Applied Thermal Engineering 91 (2015) 370–376

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Simulation and prediction of conditions for effective development of shallow geothermal energy

Zujiang Luo [a,*], Yan Wang [a], Shiling Zhou [a], Xinhui Wu [b]

[a] Institute of Hydrogeology and Environment, Hohai University, 210098 Nanjing, China
[b] Institute for Computational and Mathematical Engineering, Stanford University, USA

HIGHLIGHTS

- Established a numerical model of the underground heat exchanger system.
- Took the groundwater seepage field and temperature field as the content of evaluation.
- The land subsidence was also be evaluated.
- Predicted the migration trend of groundwater seepage field and temperature field.
- Predicted the heat exchanger's influence on the groundwater environment.

ARTICLE INFO

Article history:
Received 8 December 2014
Accepted 12 August 2015
Available online 22 August 2015

Keywords:
Geothermal
Groundwater heat pump
Land subsidence
Seepage field
Temperature field

ABSTRACT

A geothermal heat exchanger system is mathematically quantified, and simulated and modeled to understand heat transfixion and strata deformation caused by groundwater exploitation via groundwater heat pump systems. This is done to determine the requirements and parameters governing the development of shallow geothermal energy in an efficient and safe manner. The model takes into account the groundwater seepage and temperature fields, as well as land subsidence. Using an example of a groundwater heat pump project in Nantong, China, and taking into account fixed conditions of borehole layout and operation of one pumping well with two recharge wells, the underground heat exchange system is simulated. The simulations vary the circulation ratio from 100% to 80%–60%, and the extent of heat transfixion and land subsidence development is predicted over 10 working periods, each being one year in duration. The results show that heat accumulation is alleviated with a decreasing circulation ratio, but land subsidence increases. Nevertheless, a circulation ratio of 60% is found to be ideal for sufficient alleviation of heat accumulation with only limited land subsidence.

1. Introduction

In recent years, with increasing urbanization and improvement in living standards, the energy consumption in buildings and dwellings (such as heating, air conditioning, water heating, cooking and other utilities), has become an increasingly large proportion of the total societal energy consumption. In China, this type of energy consumption accounted for 27.8% of the total energy usage in 2000 and of this, 50–70% was for construction heating and air conditioning [14]. Therefore, the ability to save energy in buildings and domestic dwellings can play an important role in the overall reduction of energy demand. With the development of heat pump technology, shallow geothermal energy has become noticed as a renewable, clean, and potentially vast energy source [7]. As of 2009, more than 1500 groundwater-based heat pumps have been engineered in China [22].

With the wide application of groundwater heat pump engineering, the conceptual and mathematical models for solving practical engineering problems have been established. These are based on one-dimensional groundwater seepage and heat transport coupling models [1,5,9], and a three-dimensional numerical model that considers heat convection, heat exchange, heat exchange losses, and aquifer anisotropy [6]. Three key difficulties have been identified with respect to the efficient working of groundwater heat pump systems, namely, “heat transfixion”, “heat accumulation” and “cold cave” [17]. To overcome these, detailed

* Corresponding author.
E-mail address: luozujiang@sina.com (Z. Luo).

http://dx.doi.org/10.1016/j.applthermaleng.2015.08.028
1359-4311/© 2015 Published by Elsevier Ltd.

study of groundwater seepage and heat transport theory is required, and this has been the subject of theoretical and experimental research in terms of defining a rational arrangement of wells (i.e., well spacing) [3,11,13,16], formulating different modes of pump and recharge [10,12,15,23], and the effects of temperature differentials and the quantity of circulating groundwater [4,12,24]. These studies provide significant input into decision making for the rational development and utilization of shallow geothermal energy. In these studies, groundwater seepage fields and temperature fields are calculated for the rational development and operation of the groundwater heat pump system.

In a groundwater heat pump system, the heating and cooling load is typically high, the quantity of groundwater pumping and recharge is large, and the duration of such processes can be protracted. Additionally, changes in the water head can easily result in variation of the effective stress of the aquifer, causing rock and/or soil deformation [20]. Heterogeneous deformation may have a negative impact on any nearby buildings or other infrastructure, and may also affect the efficient running of the heat pump system. In practice, with the limited choice of engineering sites, both pumping and recharge wells are usually placed close to service buildings and the adjustable borehole distance range is limited. Further, because of the capacity for groundwater recharge and different operational parameters, differing circulation ratios will have an effect on differences in the temperature field and any related land subsidence.

For the efficient and long-term working of a groundwater heat pump system, it is necessary to not only accurately calculate the transport of groundwater seepage and the temperature field, but also to analyze land subsidence induced by groundwater exploitation. To this aim, a groundwater heat pump project is used as an example. In the example, the well spacing and working load are kept constant, but circulation ratios of 100%, 80%, and 60% are tested. The underground heat exchange system is simulated and calculated to evaluate both the extent of heat transfixion and development of land subsidence. The results provide a quantitative basis for decision making with respect to operational parameters for efficient working of groundwater heat pump systems.

2. Simulation and mathematical model of heat exchange system

The simulation and mathematical model is composed of a groundwater seepage mathematical model, a heat transport mathematical model, a groundwater flow model and a one-dimensional Terzaghi soil deformation equation.

2.1. Governing equation of groundwater seepage

Based on the continuity principle and Darcy's law, the three-dimensional (3-D) unsteady flow equation for the porous media can be expressed, with coordinates in the principal permeability directions of the anisotropic porous media, as follows

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=\mu_s\frac{\partial h}{\partial t}\quad (x,y,z)\in\Omega, \tag{1}$$

where K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities in each of the principal directions of the anisotropic medium, h is the water head at point (x, y, z) at the instant t, W is the source and sink term, μ_s is the specific storage, and Ω is the computational domain.

2.2. Governing equation of heat transport

It is assumed that the thermodynamic equilibrium between groundwater and soil is instantaneous, which means both groundwater and soil have the same temperature, and the influence of natural convection caused by the different density of water due to the temperature difference is ignored. The expression of heat transport is thus shown as follows [18]:

$$\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right)-c_w\left[\frac{\partial(v_xT)}{\partial x}+\frac{\partial(v_yT)}{\partial y}+\frac{\partial(v_zT)}{\partial z}\right]+Q_c=c\frac{\partial T}{\partial t}\quad (x,y,z)\in\Omega \tag{2}$$

where λ_x, λ_y and λ_z are the thermodynamic dispersion coefficients in each direction, calculated from thermal conductivity of the soil, the seepage velocity of groundwater, and the longitudinal and transverse dispersivity of groundwater. The seepage velocity components are represented as v_x, v_y and v_z, T is the temperature of groundwater at point (x, y, z) at the instant t, c_w is the thermal capacity of water, and c is the thermal capacity of the soil. Q_c is the heat source and sink, calculated as $Q_c = c_wW(T_Q - T)$ where T_Q is the temperature of the source and sink.

2.3. Governing equation of groundwater flow

Groundwater flow is determined as follows (see eq. (1) for explanation of terms):

$$\vec{v} = -K_x\frac{\partial h}{\partial x} - K_y\frac{\partial h}{\partial y} - K_z\frac{\partial h}{\partial z}. \tag{3}$$

Eqs. (1) and (2) are coupled with eq. (3) (Xue et al., 2007), shown below, to calculate the temperature of each point at each calculation step as it varies with groundwater flow.

2.4. One-dimensional Terzaghi soil deformation equation

According to the Terzaghi effective stress principle, and on the basis of assuming soil deformation occurs only in the vertical plane and that total stress acting on the soil is invariable with time, the one-dimensional soil deformation equation is established as follows [21]:

$$\Delta b = -\Delta h S_{sk} b_0, \tag{4}$$

where b_0 is the initial thickness of the aquifer and S_{sk} is the skeletal storage as a function of soil physical parameters. At corresponding different stages of soil deformation, skeletal storage changes, and two different values are adopted [2] as shown:

$$S_{sk} = \begin{cases} S_{ske} & \Delta\sigma'_{zz} < \Delta\sigma'_{\max} \\ S_{skv} & \Delta\sigma'_{zz} < \Delta\sigma'_{\max} \end{cases}, \tag{5}$$

where S_{ske} is the skeletal elastic storage, S_{skv} is the skeletal inelastic storage, $\Delta\sigma'_{zz}$ is the variation in vertical effective stress equal to the variation in water head, and $\Delta\sigma'_{\max}$ is the pre-consolidation pressure calculated as the approximate elevation of the aquifer roof. According to the logarithmic relationship between void ratio and effective stress, the skeletal elastic storage and skeletal inelastic storage expression is shown as follows [8]:

$$\begin{cases} S_{ske} = \rho_w g\left[\dfrac{3(1-2\nu)}{2G(1+\nu)}\right] \\ S_{skv} = \dfrac{0.434C_c\rho_w}{p'(1+e_0)} \end{cases}, \tag{6}$$