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Numerical simulation of the thermal interaction between pumping and injecting well groups

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HIGHLIGHTS

► An analysis method for the arrangement of pumping/injecting well groups is provided.
► Four typical modes are studied to determine the thermal interaction influence.
► Results show that the row arrangement of well groups may be a better choice.
► Results from numerical model are reasonably consistent with experimental data.

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ABSTRACT

In the thermal energy utilization of a closed loop groundwater system of a groundwater source heat pump (GWHP) and an aquifer thermal energy storage (ATES), thermal breakthrough always occurs. This problem causes a gradual variation in the temperature of the pumping water and impacts the efficiency of the GWHP. In particular, a large scale GWHP system requires many wells; thus, the well location and arrangement become a considerable technological challenge. The aim of this study is to develop a numerical model for groundwater systems to obtain a fair comparison of the energy efficiency between different well locations and arrangement modes. In this study, four typical modes are studied to determine the thermal interaction influences, and the numerical model was verified with test data by using an artificial rock/soil test system. The comparisons show good agreement between the numerical date and the measured data. It is shown that the temperature variation is related to the well arrangement mode, and the row arrangement of well groups may be a better choice. Therefore, a suitable spacing well pattern in the limited area is helpful and can potentially decrease the intensity of the thermal interaction and resist the occurrence of thermal breakthrough.

1. Introduction

A groundwater heat pump (GWHP) is one type of underground source heat pump (GSHP) and is a major form of earth energy utilization, which can realize the direct use of groundwater energy or the reuse of stored underground energy. Energy storage relies on the aquifer body, which is often called aquifer thermal energy storage (ATES) [1]. In recent years, GWHP has been widely used in China because of its higher energy density, faster transport and lower cost than the soil/rock GSHP (S/R-GSHP) and the soil/rock underground thermal energy storage (S/R-UTES) or borehole thermal energy storage (BTES). In China, technical regulation and policy require GWHP systems to ensure the closed-loop circulation of groundwater; thus, the water pumped must be recharged into the injecting well for the protection and conservation of groundwater resources. In particular, the excessive use of groundwater is controversial, and failing to recharge is not allowed. The recharge of a GWHP system not only relates to groundwater resource security but also involves real-time ground temperature variation due to thermal breakthrough, which is similar to the thermal response and the impact of the fluid leaving temperature in the borefield of a ground heat exchanger [2]. Bodvarsson early defined the concept of thermal breakthrough in geothermal utilization and introduced a study in which the problem of cold water injection into a fractured geothermal reservoir was considered. During injection, the cold water will advance along the fractures, gradually extracting

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Nomenclature

C	heat capacity of porous medium, J/(m^3 °C)
H	aquifer water head, m
s	elastic storage coefficient, 1/m
V	seepage velocity of groundwater, m/s
τ	experience time of heat transfer, s
C_w	heat capacity of water respectively, J/(m^3 °C)
K	permeability coefficient of aquifer, m/s
W	quantity of pumping water per unit volume, 1/s
T_0	initial aquifer temperature, °C
Ω	computational domain
Γ	boundary of computational domain
T	aquifer temperature, °C
λ	thermal diffusion coefficient of aquifer porous skeleton, W/(m °C)

Subscripts

o	outlet
i	inlet
oM	mean outlet temperature
iM	mean inlet temperature

heat from the adjacent rock matrix and eventually arriving at the pumping wells. If the injected water has not been fully heated by then, detrimental effects on energy production may result due to decreasing fluid enthalpies. Thus, it is necessary to establish criteria for designing an injection/production scheme for the closed loop thermal application of groundwater [3].

Thermal breakthrough means that the outlet temperature of the pumping water changes with the inlet temperature of the injecting well due to water mingling and causing heat conduction from the wells. Indeed, when a significant proportion of the pumping water must be returned to the aquifer to maintain the groundwater level, the thermal interaction influence after thermal breakthrough results in a gradual attenuation of the efficiency of the GWHP [4]. R Law et al. noted that if the ground system is to function correctly, the temperature of the pumping water must not be altered significantly by early thermal breakthrough of the injection water. Groundwater flow within the underground area is predominantly through fractures, which provide the primary route by which thermal breakthrough may occur. The nature of the underground structure and its impact on the thermal transport beneath a proposed site must be understood to indicate with confidence that the ground energy system will function effectively. In particular, the thermal breakthrough and the sequential thermal interaction result from the groundwater movement, such as natural advection, the flow of the water level between pumping and injecting wells, and underground heat conduction. Thus, the thermal extraction progress in the closed circulation of groundwater has a possibility of thermal breakthrough. Therefore, to exploit groundwater resources for energy, designers must be scientific, rational and efficient.

Theoretical study on underground aquifer energy utilization was conducted worldwide in the 1970s. An early work on the temperature variation due to groundwater injection was reported by C.F. Tsang et al. of the University of California in 1981. These researchers created a numerical simulation and established the numerical model on a seasonal ATES experiment in 1976. The simulated temperature variation and energy recovery factors agree very well with the field test data [5]. Since then, designers and engineers have begun to pay attention to the temperature variation and the impact of groundwater injection. A multidimensional, finite-difference model for groundwater flow and heat transport has been used to analyze the thermal energy storage experiment, and the numerical model includes the effects of hydraulic anisotropy, thermal convection and conduction, and heat loss to the adjacent confining strata [6]. In practice, Epstein et al. monitored and analyzed the GSHP installation at Stockton College, in which the geothermal well field commenced operations in 1994. However, it soon became apparent that the college was air conditioning far more than it was heating. More heat was being added to the ground than was being removed. Temperatures within the Stockton College geothermal well field have risen by as much as 11 °C since the start of operation in 1994. Thus, more heat is stored within the field during the air conditioning season than is removed during the heating season. Consequently, ground temperatures slowly rose as time passed [7,8]. The purpose of their study was to document the rise in ground temperature over the last ten years and to illustrate the need to pay more attention to the thermal interactions of well fields. They also noted one possible technique in which groundwater flow in the upper and lower aquifers can function as a “stiff breeze”, drawing cooler groundwater into the well field while advecting heat accumulated during its operation downflow.

A workshop on well construction for enhanced geothermal systems (EGS) was held in Houston, Texas in October, 2007 [9]. The intent was to motivate a facilitated discussion on technology gaps related to well construction, and the work was focused on identifying technology gaps associated with the design and construction of wells and well fields for efficiently exploiting EGS resources. In recent years, work has not been limited only to the geothermal field, as common groundwater energy utilization has attracted more attention, making it a hot subject in the international academy. In Japan, Y Nam et al., Tokyo University, conducted a numerical simulation of ground heat and water transfer for a GWHP system based on a real-scale experiment with a pattern of double wells for pumping and injecting [10]. This research has included heating and cooling experiments with real-scale equipment and numerical simulations using 3D ground heat and groundwater transfer simulation tools. The results confirmed that the condition of the groundwater flow and the position of a well should be taken into account in the design of a GWHP system. Finally, it was demonstrated that, in the future, studies on the optimum design method for GWHP systems should be conducted by utilizing simulations. Y Fujimitsu et al. at Kyushu University monitored the underground temperature and groundwater level in some observation wells around the heat exchanging well for a GCHP system on the premises of an experimental house in Fukuoka city and performed a numerical simulation of the underground temperature change with a computer program to evaluate the subsurface thermal environmental changes caused by heat exchange with the ground [11]. To determine the optimum system for the GWHP system, field case studies of wells under several conditions should be conducted, such as natural groundwater advection velocity, the difference of the water temperature between pumping and injection, the heating and cooling of HVAC, the combination of GWHP and ATES etc.

K Woods et al., researchers at Villanova University, carried out a comprehensive analysis of the thermal response of a line of evenly spaced wells, and a numerical model was developed and its validity verified by the experiment [12]. Using the analytical model, the temperature response of the well in a line, a standing column well, was compared to that of an isolated well, showing the degradation in well performance with time. Meanwhile, knowledge of the time to thermal breakthrough associated with these injection fluids is required for optimal management. For this problem, American Idaho National Laboratory, Lawrence Berkeley National