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A comprehensive review on 2D and 3D models of vertical ground heat exchangers

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ABSTRACT

The ground source heat pumps (GSHPs) have been extensively applied to commercial and residential buildings owing to their high-energy efficiencies and low running costs. The key component of the GSHP is a ground heat exchanger (GHE). The state-of-the-art two-dimensional (2D) and three-dimensional (3D) heat transfer models for borehole heat exchanger (BHE) and energy pile (EP) systems are reviewed in this paper. The physical procedures of heat transfer and the derivation of energy conservation within different channels of BHE (e.g., U-, W-, helical-shaped or coaxial-shaped) are summarized, in addition to the primary merits and demerits of each model. The main influencing factors on 2D and 3D model solutions including axial heat transfer, friction heat, spacing shack, thermal resistance, thermal short-circuiting between the inlet-pipe and outlet-pipe, are analysed and compared. Furthermore, various applications of these 2D and 3D models are elaborated. Finally, the recommendations, standpoints and potential future research on BHE heat transfer model are highlighted. It is believed that the work presented will contribute to the record of information and experiences necessary to develop BHEs for GSHP systems.

1. Introduction

Air pollution, global warming and energy shortage have been great challenges since the last century. The carbon dioxide (CO_2) emission from fossil fuel is widely known as the largest contributor to global warming [1]. To ensure energy conservation, more attention has been paid on reducing CO_2 emissions through numerous ways [2–4]. The transformation from fossil fuel to sustainable energy sources has focused mostly on wind [5], solar [6], biomass [7], hydropower as well as geothermal energy [8,9]. In this context, the ground source heat pump (GSHP) has already become a prevalent option for heating, cooling and hot water source in residential and commercial buildings because of its high-energy efficiency which renders it to be applicable in many countries [10–16], with the annual increase of approximately 10–30% in 30 countries over the previous decade [12]. In general, GSHPs can be divided into two categories: closed-loop system which is based on the coupling with borehole heat exchangers (BHEs) and open-loop system that utilizes groundwater or surface water directly [17,18]. Different kinds of BHEs, for example horizontal and vertical loops, are used in the modern techniques [19–23]. The main merit of the GSHP systems over the traditional air-conditioning (A/C) systems is that they have higher Coefficients of Performance (COPs). This is because the soil region can be utilized as a heat source in heating season or as a heat sink in cooling season [24–26]. However, there are two main factors that hinder the popularity of GSHP application: land availability and initial cost. The land availability is the first issue which should be considered. The cost of installing a deep BHE and the risk of the system failure are high. Normally, the payback period varies in the range of 5–10 years, making it the key barrier for their exploration and dissemination in the current market [25]. It is reported that the GSHP systems provide the largest amount of applied and installed energy resources, accounting for about 55.30% of the annual energy utilization and about 70.95% of the global installed capacity respectively. A huge amount of GSHP installations took place in Europe, China and North America, increasing from 26 in 2000, to 33 in 2005, to 43 in 2010, and to 48 in 2015 [25]. Fig. 1 presents the annual energy application and installed capacity during the last period of 20 years.

The first known idea of utilizing the soil as a heat source for a heat pump system is presented in a Swiss patent issued in 1912 [26]. Interestingly, the first successful demonstration of a GSHP system is traced back to 1946 in the USA [27]. At that time, Ingersoll and Plass [28] developed a fundamental analytical model for heat conduction within the GSHP system, which served as a basis for some later GSHP designs. The next period of intense activity on GSHP development occurred in 1970s after the first oil crisis. For this period, the primary focus was to develop the vertical BHE because of its minimal land area

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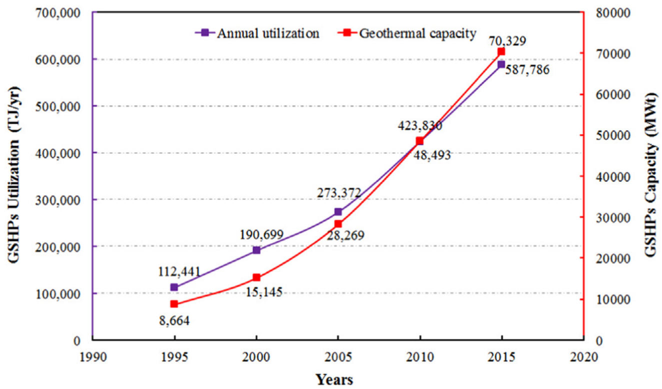

Fig. 1. The annual energy application and installed capacity of GSHP system between 1995 and 2015 [25].

needed for system installation. Twenty years after that, the BHE heat transfer theoretical models and installation standards were formulated [10,29–31]. In recent years, a relatively novel technology, known as energy pile (EP) which combines the pile foundation with heat exchanger to fulfil the building load requirements, has been developed [32]. In the EP system, the BHEs are embedded into a cast-in-place concrete pile with a steel frame [13,33–39].

Normally, BHEs are made of high density polyethylene pipes with around 30 mm diameter and a borehole with 150 mm diameter [40]. Various configurations involving single-, double-, triple U-tube [41], W-shaped tube [32], coaxial tube [42] and helical-shaped tube [43] are shown in Fig. 2. Some review studies about the BHEs have been done, but the majority concentrate on applications and system related work for example heat pump technologies [44], categories of BHEs and GSHP systems [45], integrated solutions [46], comparison of heating sources [47], in addition to the status of BHE applications in different regions and countries [48–50]. There are many approaches are utilized to analyse the heat transfer performance of the vertical BHE as reported in previous researches [51–61], in which it is indicated that the development of the BHE heat transfer models involving three stages. The first stage from the 1940's to 1960's focused on theoretical models. The second stage from the 1970's to 1980's concentrated on analytical models. The last stage targeted on numerical models which started with the advent of computers since the late 1980's [51]. More specifically, the line source model proposed by Ingersoll et al. [52] and the cylinder source model presented by Carslaw et al. [53] are two examples of the fundamental theoretical methods. They provide the rough approximations to the actual heat transfer processes in the BHE systems. Hart and Couvillion [54] proposed the far-field radius to simulate the soil temperature variation. IGSHPA [55] developed a soil thermal resistance model within a single BHE based on the line source approach, where the superposition principle is adopted to determine the effect of thermal interaction between the adjacent BHEs. Kavanaugh [56] improved the cylinder source model to analyse the uneven heat flow rate within a pipe. A g-function model, with a dimensionless temperature response factor, is another solution [57] that illustrates the response of a single BHE to a unit step heat pulse for estimating the long-term performance of GSHP. A duct storage model (DST) is correspondingly defined to predict the total temperature variation based on the spatial superposition method [58]. Meanwhile, the 2D finite differential equations are applied to determine the BHE heat transfer rate by using the thermal resistance network method [59]. Shonder and Beck [60] analysed the effective ground thermal conductivity by utilizing different soil equations based on the finite difference method (FDM) and the Crank-Nicolson scheme. Lee and Lam [61] developed a 3D implicit FDM in a rectangular coordinate system to depict the quasi-steady state heat transfer process within a BHE through an equivalent thermal circuit. Nowadays, the research is not only carried out on the traditional BHEs but also expanded to EP foundation BHEs. To compensate for the shallow depth of the EP, a helical coil type of BHE is widely used as it can increase the heat transfer [33]. Although several recent studies have covered the heat transfer computations like design method, penalty temperature [62], parameter estimation [63–65], traditional approaches and quasi-steady heat transfer [12,66,67], a review of the recent development on 2D and 3D models of the vertical BHE and EP

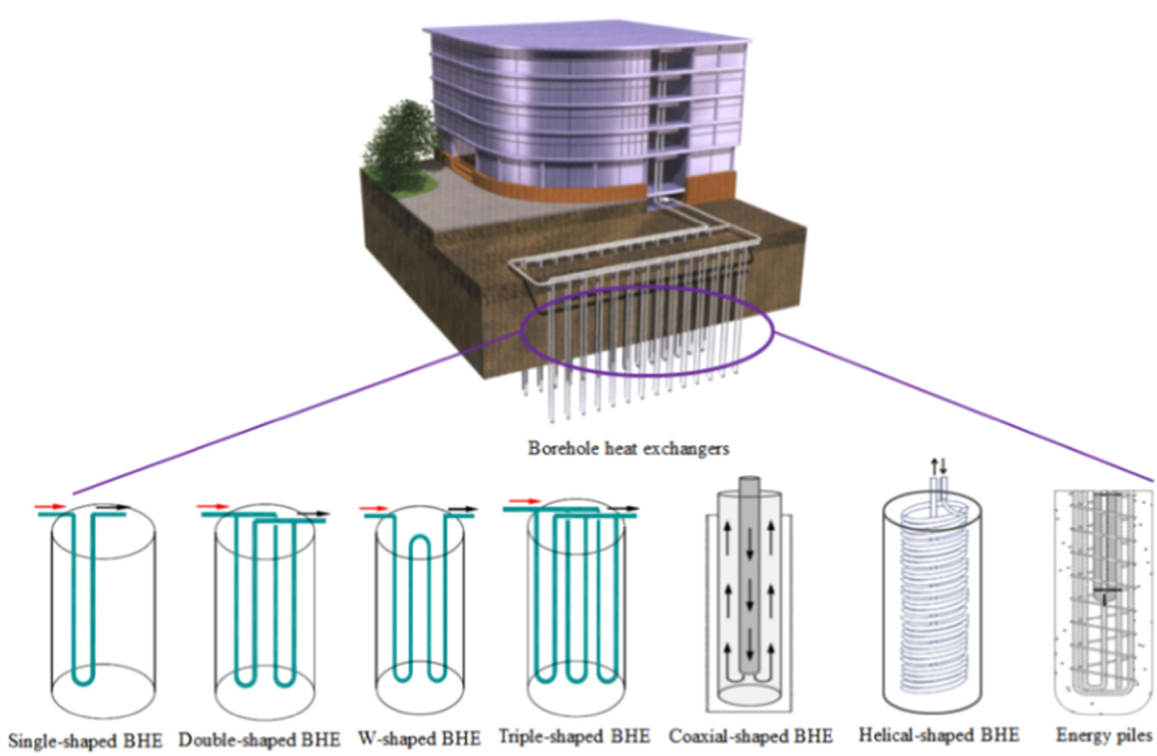

Fig. 2. The diagram of BHEs and EP investigated [32,42,43].