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Research papers

Experimental investigation of the thermal dispersion coefficient under forced groundwater flow for designing an optimal groundwater heat pump (GWHP) system

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ABSTRACT

Mechanical thermal dispersion has often been neglected or underestimated in the simulation of heat transport in porous media, e.g., by using zero or the default value in simulators, or by using the scaling law for solute dispersivity as a thermal dispersivity value. However, large amounts of water usually injected in groundwater heat pump (GWHP) systems may increase the groundwater flow velocity much faster than natural flow and thus change the importance of mechanical dispersion in heat transport. In this study, to investigate the effects of water injection on the flow field, thermal dispersion coefficient, and associated heat transport process, a laboratory experiment using two different heat sources as tracers was performed at various background flow velocities ($Re < 0.52$). The analysis results from analytical and numerical models indicate that injected water increases both flow velocities and thermal dispersion coefficients, especially near the injection well, and thus makes the effect of mechanical dispersion on heat transport very important even at low background flow velocity. This result was also found in the field-based modeling results, but the radius of hydraulic and thermal effects was larger. In particular, thermal dispersivity on a field scale is known to increase depending on the scale of measurement and the degree of aquifer heterogeneity. Therefore, to ensure the efficiency and sustainability in field applications such as GWHP systems, it is necessary to evaluate site-specific thermal dispersivity through field experiments.

1. Introduction

The Ground Source Heat Pump (GSHP) system is a space heating and cooling system that uses ground or groundwater as a heat source in the winter and a heat sink in the summer because the temperature a few meters below the ground surface remains relatively constant throughout the year. As it has a higher efficiency than conventional heating and cooling systems, it can contribute to reducing CO_2 emissions and saving energy costs (Michopoulos et al., 2007; Ozlu et al., 2012; Park et al., 2013). Such benefits, as well as governmental supports, have promoted the use of the GSHP system in South Korea (Lee, 2009; Kwon et al., 2012).

In general, GSHP systems are classified into closed-loop and open-loop systems. The Groundwater Heat Pump (GWHP) system is an open-loop GSHP system that draws groundwater from one well with relatively stable temperatures throughout the year, exchanges heat energy with the water, and discharges it through another well. For large-size heating and cooling plants, the GWHP systems are more economical and require a smaller installation area compared to closed-loop GSHP systems. However, due to direct use of groundwater, their efficiency has a complex dependence on hydrogeological and thermal properties of the aquifer, which makes it difficult to design an efficient and stable GWHP system (Nam and Ooka, 2010; Casasso and Sethi, 2015; Park et al., 2015a, 2015b).

Although a few studies have recently been conducted to investigate the factors that significantly affect the performance of GWHP systems to design efficient systems, most of them have focused on groundwater flow conditions (e.g., flow direction and velocity) and well placement (Nam and Ooka, 2010; Lo Russo et al., 2011; Gao et al., 2013; Zhou et al., 2013). Moreover, unlike the solute dispersivity estimated by a solute tracer test, the thermal dispersivity has often been neglected or underestimated in applications by using solute dispersivity values or default values of numerical models without any field-based evaluation.

However, some studies performed in the field of shallow-depth geothermal applications have reported the influence of thermal dispersion on the relevant heat transport process. For example, Sauty et al. (1982) analyzed the experiments on aquifer thermal energy storage (ATES) with mathematical models and found that the thermal

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dispersion plays an important role in estimating the energy recovery ratio. Their findings were also observed in the numerical studies on ATES experiments (Dwyer and Eckstein, 1987; Xue et al., 1990). Lo Russo and Civita (2009) and Park et al. (2015a) reported in their research on GWHP systems that the evolution of a thermal plume from the injection well towards the pumping well, which may degrade system performance, can depend considerably on thermal properties, especially thermal dispersivity. Most recently, Alcaraz et al. (2016) used a GIS-based methodology to estimate shallow geothermal resources at a regional scale. Analysis results for the geothermal potential and the associated environmental impacts indicate that considering dispersion effects is significant for obtaining reliable results. Therefore, investigation of the importance of the thermal dispersion on heat transport is needed.

For the last few decades, laboratory experiments have been conducted to investigate thermal dispersion behavior in porous media under natural groundwater flow conditions (Green et al., 1964; Levec and Carbonell, 1985; Metzger et al., 2004; Rau et al., 2012a, 2014). The experimental results indicated that the thermal dispersion increases with flow velocities, but there was a controversy over the relationship between them. One group of researchers suggested a linear relationship (Yagi et al., 1960; de Marsily, 1986; Anderson, 2005; Vandenbohede et al., 2009), while others proposed various nonlinear forms to describe the relationship (Green et al., 1964; Metzger et al., 2004; Lu et al., 2009; Rau et al., 2012a). Green et al. (1964) first suggested a power law relationship, which was verified later by Metzger et al. (2004) with the same coefficients, and by Lu et al. (2009) with different coefficients. Such disagreements were clarified by Rau et al. (2012a), who showed that the thermal dispersion can be described by a square law, and the importance within natural groundwater flow velocities ($Re < 2.5$).

On the field scale, thermal dispersion is known to occur due to the heterogeneity of aquifer properties (Sauty et al., 1982; de Marsily, 1986; Ferguson, 2007; Hidalgo et al., 2009). This can be the reason why the macroscopic thermal dispersivity has a wide range of values in the literature (see Stauffer et al., 2013). Sauty et al. (1982) inferred from the experimental results that the macrodispersivity increases with the travel distance and stabilizes after reaching a certain scale of heterogeneity. Their findings correspond with the recent studies on the scaling behavior of macrodispersivity, indicating that the macrodispersivity increases with travel distance to their asymptotic values (Chang and Yeh, 2012; Zech et al., 2015). Therefore, the thermal dispersivity on the field scale can be higher by several orders of magnitude than on the laboratory scale.

In addition to the heterogeneity of aquifer properties, pumping and injection in field applications can further increase the magnitude of thermal dispersion. Because the GWHP system generally utilizes large volume of groundwater as a heat source (or heat sink), it can greatly disturb the natural flow field. Under such conditions, the influence of the thermal dispersion on the relevant transport processes can be increased. However, most studies on thermal dispersion have focused on the natural groundwater flow conditions (Green et al., 1964; Levec and Carbonell, 1985; Metzger et al., 2004; Rau et al., 2012a, 2014). In a few studies, water injection at different temperatures was conducted; however, there was too high a contrast in temperature to neglect the change in density and viscosity of water (see Kim et al., 2005; Saeid et al., 2014).

In this study, we designed a laboratory experimental system to investigate the thermal dispersion behavior in forced flow by water injection. Heat tracer tests using two different heat sources were performed with various background flow conditions. First of all, tracer tests using a resistor as a heat source were conducted with/without background flow and analyzed by analytical models to evaluate the thermal properties of a saturated porous medium. Then, using injected water as a heat source, tracer tests were performed under the same flow conditions as the resistor test and analyzed by a numerical model to examine the effect of injected water on the flow fields, thermal dispersion coefficients, and relevant heat transport processes. This paper also analyzes the impacts of injection on a macroscale through a field-based model and discusses their meanings in field applications.

2. Materials and methods

2.1. Laboratory experiments

2.1.1. Overall design of the experimental system

The experimental system was designed to carry out heat tracer tests in a saturated porous medium with/without artificial water injection. The core of the experimental device consists of a rectangular sand tank made of acrylic glass. The external dimension of the sand tank is $1.3\,\text{m} \times 0.6\,\text{m} \times 0.8\,\text{m}$ ($L \times W \times H$), and the thickness of the wall is 1.5 cm. The size was determined by simulating laboratory-scale experiments through a numerical model to roughly estimate thermal plume propagation. The tank is supported by a manually assembled aluminum frame enclosing the tank. There are three divided chambers in the tank: a 1 m long chamber in the middle filled with coarse sand, and two 0.12 m long chambers on both sides, which are used as constant hydraulic head tanks containing different levels of water. These chambers are partitioned by 1.5 cm thick acrylic glass plates with a large number of holes so that water in the higher constant-head tank can flow through the sand and create a uniform flow toward the lower head tank. A fine wire mesh is attached to the plates inside the middle chamber to prevent sand particles from entering the constant-head tanks through the small holes.

An acrylic pipe with an inner diameter of 14 mm and a length of 0.7 m served as an injection well. At a height of 0.29–0.31 m, a slot was drilled through a 0.02 m long section of the pipe to simulate a partially screened well and to spread the injected water radially from the injection point. The screen section of the well was then wrapped with nylon mesh to avoid possible infiltration of sand grains and clogging issues. As shown in Fig. 1, the well pipe is located 0.35 m apart from the higher constant-head tank on the centerline of the middle chamber. The sand tank is equipped with a temperature measurement system both inside and outside. In addition, water inlet/outlet tanks supply water to the constant-head tanks and control the water levels, and a thermostatic water barrel linked to a peristaltic pump controls the warm water injection (Fig. 1). These devices together make up the complete laboratory experimental system. A detailed description is included in the following sections.

2.1.2. Heat sources and sensor equipment

There are two types of heat sources. One is a small resistor acting as a point heat source, and the other is warm water passing through the well screen, disturbing the background flow field. A small wire-wound resistor (7 mm in diameter, resistance of 47 Ω, and power rating of 5 W) was wrapped with Teflon tape for waterproofing and mounted on the acrylic tube at a height of 30 cm. The laboratory DC power supply (AC input: 220 V, DC output: 0–30 V) applied a constant voltage to the resistor so that the resistor could act as a continuous heat source.

In a heat tracer test under forced flow conditions, warm water in the thermostatic barrel was transferred by PVC tubing installed on a peristaltic pump (GILSON), injected at a height of 30 cm into the injection well screen. The heat flow rate (Q_h) from the injected water was determined using Q_h [W] = Q_w [ml/s] × $\rho_w c_w$ [J ml^{-1} K^{-1}] × ΔT [K]. Prior to the heat tracer test, a pretest was performed to determine the injection rate (Q_w) and temperature increment (ΔT). In the peristaltic pump, the pumping/injection rate depends on the RPM of the pump. When the RPM of the pump is low, the pumping/injection become discontinuous. We changed the RPM of the pump and examined if pumping is continuous, and then we chose three RPMs (12, 18, and 24) for the injection tests. The temperature difference between the injected water and the background water was determined to be maintained within 5 °C to prevent free convection (see Ma and Zheng, 2010; Leaf