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Research Paper

Numerical investigations on thermal performance between the traditional full-filter well and improved semi-filter well in moderate climates

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HIGHLIGHTS

- Effectiveness of the simulation has been validated.
- An improved semi-filter well has been proposed.
- Effects of various factors on thermal flow characteristics are investigated.
- The semi-filter well can better decrease thermal breakthrough and energy loss.

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ABSTRACT

The operating efficiency of groundwater heat pump (GWHP) gets reduced because of thermal breakthrough. In order to explore an effective approach to minimize thermal breakthrough, an improved semi-filter well (SFW) that is different from the traditional full-filter well (FFW) has been proposed to achieve active control over the direction of groundwater advection. Based on the numerical simulation method, this paper has first analyzed the thermal flow differences between FFW and SFW in terms of heating/cooling load, flow rate and extraction-injection temperature difference. The results show that SFW can better govern the fluctuation in the pumping temperature and decrease thermal breakthrough, while as to FFW, thermal breakthrough tends to deteriorate and energy loss is about 195% higher compared with SFW. Subsequently, the simulation results of the allocation of the extraction-injection well types indicate that changing the extraction well type can enhance the influence on thermal flow. As long as the extraction well is SFW, thermal breakthrough and energy loss can be decreased. In addition, the simulation results were validated and the maximum relative error was less than 6%.

1. Introduction

The increasing concern for efficient energy-saving applications in buildings has led to the utilization of innovative techniques to meet heating and cooling demands [1,2]. The usage of shallow geothermal energy to achieve a reduction in fuel consumption has come into notice [2]. The shallow ground is a large solar collector as well as a huge dynamic energy balance system. It naturally preserves the relative balance of energy absorption and release and is an ideal heat/cold source of the geothermal heat pump (GHP) [3]. As a new and clean technology for building heating and cooling, GHP occupies great advantages such as high operational performance [4], energy conservation [5] and environmental protection [6]. Thus it has been universally accepted [7]. In many countries the annual rate of growth is over 25–60% [8].

As one type of GHPs [9], the groundwater heat pump (GWHP) possesses higher operating efficiency because it directly takes the groundwater, whose specific heat is higher than the soil, as the low-temperature heat source [10]. Undeniably, the development of GWHP is confronting numerous challenges, such as the design of well frame parameters, exploration on heat transfer mechanism in aquifers, the damage of thermal breakthrough. In the running process of GWHP, the local aquifer temperature is out-of-balance because the extracted groundwater deviates from the initial aquifer temperature after heat exchange and is re-injected into the same aquifer [11]. The self-recovery of groundwater temperature is just an extremely slow course. With the system working continuously,

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Nomenclature

C	thermal capacity of the porous medium, J/(m^3·K)
C_W	thermal capacity of water, J/(m^3·K)
V	seepage velocity vector of aquifer, m/s
H	aquifer water head, m
H_0	initial aquifer water head, m
W	quantity of pumping water per unit volume, m^3/s
K	permeability coefficient of aquifer, m/s
s	elastic storage coefficient, 1/m
n	normal direction;
T	aquifer temperature, K
T_0	initial aquifer temperature, K
T_p	pumping temperature, K
ΔT_W	extraction-injection temperature difference in winter, K
ΔT_S	extraction-injection temperature difference in summer, K
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
q_v	volume rate, m^3/s
Q	Heating/cooling load, kW; energy loss, kW
ρ	density, kg/m^3
λ	thermodynamic dispersion of the porous medium, W/(m· K)
Γ	boundary of computational domain
Ω	computational domain
τ	time, s
RMSE	root mean square error
GHP	geothermal heat pump
GWHP	groundwater heat pump
FFW	full-filter well
SFW	semi-filter well

thermally affected zone in aquifers is gradually expanding. Finally the temperature distribution in the pumping zone is redistributed to lead to a change of the pumping temperature. With that, thermal breakthrough occurs [12]. Thermal breakthrough is a critical factor that determines the unit efficiency [13]. Researches by Mehrpooya et al. [14] showed that long-term operation of the unit induced redundant thermal accumulation in aquifers and severe thermal breakthrough occurred, cutting down the system's service life and operational efficiency.

Increasing studies in recent years have been done to improve the unit efficiency. Xiao et al. [15] proposed to place the cool water supply wells upstream of the warm water storage wells to reduce the hydraulic gradient and weaken the energy loss due to advection. The extraction-injection well spacing has been regarded as one important factor influencing thermal breakthrough, which was demonstrated by Somogyi et al. [16]. Researches by Yapparova et al. [17] pointed out that the efficiency of energy storage increased with the increase of the well spacing. It is important to note that increasing the well spacing means a wider field. However, the available space is usually limited. Therefore, some other attempts have been made. Gao et al. [18] investigated four different well locations and arrangement modes. The results showed that the pumping temperature variation was related to well arrangement modes and the row arrangement of well groups could be better. Zheng et al. [19–20] inspected the efficiency of the helical coil heat exchanger by means of experiments and simulations and found that the helical coil heat exchanger had a better economic value. Jiang et al. [21] proposed a novel underground well pattern system, the most important feature of which was the whole closed circulation inside the well bores. Results showed that the system with CO_2 as the working fluid had better performance.

Moreover, hybrid GHPs have also been attached to great importance since GHP with single heat source brings about hot/cold stack. Emmi et al. [22] and Ghaebi et al. [23] demonstrated that the solar assisted GHP could effectively raise the system's operating performance. Fan et al. [24] suggested that the cooling tower assisted GHP could lower geothermal accumulation and lift the operational efficiency. Yang et al. [25] found that intermittent operation of cooling-assisted GHP could reduce the degree of thermal accumulation and increase the rate of geothermal recovery. These researches have doubtless afforded a better platform for further investigation on the geothermal energy utilization.

At present, the investigations on GWHP mainly concentrate on aboveground parts, which are embodied in the combined application of a heat pump with auxiliary equipment such as solar thermal collector or cooling tower. Few researches are focused on thermal interaction in aquifers and thermal breakthrough under the condition of long-term operation of the system. As for the groundwater wells, numerous literatures place emphasis on the well spacing, the well arrangement etc. And the extraction-injection well is the traditional full-filter well (FFW). The paper has improved the traditional FFW and proposed a novel semi-filter well (SFW) to achieve active control over the direction of groundwater advection, which aims at reducing the influence of recharge water on the pumping temperature to realize stable and long-term operation of the system. Considering the heating/cooling load, the match of flow rate and extraction-injection temperature difference, and the allocation of the extraction-injection well type, simulation studies on FFW and SFW have been conducted to search for an effective way to decrease thermal breakthrough.

2. Numerical calculation

Thermal interaction in aquifers resulting from groundwater flow and heat transfer determines the evolution of aquifer temperature distribution, further acting on thermal breakthrough and system efficiency. Numerical simulations can be used to model different operational conditions in advance, thus extending limitations of practical experiments and helping designers make a scientific decision. Based on the commercial code Fluent that is worldwide recognized in the fields of hydrology, geology and geotechnical engineering, the paper has investigated the transient heat transfer in the extraction-injection well domain.

2.1. Assumptions

The groundwater flow and heat transfer are a complicated process that integrates the performance of a heat pump with the building thermal load. In order to lighten computational efforts, model assumptions reduce to: The soil is viewed as a homogeneous, isotropic porous medium; Thermal properties of the groundwater well and the porous medium remain constant within the investigated temperature range; Thermal physical parameters of the soil and groundwater are constant and the initial aquifer temperature is uniform; The porosity of the porous medium does not change; Thermodynamic equilibrium between groundwater and porous skeleton is done instantly; The natural flow of groundwater is ignored; Heat transfer in aquifers only occurs in the horizontal direction; The effects of thermal expansion and thermal dissipation are neglected.