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

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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.

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 building square footage served by GCHP systems at the end of 2020 must reach $1.5 \times 10^9\,\mathrm{m}^2$, 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

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Nomenclature

List of abbreviations

COP	Coefficient of Performance
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
MAE	Mean Absolute Error
MLA	Multiple Load Aggregation
RMSE	Root Mean Squared Error

List of symbols

c	Fluid heat capacity, J/kg·°C
D	Distance between center of pipe and center of 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 ICMLS model
G_{ILS}	G-function response factor for ILS model
G_b	G-function response factor at borehole wall
G_{inside}	G-function response factor inside the borehole
$G_{outside}$	G-function response factor outside the borehole
h	Heat transfer coefficient
H	The depth of the borehole, m
J_D	Sensitive coefficient
J_D^*	Relative sensitive coefficient
l	Vertical coordinate of the pipe, m
L	The length of the pipe, m
L_D	Dimensionless vertical coordinate of the pipe, m
m	Mass flow rate, kg/s
N	Numbers of borehole
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
Q	Input power, W
Q_g	Heat injected into the ground, W
Q_{hp}	Energy consumption of the Heat Pump, W
Q_l	Building load, W
r	Radius, m
r'	The radius of U-pipe legs, m
r^+	The radius of the point in the pipe wall, m
r_b	The radius of the borehole, m
r_i	Inside radius of the pipe, m
r_o	Outside radius of the pipe, m
R_b	Borehole thermal resistance, m·°C/W
$R_{b,steady}$	Steady state borehole thermal resistance, m·°C/W
$R_{b,test}$	Tested borehole thermal resistance, m·°C/W
$R'_{b,transient}$	Transient borehole thermal resistance, m·°C/W
$R_{bp}(t)$	Improved borehole-to-pipe thermal resistance, m·°C/W
$R_{bp,transient}$	Transient borehole-to-pipe thermal resistance, m·°C/W
R_p	Pipe-fluid thermal resistance, m·°C/W
t	Time, s
T	Temperature, °C
T_0	Undisturbed soil temperature, °C
T_f	Fluid temperature inside the pipe, °C
T_{in}	Inlet temperature, °C
T_{out}	Outlet temperature, °C
z	Vertical coordinate of borehole, m
z'	Vertical coordinate of U-pipe, m

List of Greek letters

a	Thermal diffusivity ratio between the ground and grout
α_b	Grout thermal diffusivity, m2/s
α_p	Thermal diffusivity of pipe, m2/s
α_s	Ground thermal diffusivity, m2/s
κ_b	Grout thermal conductivity, W/m·°C
κ_f	Thermal conductivity of Fluid, W/m·°C
κ_p	Thermal conductivity of pipe, W/m·°C
κ_s	Ground thermal conductivity, W/m·°C
θ	Angle
θ'	Angle of the U-pipe legs
θ^+	Angle at the point in the pipe wall
Θ_1	Dimensionless temperature profile for the supply pipe
Θ_2	Dimensionless temperature profile for the return pipe

List of subscripts

1, 2	Supply and return pipe in borehole
b	Borehole
f	Fluid
g	Grout
p	Pipe
s	Ground
steady	Steady-state
test	tested

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