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Research Paper

Analysis on thermal behavior of the type of filter tubes of extraction-injection wells in geothermal utilization

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HIGHLIGHTS

- Simulation results correspond well with experimental results.
- Simulation models for types of filter tubes of extraction-injection wells are set up.
- Comprehensive comparisons between the two types of filter tubes are conducted.
- The semi-circumference filter tube is superior under proper conditons.

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ABSTRACT

Groundwater heat pump (GWHP) has recently gained popularity because of its high efficiency, energy conservation, environment protection, etc. However, thermal breakthrough restricts its sustainable development. In order to delay and minimize thermal breakthrough, a new type of filter tube named as semi-circumference filter tube was proposed and numerical simulations followed. The reliability of the simulation has been validated. The extraction-injection well spacing and the degree of thermal imbalance were selected as the independent variable to study thermo-fluid difference between the semi-circumference filter tube and the traditional one. The pumping temperature evolution, the extent of thermal breakthrough and the energy loss resulting from thermal breakthrough were analyzed. Results show that the semi-circumference filter tube can delay the occurrence time of thermal breakthrough and decrease the energy loss. With a proper extraction-injection well spacing, the pumping temperature of the semi-circumference filter tube can almost keep a constant value, which is in favor of stable and long-term operation of the system.

1. Introduction

In recent years, geothermal heat pump (GHP) using underground thermal energy storage (UTES) has drawn great attention [1]. As a clean and unconventional heating/cooling technology for buildings, GHP possesses great advantages such as high thermal performance [2], energy conservation [3], environment protection [4]. It has been widely applied in many countries such as Asian countries [5,6], European countries [7] and America [8].

GHP is generally divided into ground coupled heat pump (GCHP), surface water heat pump (SWHP) and groundwater heat pump (GWHP) [9]. The groundwater extracted by an extraction well is re-injected into the same aquifer after heat exchange for GWHP, which achieves direct utilization of groundwater energy or cyclic utilization of seasonal thermal energy storage [10] and further improves the efficiency of geothermal energy utilization [11].

However, the recharge temperature has changed to interfere with the original temperature field leading to geothermal imbalance in the local aquifer [12]. In the meantime, the local thermal imbalance is constantly expanding. When it acts on the pumping area, the pumping temperature changes. The phenomenon is called thermal breakthrough [13,14]. Especially, the recharge heat or cold energy may overly accumulate in the aquifer due to the long-time operation of GWHPs in districts where thermal load is out-of-balance. As a consequence, it shortens the service life of the system and lowers operational efficiency of the unit [15,16].

Consequently, how to delay and minimize thermal breakthrough is an urgent problem to solve for the utilization of aquifer thermal energy storage (ATES) [17], and it is the point to study in this paper. To solve the problem as much as possible, a

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Nomenclature

C	heat capacity, J/(m^3·K)
C_W	heat capacity of water, J/(m^3·K)
V	seepage velocity of groundwater, m/s
H	aquifer water head, m
W	quantity of pumping water per unit volume, 1/s
K	permeability coefficient of aquifer, m/s
s	elastic storage coefficient, 1/m
T	aquifer temperature, K
T_0	initial aquifer temperature, K
T_{TI}	thermo-interaction temperature, K
T_{pi}	average pumping temperature, K
ΔT_W	temperature difference in winter, K
ΔT_S	temperature difference in summer, K
Q	quantity of heat loss, kJ
L	extraction-injection well spacing, m
q_{vw}	volume rate of flow for single well in winter, m^3/h
q_{vs}	volume rate of flow for single well in summer, m^3/h
d	day
y	year
τ	time, s
λ	thermal diffusion coefficient of aquifer porous skeleton, W/(m·K)
Γ	Boundary of computational domain
Ω	computational domain
ξ	degree of thermal imbalance
σ	density, kg/m^3

comprehensive understanding of the mechanism of heat transfer of the porous system in the aquifer is especially important [18]. The fact is that it is hard to get dynamic changes of the temperature field in a practical site because of complex geological and hydrological conditions, while the numerical calculation provides a feasible solution [19].

Numerical models of 2-D for groundwater systems for different well locations and arrangement modes were developed by Gao et al. [20] to obtain a comparison of the energy efficiency. Results showed that variations of the pumping temperature were related to well arrangements and the row arrangement of well groups could be better. Nam and Ooka [19] built a 3-D numerical heat-water transfer simulation model based on a real-scale equipment and simulation results were compared with the experimental results. It was confirmed that the condition of groundwater flow and the position of wells for designing a GWHP system should be taken into account. Considering double-well intervals and cooling-load design fluctuations in summer, Zhou and Zhou [21] established a convection-dispersion model for the thermal transport in aquifers and modeled the thermal transport processes in an unconfined aquifer of a GWHP system. Results revealed that the thermal transport in aquifers was closely related to the distance between the extraction and injection well and the cooling-load design fluctuations, especially to the volume of the cycling water.

In order to show the magnitude of thermal affected zone, Somogyi et al. [22] modeled the effects of GHP systems installed to shallow geothermal reservoirs in sedimentary formation based on the results of a real system. If two neighboring open-loop systems are installed on the same reservoir, the minimum distance between wells should be 55 m. Studies by Galgaro and Cultrera [13] revealed the risk of the thermal breakthrough between well doublets and suggested that there were several possible heating/cooling daily timetables that reduced the risk of thermal feedback between the extraction well and the injection well. Without a doubt, these works have offered a good platform for better use of GWHP and ATES.

In addition, many other attempts such as the hybrid geothermal heat pump have been done to reduce the underground heat stack due to the single underground heat source. Researches by Dai et al. [23] and Ozgener and Hepbasli [24] concluded that solar-assisted GHP could in part improve the operation performance of the hybrid system. Yang et al. [25] studied the hybrid GHP assisted with the cooling tower. It indicated that intermittent running mode of the system effectively reduced heat accumulation in the aquifer and enhanced the ability of geothermal recovery.

Although large quantities of studies on GWHP and ATES have been conducted, reports that concern the re-injection temperature influencing the extraction temperature are scarce. Moreover, previous studies mainly focus on the traditional filter tube whose surface is perforated with even holes, while reports on the change of types of filter tubes are rare. In fact, under the condition of constant physical parameters such as the inter-well distance, arrangement pattern of wells and specific heat of aquifers, if we can lengthen the distance of the recharge water flowing to the pumping region in the aquifer, the recharge water will have more time to exchange heat deeply with the aquifer. Finally, influences of the recharge water on the temperature filed in the pumping area are weakened. And it is what we best hope for.

Based on above considerations, a new type of filter tube named as semi-circumference filter tube (SCFT) has been proposed in the paper and numerical calculations follow. Comparisons and analyses between the semi-circumference filter tube and the traditional filter tube have been conducted. In addition, a test rig of geothermal exchange has been set up to validate the simulations.

2. Numerical simulations of groundwater seepage and heat transfer

Transient heat transfer in the underground aquifer has been modeled. Scientific managements may be provided for the practical project by means of the study on the coupling of underground seepage field and temperature field.

2.1. Assumptions

The groundwater flow and heat transfer are a complex process that integrates the buildings thermal load with the performance of a heat pump. The numerical model has been developed taking into account the following assumptions:

- The soil is regarded as a rigid porous medium. The process of heat transfer accords with Fourier's law.
- Pores of the porous medium are uniform and the porosity is constant.
- Parameters of fluid and medium such as density and specific heat keep constant.
- The groundwater flow fits with Darcy law and the quantity of groundwater is sufficient.
- The groundwater flow is just along the horizontal direction.
- The effects of thermal expansion and thermal dissipation due to viscosity are ignored.