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Multifactor analysis on beach well infiltration intake system for seawater source heat pump

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ABSTRACT

The seawater source heat pump (SWHP) is a renewable energy utilization system. The beach well infiltration intake system (BWIS) effectively improves the stability, reliability, and energy efficiency of SWHP systems in cold climate areas. BWIS research requires a multidisciplinary approach that involves both hydrogeology and heat transfer theory. There are many factors influencing the energy consumption and life-cycle costs of the systems, with each factor having many possible values. This paper aims to determine the degree of influence of ten representative factors of BWIS: specific heat capacity of rock-soil, rock-soil density, thermal conductivity of rock-soil, void fraction of rock-soil, rock-soil permeability, beach well radius, site length, site width, row number of beach wells, and column number of beach wells. In this paper, a BWIS seepage and heat transfer model is established. Based on the model, an orthogonal design optimization method is presented and analyses are conducted for heat pump unit energy consumption, seawater pump energy consumption, and economic cost for various conditions using MATLAB code. The results indicate that a greater number of beach wells is not always better and the number and placement of beach wells should be scientifically and objectively optimized by the orthogonal design method. The optimization method can scientifically guide engineering design for BWIS and offset the design deficiency that results from the current practice of only using a hydrogeological report of randomly selected test wells.

1. Introduction

A seawater source heat pump system (SWHP) is an energy-saving and environmentally-friendly technology for cooling and heating buildings; it has practical scientific and technological applications as well as providing energy-conservation related social benefits [1]. Building-based SWHP systems have been utilized in Europe for three decades, with countries such as Sweden and Norway using seawater as a district heating heat source since 1984 [2–4]. Since 1993, areas in Japan, including Fukuoka Seaside Momochi, Osaka Nanko Cosmosquare, and Sunport Takamatsu have also used seawater heat sources for district heating and cooling [5]. China has been using seawater as a heat source for district heating since early 2000, and SWHP has a large popularizing and utilizing value in cold areas [6–14]. For China, the lowest seawater temperature is approximately 0 °C, salinity is 30‰, and the freezing point is −1.7 °C. Seawater in the heat exchanger freezes under extreme weather conditions, which seizes up heat pump units. The beach well infiltration intake system (BWIS) effectively improves stability, reliability, and energy efficiency of SWHP systems in cold climate areas. BWIS is an integrated renewable energy system that integrates the use of seawater thermal energy and ground thermal energy.

Previous research has investigated seepage and heat transfer models for ground source heat pump systems [15–17] and groundwater source heat pump systems [18–20]. The primary difference between ground source heat pump systems and groundwater heat pump systems was that the ground source systems had the same velocity and direction in the seepage field. Due to the complex velocity field in the groundwater source heat pump system, the main research method was a numerical solution for the groundwater flow and temperature models. Due to the large-scale region, simulation time, multiple placement schemes for wells, and numerous BWIS influencing factors, this paper uses MATLAB to establish seepage and heat transfer models for regional-scale systems. The seepage model is analytically solved by the reflection method and the superposition principle, with the solution being a fast-solving method compared with the numerical solution. The analytical solution explicitly analyzes the qualitative and quantitative relationships among the influencing factors of the system.

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Nomenclature

h	water head (m)
K	permeability (m/s)
G	seepage flux per second (m^3/s)
r	radius in the cylindrical coordinate (m)
d	the distance between the well and the shoreline (m)
n	number of wells
t	temperature of the porous media (°C)
u	seepage velocity in x-direction (m/s)
v	seepage velocity in y-direction (m/s)
c	specific heat capacity (J/kg °C)
a	thermal diffusivity (m^2/s)
Q	heating load of the building (kW)
N	cumulative energy consumption (kWh)
L	pipeline length (m)
Time	cumulative time of heating season (h)
p	compression power of the heat pump unit (kW)

Greece symbols

μ	specific yield
ε	vertically supplementary and discharge intensity (m/s)
ρ	density of seepage fluid (kg/m^3)
λ	thermal conductivity (W/m °C)
γ	void fraction

Subscripts

eff	effective
s	solid
f	fluid
sh	shoreline
w	beach well
a	actual well
v	virtual well
unit	heat pump unit
water pump	seawater pump
system	system (consisted of heat pump unit and seawater pump)

Based on the solved seepage field, the heat transfer model is numerically solved.

Previous research also investigated the thermal performance of different systems. Numerical solutions for the fluid flow and heat transport equations quantified the effects of groundwater flow on the subsurface thermal regime [17]. Yuanzhi Xu et al. introduced a simulation that accommodated variable groundwater flow, mass, and temperature values for two different wells arrangement schemes [19]. The performance of the beach well infiltration intake system was numerically simulated. Simulations explored the effects of the beach well parameters and the system operation on water extraction temperatures [20]. Although various models and experiments for the heat pump system were simulated and tested, only a few studies systematically investigated the degree of influence of different factors on energy consumption and life-cycle costs of the systems. There are many factors influencing the energy consumption and life-cycle costs of the systems, with each factor having many possible values. As such, it is not feasible to experimentally evaluate the respective or combinational effects of every factor and corresponding value. However, it is feasible to sample a small but representative combination of variables for molding and testing. The orthogonal design method optimally investigates multifactor and multilevel cases; as such, it is suitable for the present work [21].

This paper aims to determine the degree of influence of ten representative factors of BWIS on system energy consumption and life-cycle costs: specific heat capacity of rock-soil, rock-soil density, thermal conductivity of rock-soil, void fraction of rock-soil, rock-soil permeability, beach well radius, site length, site width, row number of beach wells, and column number of beach wells. The optimization results can scientifically guide engineering designs for BWIS.

2. Seepage model

2.1. Assumptions

The seepage model is termed, 'unconfined aquifer' or 'confined aquifer' based on whether there is a water table. The following assumptions are applied to the model.

1. Seepage complies with Darcy's Law.
2. Seepage complies with the Dupuit assumption, the vertically supplementary and discharge intensity is negligible [22].
3. Aquifer is homogeneous and isotropic.
4. Seepage field is in steady state.
5. Beach well is completely penetrating.

2.2. Analytical model of unconfined aquifer

Based on mass conservation, the governing equation of an unconfined aquifer with a Cartesian coordinate can be written as:

$$\frac{\partial}{\partial x}\left(Kh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kh\frac{\partial h}{\partial y}\right)+\varepsilon=\mu\frac{\partial h}{\partial t} \tag{1}$$

where h is the depth or water head of the unconfined aquifer, m; μ is specific yield; ε is the vertically supplementary and discharge intensity, m/s; and K is permeability, m/s.

Given that the seepage field is irrotational, it can have a potential flow equation. The governing equation is simplified by the above assumptions and is formulated by the potential function.

$$\frac{\partial^2 \Phi}{\partial x^2}+\frac{\partial^2 \Phi}{\partial y^2}=0 \tag{2}$$

The potential function of an unconfined aquifer can be expressed as:

$$\Phi=\frac{1}{2}Kh^2+C \tag{3}$$

where C is a constant.

The potential flow function of a well in an unbounded aquifer (that can be used for both unconfined and confined aquifer) with a cylindrical coordinate can be written as:

$$\Phi=\frac{G}{2\pi}\ln r+C \tag{4}$$

where G is seepage flux per second, m^3/s, and r is radius of the cylindrical coordinate, m.

Using the reflection method and superposition principle, the potential flow function of the beach well can be obtained as:

$$\Phi=\frac{G}{2\pi}\ln\frac{r_a}{r_v}+C \tag{5}$$

where r_a is the distance between the actual well and a specified point, A, in the seepage field, m, and r_v is the distance between the virtual well and point A in the seepage field, m. Fig. 1 shows the positions of the actual and virtual wells.

For the boundary condition, the water head of the aquifer at the shoreline, h_{sh}, is 100 m and all points satisfy $r_a = r_v$.