermal diffusivity, m2/s G- | T | 1.1 | | |
| D Distance between center of pipe and center of borehole, m borehole and borehole and borehole and borehole, m bo | | | | |
| borehole, m f The friction factor G G-function response factor G _{FLS} G-function response factor for FLS model G _{ICMLS} G-function response factor for ILS model G _{ICMLS} G-function response factor for ILS model G _{ICMLS} G-function response factor at breinder ground and grout G _{ILS} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout G _{ID} G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s G-function response factor at breinder ground and grout A _D Thermal diffusivity, m2/s Ground thermal diffusivity, m2/s Ground thermal diffusivity, m2/s Ground thermal diffusivity, m2/s Ground thermal conductivity, W/m·°C A _S Ground thermal conductivity, W/m·°C A _S Ground thermal conductivity of pipe, w/m·°C A _S Ground thermal conductivity of pipe, w/m·°C A _S Ground thermal conductivity, W/m·°C A _S Ground thermal conductivity, w/m·°C A _S Ground thermal conductivity, w/m·°C A _S Ground thermal conductivity of Pluid, W/m·°C A _S Ground ther | 1 | | | |
| f The friction factor List of Greek letters G G-function response factor for FLS model a Thermal diffusivity ratio between the ground and grout G(CMISS) G-function response factor for ILS model a Thermal diffusivity ratio between the ground and grout G(MISS) G-function response factor of ILS model ab Grout thermal diffusivity, m2/s Gb G-function response factor at borehole wall ap Thermal diffusivity of pipe, m2/s G-function response factor outside the borehole as Ground thermal diffusivity, m2/s G-function response factor outside the borehole borehold fiftusivity, m2/s G-function response factor outside the borehole as Ground thermal diffusivity, m2/s G-function response factor outside the borehole borehold fiftusivity, m2/s derout thermal diffusivity, m2/s G-function response factor outside the borehole for function response factor outside the borehole for function response factor outside the borehole for Grout thermal diffusivity, m2/s G-function response factor outside the borehole wall fiftusivity of pipe, m2/s for function response factor outside the borehole wall fiftusivity of pipe, m2/s Heat transfer coefficient for function response factor at borehole pipe, m for Angle of the U-pipe leg for the supply pipe | | | | |
| G-function response factor G_{RIS} G-function response factor for FLS model G_{ICMLS} G-function response factor for ICMLS model G_{ICMLS} G-function response factor for ICMLS model G_{IIS} G-function response factor for ILS model G_{IIS} G-function response factor at borehole wall G_{IIS} G-function response factor at borehole wall G_{IIS} G-function response factor inside the borehole G_{IIS} G-function response factor inside the borehole G_{IIS} G-function response factor outside the borehole G_{III} G-function response factor inside the borehole G_{III} G-function response factor at borehole G_{III} G-function response factor outside the borehole G_{III} G-function response factor outside the borehole G_{III} G-function response factor outside the borehole G_{III} G-function response factor at borehole G_{III} G-function response factor outside the borehole G | _ | | Z | vertical coordinate of 0-pipe, in |
| GFLS G-function response factor for FLS model GICMLS G-function response factor for ICMLS model GILS G-function response factor for ICMLS model GILS G-function response factor at borehole wall GILS G-function response factor outside the borehole Heat transfer coefficient H The depth of the borehole, m Heat transfer coefficient H The depth of the borehole, m Sensitive coefficient H The depth of the borehole, m Sensitive coefficient H Vertical coordinate of the pipe, m H The length of the pipe, m H The length of the pipe, m H Mass flow rate, kg/s N Numbers of borehole N12,Ns1 Dimensionless termal resistance in Eq. (10) P The weight for the outlet temperature calculation H Heat flux per meter, W/m Q Input power, W Q Input power, W Q Input power, W Q Input power, W Q Building load, W F The radius of the pipe that Pump, W F Fluid QI Building load, W F The radius of the point in the pipe wall, m F The radius of the point in the pipe wall, m F The radius of the point in the pipe wall, m T The radius of the borehole, m The radius of the borehole, m Thermal diffusivity, m2/s Grout thermal conductivity, W/m·°C Angle of Fulid, M/m·°C Angle of Fulid, M/m·° | | | List of Crack latters | |
| G_{ICMIS} G-function response factor for ICMLS model α_b Grout thermal diffusivity, m2/s G_{ILS} G-function response factor at borehole wall α_p Thermal diffusivity of pipe, m2/s G_{inside} G-function response factor at borehole wall α_p Thermal diffusivity, m2/s G_{inside} G-function response factor outside the borehole α_s Ground thermal diffusivity, m2/s $G_{outside}$ G-function response factor outside the borehole κ_b Grout thermal conductivity, W/m $^{\circ}$ C h Heat transfer coefficient κ_f Thermal conductivity of Fluid, W/m $^{\circ}$ C H The depth of the borehole, m κ_p Thermal conductivity of pipe, W/m $^{\circ}$ C J_D^* Sensitive coefficient κ_p Thermal conductivity of pipe, W/m $^{\circ}$ C J_D^* Relative sensitive coefficient θ Angle I Vertical coordinate of the pipe, m θ' Angle of the U-pipe legs I The length of the pipe, m θ' Angle at the point in the pipe wall I Dimensionless vertical coordinate of the pipe, m θ_1 Dimensionless temperature profile for the supply pipe M Mass flow rate, kg/s θ' Angle at the point in the pipe wall N Numbers of borehole θ_2 Dimensionless temperature profile for the return pipe N_{12} , N_{31} Dimensionless thermal resistance in Eq. (10) θ' Dimensionless temperature profile for the return pipe Q Input power, W θ' θ' θ' θ' θ' Q <td></td> <td></td> <td>•</td> <td></td> | | | • | |
| Gilss G-function response factor for ILS model α_b Grout thermal diffusivity, m2/s G_b G-function response factor at borehole wall G_b G-function response factor inside the borehole G_b Ground thermal diffusivity, m2/s Grout fermal diffusivity of pipe, m2/s Grout fermal diffusivity, m2/s Grout fermal diffusivity of pipe, m2/s Grout fermal diffusivity, m2/s Grout fe | G_{FLS} | | а | |
| Gibside G-function response factor at borehole wall α_p Thermal diffusivity of pipe, m2/s G_{inside} G-function response factor inside the borehole α_s Ground thermal diffusivity, m2/s Goutside G-function response factor outside the borehole κ_b Grout thermal conductivity, W/m·°C heat transfer coefficient κ_f Thermal conductivity of Fluid, W/m·°C heat transfer coefficient κ_f Thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of pipe, W/m·°C heat transfer coefficient κ_f Ground thermal conductivity of Pluid, W/m·°C heat transfer coefficient κ_f Ground hermal conductivity of Pluid, W/m·°C heat transfer coefficient κ_f Ground hermal conductivity of Pluid, W/m·°C heat transfer coefficient κ_f Ground hermal conductivity of Pluid, W/m·°C heat transfer coefficient heat Pluid, W/m·°C heat Pluid, | G_{ICMLS} | | | S . |
| G_{inside} $G_{outside}$ G | | | | |
| Goutside G-function response factor outside the borehole h Heat transfer coefficient κ_f Thermal conductivity of Fluid, $W/m \cdot {}^{\circ}C$ H The depth of the borehole, m κ_p Thermal conductivity of pipe, $W/m \cdot {}^{\circ}C$ JD Sensitive coefficient κ_s Ground thermal conductivity, $W/m \cdot {}^{\circ}C$ JD Sensitive coefficient ω Angle of the U-pipe legs ω Dimensionless vertical coordinate of the pipe, ω ω Dimensionless vertical coordinate of the pipe, ω ω Dimensionless temperature profile for the supply ω ω Dimensionless thermal resistance in Eq. (10) ω Dimensionless temperature profile for the return pipe ω Dimensionless thermal resistance in Eq. (10) ω Dimensionless temperature profile for the return pipe ω Dimensionless thermal resistance in Eq. (10) ω Dimensionless temperature profile for the return pipe in Dimensionless temperature profile for the return pipe ω Dimensionless temperature profile for the return pipe ω Dimensionless temperature profile for the return pipe ω Dime | | | α_p | |
| hHeat transfer coefficient $κ_f$ Thermal conductivity of Fluid, $W/m \cdot ^{\circ}C$ HThe depth of the borehole, m $κ_p$ Thermal conductivity of pipe, $W/m \cdot ^{\circ}C$ J _D Sensitive coefficient $κ_s$ Ground thermal conductivity, $W/m \cdot ^{\circ}C$ J $_p^*$ Relative sensitive coefficient $θ$ AnglelVertical coordinate of the pipe, m $θ'$ Angle of the U-pipe legsLThe length of the pipe, m $θ'$ Angle at the point in the pipe wallLDimensionless vertical coordinate of the pipe, m $θ_1$ Dimensionless temperature profile for the supply pipeNNumbers of borehole $θ_2$ Dimensionless temperature profile for the return pipeNNumbers of borehole $θ_2$ Dimensionless temperature profile for the return pipeN12, N ₅₁ Dimensionless thermal resistance in Eq. (10) $θ_2$ Dimensionless temperature profile for the return pipeQInput power, W1, 2Supply and return pipe in boreholeQ _g Heat injected into the ground, WbBoreholeQ _{hp} Energy consumption of the Heat Pump, WfFluidQ _l Building load, WgGroutrRadius, mpPiper'The radius of the point in the pipe wall, msGroundr+The radius of the borehole, mtesttested | G_{inside} | | α_s | |
| H The depth of the borehole, m J_D Sensitive coefficient J_D Sensitive coefficient J_D Relative sensitive coefficient J_D Rangle of the U-pipe legs J_D Rangle of the U-pipe l | $G_{outside}$ | G-function response factor outside the borehole | | |
| J_D Sensitive coefficient κ_s Ground thermal conductivity, W/m·°C J_D^* Relative sensitive coefficient θ Angle l Vertical coordinate of the pipe, m θ' Angle of the U-pipe legs L The length of the pipe, m θ' Angle at the point in the pipe wall L_D Dimensionless vertical coordinate of the pipe, m θ_1 Dimensionless temperature profile for the supply pipe m Mass flow rate, kg/spipe N Numbers of borehole θ_2 Dimensionless temperature profile for the return pipe N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10)pipe p The weight for the outlet temperature calculation p List of subscripts q Heat flux per meter, W/m p List of subscripts Q Input power, W p p Supply and return pipe in borehole Q_g Heat injected into the ground, W p Borehole Q_h Energy consumption of the Heat Pump, W p Fluid Q_l Building load, W p p r Radius, m p Pipe r' The radius of U-pipe legs, m p p r' The radius of the point in the pipe wall, m p p r_b The radius of the borehole, mtesttested | h | Heat transfer coefficient | κ_f | |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | Н | The depth of the borehole, m | κ_p | Thermal conductivity of pipe, W/m·°C |
| l Vertical coordinate of the pipe, m L The length of the pipe, m L D Dimensionless vertical coordinate of the pipe, m Mass flow rate, kg/s N Numbers of borehole N12, Ns1 Dimensionless thermal resistance in Eq. (10) p The weight for the outlet temperature calculation q Heat flux per meter, W/m Q Input power, W Qg Heat injected into the ground, W Qhp Energy consumption of the Heat Pump, W Ql Building load, W r Radius, m r' The radius of U-pipe legs, m r' The radius of the pipe, m θ' Angle of the U-pipe legs θ' Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile for the supply pipe θ_2 Dimensionless temperature profile for the supply pipe θ_2 Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile for the supply pipe θ_2 Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile for the supply pipe θ_2 Dimensionless temperature profile for the supply pipe θ_1 Dimensionless temperature profile | J_D | Sensitive coefficient | K_S | Ground thermal conductivity, W/m·°C |
| l Vertical coordinate of the pipe, m θ' Angle of the U-pipe legs L The length of the pipe, m θ^+ Angle at the point in the pipe wall L_D Dimensionless vertical coordinate of the pipe, m θ^+ Dimensionless temperature profile for the supply pipe M Numbers of borehole Θ_2 Dimensionless temperature profile for the return N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10)pipe p The weight for the outlet temperature calculationpipe q Heat flux per meter, W/m $List \ of \ subscripts$ Q Input power, W 1, 2Supply and return pipe in borehole Q_g Heat injected into the ground, W D Borehole Q_{hp} Energy consumption of the Heat Pump, W D D Q_l Building load, D | J_D^* | Relative sensitive coefficient | θ | Angle |
| L The length of the pipe, m θ^+ Angle at the point in the pipe wall L_D Dimensionless vertical coordinate of the pipe, m Θ_1 Dimensionless temperature profile for the supply pipe M Numbers of borehole Θ_2 Dimensionless temperature profile for the return N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10)pipe p The weight for the outlet temperature calculation $pipe$ q Heat flux per meter, W/m $pipe$ Q Input power, W $pipe$ Q_g Heat injected into the ground, W $pipe$ Q_{hp} Energy consumption of the Heat Pump, W $pipe$ Q_l Building load, W $pipe$ q <t< td=""><td></td><td>Vertical coordinate of the pipe, m</td><td>heta'</td><td>Angle of the U-pipe legs</td></t<> | | Vertical coordinate of the pipe, m | heta' | Angle of the U-pipe legs |
| $ \begin{array}{cccccccccccccccccccccccccccccccccccc$ | L | | θ^+ | |
| m Mass flow rate, kg/spipe N Numbers of borehole Θ_2 Dimensionless temperature profile for the return N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10)pipe p The weight for the outlet temperature calculation $pipe$ q Heat flux per meter, W/m List of subscripts Q Input power, W 1, 2Supply and return pipe in borehole Q_g Heat injected into the ground, W pi Borehole Q_{hp} Energy consumption of the Heat Pump, W pi Fluid Q_l Building load, W pi pi r Radius, r pi pi r^* The radius of U-pipe legs, r r r r The radius of the point in the pipe wall, r r r r The radius of the borehole, r r r | | | | |
| Numbers of borehole Θ_2 Dimensionless temperature profile for the return N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10) p The weight for the outlet temperature calculation q Heat flux per meter, W/m List of subscripts Q_s Input power, Q_s Heat injected into the ground, Q_s Energy consumption of the Heat Pump, Q_s Building load, Q_s Q_s Building load, Q_s $Q_$ | | | ∪ I | |
| N_{12}, N_{s1} Dimensionless thermal resistance in Eq. (10) pipe The weight for the outlet temperature calculation q Heat flux per meter, W/m Q Input power, W Q_g Heat injected into the ground, W Q_h Energy consumption of the Heat Pump, W Q_h Building load, W Q_h Radius, m Q_h The radius of U-pipe legs, m Q_h The radius of the point in the pipe wall, m Q_h The radius of the borehole, m | | | Θ_{\circ} | * * |
| The weight for the outlet temperature calculation q Heat flux per meter, W/m List of subscripts Q Input power, Q Input power, Q Heat injected into the ground, Q Benergy consumption of the Heat Pump, Q Building load, Q Buildi | 1 | | 02 | |
| $\begin{array}{lllll} q & \text{Heat flux per meter, W/m} & \textit{List of subscripts} \\ Q & \text{Input power, W} & 1, 2 & \text{Supply and return pipe in borehole} \\ Q_g & \text{Heat injected into the ground, W} & b & \text{Borehole} \\ Q_{hp} & \text{Energy consumption of the Heat Pump, W} & f & \text{Fluid} \\ Q_l & \text{Building load, W} & g & \text{Grout} \\ r & \text{Radius, m} & p & \text{Pipe} \\ r' & \text{The radius of U-pipe legs, m} & s & \text{Ground} \\ r^+ & \text{The radius of the point in the pipe wall, m} & \text{steady} & \text{Steady-state} \\ r_b & \text{The radius of the borehole, m} & \text{test} & \text{tested} \\ \end{array}$ | | | | pipe |
| $\begin{array}{cccccccccccccccccccccccccccccccccccc$ | | | List of sub | ccrints |
| Q_g Heat injected into the ground, W b Borehole Q_{hp} Energy consumption of the Heat Pump, W f Fluid Q_l Building load, W g Grout r Radius, m p Pipe r' The radius of U-pipe legs, m s Ground r^+ The radius of the point in the pipe wall, m steady Steady-state r_b The radius of the borehole, m test tested | 1 | | - | • |
| Q_{hp} Energy consumption of the Heat Pump, W f Fluid Q_l Building load, W g Grout r Radius, m p Pipe r' The radius of U-pipe legs, m s Ground r+ The radius of the point in the pipe wall, m steady Steady-state r_b The radius of the borehole, m test tested | _ | | | |
| Q_l Building load, W g Grout r Radius, m p Pipe r' The radius of U-pipe legs, m s Ground r^+ The radius of the point in the pipe wall, m steady Steady-state r_b The radius of the borehole, m test tested | | | | |
| rRadius, mpPiper'The radius of U-pipe legs, msGroundr+The radius of the point in the pipe wall, msteadySteady-stater_bThe radius of the borehole, mtesttested | | | | |
| r' The radius of U-pipe legs, m s Ground r^+ The radius of the point in the pipe wall, m steady Steady-state r_b The radius of the borehole, m test tested | 1 | <u> </u> | | |
| r^+ The radius of the point in the pipe wall, m steady Steady-state r_b The radius of the borehole, m test tested | | | | |
| r _b The radius of the borehole, m test tested | | | | |
| | | | | = |
| r_i inside radius of the pipe, m | | | test | testeu |
| | r_i | inside radius of the pipe, m | | |

flexibility, which is not easy for practical use [10]. Thus, analytical models are recommended.

According to previous studies, many analytical models can be implemented in GCHP performance simulation, such as the infinite line source model (ILS) [11], finite line source model (FLS) [7], and infinite cylinder source model (ICS) [12]. However, these models are not acceptable for hourly GCHP system simulation due to the ignorance of grout thermal capacity [13], and the maximum absolute error (MAE) of the predicted fluid temperature can reach 6 °C [14]. Thus, short-term response analytical models which can consider the grout thermal capacity becomes necessary. Due to the complex configuration of GHEs, many short-term response analytical models use simplified borehole geometries to predict fluid temperature, such as the boundary element method [15],

corrected g-function method [16], equivalent diameter method [17], infinite composite-medium line source (ICMLS) method [18] and full scale model (titled as Li's method thereafter) [19]. All these models perform well initially but not satisfactorily over a longer duration. The MAE of the fluid temperature predicted in the late time period can reach 2-3 °C [20].

To solve this problem, the difference between the calculated and the measured borehole thermal resistance, which are steady-state values, was used to calibrate the transient borehole thermal resistance calculated using the method proposed by Li et al. [20] in order to alleviate the impact of the simplification of the borehole configuration (titled as Zhang's method thereafter) [21]. Although numerical studies demonstrated that the prediction accuracy of the fluid temperature was improved (the absolute error can be limited

دريافت فورى ب متن كامل مقاله

ISIArticles مرجع مقالات تخصصی ایران

- ✔ امكان دانلود نسخه تمام متن مقالات انگليسي
 - ✓ امكان دانلود نسخه ترجمه شده مقالات
 - ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
 - ✓ امكان دانلود رايگان ۲ صفحه اول هر مقاله
 - ✔ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
 - ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات