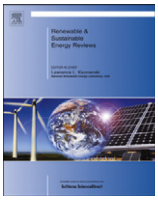
Renewable and Sustainable Energy Reviews 16 (2012) 6814–6822

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

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



Ground source heat pump system: A review of simulation in China

Yanping Yuan*, Xiaoling Cao, Liangliang Sun, Bo Lei, Nanyang Yu

School of Mechanical Engineering, Southwest Jiaotong University, 610031 Chengdu, PR China

ARTICLE INFO

Article history:
Received 4 June 2012
Received in revised form
19 July 2012
Accepted 23 July 2012
Available online 9 October 2012

Keywords:
Ground source heat pump (GSHP)
Ground heat exchanger (GHE)
System simulation
Operation performance
Experimental investigation
Hybrid ground source heat pump (HGSHP)

ABSTRACT

With attractive advantages of high efficiency, energy saving and environmental friendliness, the ground source heat pump (GSHP) system has been used widely in China in recent years. This paper summarizes the analytical solution, numerical solution and experimental investigation of the heat transfer of the ground heat exchanger (GHE), analyzes the simulation model and long-term operation performance of the GSHP system, and introduces the lastest hybrid ground source heat pump (HGSHP) system. In addition, this paper discusses and summarizes the shortages and imperfects of the current research on the simulation of the GSHP system and gives some recommendations for future work.

Contents

1. Introduction

As the global energy crises and environmental problems become more and more serious, the ground source heat pump (GSHP) technology has showed a trend of booming growth in world due to its attractive advantages of high efficiency, energy saving and environmental friendliness and the GSHP system has become a hotspot in clean energy research. In recent years, great numbers of the GSHP systems have been used in commercial and residential buildings throughout China. According to the Ministry of Science and Technology of China, the total area adopting the GSHP systems will be up to 350 million square meters by the end of 2015 [1]. Now in China, the GSHP technology is in the stage of rapid development.

2. Heat transfer model and operation performance of GHE

Ground heat exchanger (GHE) is an important part of the GSHP system [2]. The heat transfer of the GHE is a very complicated dynamic process. On one hand, the heat transfer of the GHE

---

* Corresponding author.
E-mail address: ypyuan@home.swjtu.edu.cn (Y. P. Yuan).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.07.025

Nomenclature

q	heat flux (W/m^2)
T	temperature (K)
c_p	specific heat at constant pressure (J/((kg K))
r	distance from the borehole axis (m)
t	time (s)
m	mass flow rate of the circulating fluid in the U-tube (kg/s)
R	heat transfer resistant ((m K)/W)
L	borehole length (m)
u	velocity of circulating fluid in the U-tube (m/s)
F_o	Fourier constant (–)

Greek letters

λ	thermal conductivity (W/(m K))
a	thermal diffusivity (m^2/s)
β	I integration variable (–)
ρ	density (kg/m^3)

Subscripts

0	initial
f	fluid
s	solid
p	ground heat exchanger
b	borehole wall
in	inlet of the U-tube
out	outlet of the U-tube
a	air
1	inlet branch of the U-tube
2	outlet branch of the U-tube

depends on the buried method, soil characteristics underground hydrological parameters, backfill materials and meteorological data. On the other hand, the heat transfer of the GHE interplays with the operation performance of heat pump unit and the load of buildings [3]. GHEs are divided into two categories: horizontal GHEs and vertical GHEs. Since the horizontal GHE covers larger area and the heat transfer process is considerably influenced by the ground surface temperature and ambient air temperature, this paper focuses on the vertical GHE.

2.1. Analytical solution

2.1.1. Line source theory

In 1948, Ingersoll et al. [4] improved Kelvin's line source theory to solve the heat transfer problem of the GHE. In Ingersoll's theory, the heat transfer of the GHE is simplified as the heat transfer of the heat source which has the same axis of the borehole. The model has several assumptions listed as follows: the ground is an infinite medium with the initial uniform temperature and its thermophysical properties are homogeneous and stable; the heat transfer in the direction of the borehole axis, including the heat flux across the ground surface and down the bottom of the borehole, is neglected; the geometric dimensions of the borehole are neglected and assumed as a line source of the borehole axis.

According to the Ingersoll's line-source theory, the temperature response in the ground due to a constant heat flux is given by:

$$T_s - T_0 = \frac{q}{2\pi\lambda_s}\int_X^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta = \frac{q}{2\pi\lambda_s}I(X) \tag{1}$$

where $I(X)$ is the exponential integral function, $X = r/(2\sqrt{\alpha_s t})$; T_S is the ground temperature, *K*; T_0 is the initial ground temperature, *K*; q is the constant heat flux of the line-source, *W*/*m*; r is the distance from the borehole axis, *m*; λ_s is the thermal conductivity of the ground, *W*/(*m* K), α_s is the thermal diffusivity of the ground, m^2/s; t is the time since the beginning of operation, *s*; β is integration variable.

The investigation indicated that the third assumption is not reasonable when the time is very short ($t < 5r_b^2/\alpha_s$, several hours in general). For the GHE with constant thermal capacity, the analytical solution shows major errors, especially for short time.

The traditional infinite line source model ignored the influence of the finite length of the borehole and the boundary condition of the ground surface. Fang et al. [5] utilized the Green function method to obtain the temperature response of the finite line heat source in the semi-infinite medium and the temperature response is expressed as:

$$T_s - T_0 = \frac{q}{4\lambda_s\pi}\int_0^L\left\{\frac{erfc\left[\frac{\sqrt{\rho_s{}^2+(z-h)^2}}{2\sqrt{\alpha_s t}}\right]}{\sqrt{\rho_s{}^2+(z-h)^2}} - \frac{erfc\left[\frac{\sqrt{\rho_s{}^2+(z+h)^2}}{2\sqrt{\alpha_s t}}\right]}{\sqrt{\rho_s{}^2+(z+h)^2}}\right\}dh \tag{2}$$

where z is the axis of the vertical direction, h is the integration variable of the finite line heat source.

2.1.2. Cylindrical source theory

2.1.2.1. Cylindrical source theory with a constant heat flux. Cylindrical source theory extends a line source to a cylindrical source with a constant radius. Since the analytical solution of the cylindrical source model has distinct physical meanings, and the cylindrical source theory is more accurate than the line source theory, the cylindrical source theory is more popular in application and plays as the foundation of the great majority of numerical simulation models.

In 1954, Ingersoll et al. [6] developed the analytical solution of the cylindrical source with a constant heat flux and the solution is described as:

$$\Delta T_g = T_w - T_g = \frac{q}{L}\frac{G(Fo,P)}{\lambda_s} \tag{3}$$

where q is the heat flux of the GHE, *W*; L is the borehole length, m; *Fo* is Fourier constant; P is the ratio between the distance from the borehole axis and the borehole radius; λ_s is the mean thermal conductivity of the ground, m^2/s. As defined by Carslaw et al. [7], the expression G (*Fo*, *p*) is only a function of time and distance from the borehole center.

2.1.2.2. Cylindrical source theory with varied heat fluxes. In actual operation, the heat extracted or released by the GHE varies as the operation conditions. Eq. (1) should be improved since it is derived on the base of the constant heat flux. Bernier [8] utilized the step heat flux to resolve the problem of the varied heat flux. Any load which changes with the time is regarded as the superposition of the thermal effect on the borehole caused by several piecewise linear step heat fluxes. Thus, the solution of temperature distribution is treated as the temperature response of an infinite medium caused by a series of step load with different heat fluxes.