The effect of particle size on thermal and solute dispersion in saturated porous media

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ABSTRACT

Thermal dispersion, caused by fluid velocity and temperature fluctuations in the pore space and the effects of hydrodynamic mixing on the temperature field, controls convective heat transport in saturated porous media. While the thermal dispersion coefficient, a governing parameter in the thermal equilibrium model (TEM), has been investigated for natural systems, the dependence of the thermal dispersion coefficient on particle size remains undetermined. Previous research found that the relationship between the thermal dispersion coefficient and flow velocity follows a power law and that there may be a temperature difference between the solid and fluid phase (thermal non-equilibrium). However, experiments are limited to discrete particle sizes and comparison of the dispersion-velocity relationship is impeded by different experimental approaches. We conducted a series of separate heat and solute transport experiments in a column filled with uniform porous media consisting of different sized glass spheres for a range of flow velocities. The thermal and solute dispersion coefficients obtained from experimental measurements were correlated with flow velocities through the thermal or solute Péclet number. Our results demonstrate that, while solute dispersion is independent of particle size, the dependence of the TEM based thermal dispersion coefficient on flow rates is influenced by the particle size. This is caused by the fact that, unlike solute transport, heat exchanges between fluid and particles and that this induces thermal non-equilibrium between both phases. The results have significant implications for quantifying forced convective heat transport in natural porous media because thermal non-equilibrium between the phases is not considered. The porous media particle size must be considered when selecting appropriate values for the thermal dispersion coefficient.

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1. Introduction

Thermal dispersion is a key parameter required when quantifying forced convective heat transport through saturated porous media encountered in many research areas, such as quantifying subsurface water flow using temperature measurements [1–4], evaluating the performance and thermal impact of ground source heat pump systems [5–7], and evaluating fixed bed reactors in chemical engineering [8,9]. The term thermal dispersion refers to the heat transport mechanism caused by fluid velocity and temperature fluctuations in the pore space and the effects of hydrodynamic mixing on the temperature field [10–12].

Many investigations have demonstrated thermal dispersion is important for field applications. For example, Sauty et al. [13] evaluated aquifer heat storage and found that thermal dispersion is important when calculating the energy recovery. Vandenbohede et al. [14] conducted aquifer push-pull tests and found that thermal dispersion must be considered when modeling temperature breakthrough curves. Hidalgo et al. [15] concluded that transverse thermal dispersion, which acts perpendicular to the direction of flow, determines the shape and width of the thermal plume caused by ground source heat pump systems in heterogeneous aquifers.

Molina-Giraldo et al. [5] carried out numerical simulations and illustrated that thermal dispersion has a large effect on the temperature distribution around ground source heat pump systems. Bhaskar et al. [2] investigated water flow under streambeds and showed that neglecting thermal dispersion may affect the accuracy and interpretation of estimated streambed water fluxes from temperature measurements. Park et al. [7] noted that thermal dispersion has a significant effect on the aquifer temperature distribution around ground source heat pump systems. Consequently, advancing fundamental knowledge of thermal dispersion in saturated porous media underpins forced convective heat transport problems in many different fields of engineering and science.

Theoretical formulation has been carried out to quantify thermal dispersion in saturated porous media. In the early stage, thermal non-equilibrium model which describes energy balance equations for the solid and fluid phases separately was employed to analyze thermal dispersion [e.g. [16]]. Levec and Carbonell [17] theoretically analyzed the thermal non-equilibrium model and showed that the thermal response curves to a pulse disturbance have the same shape for each phase but show a finite time delay. This theoretical finding was verified by laboratory experiments where the solid and fluid temperature response curves were measured separately [8]. Consequently, it is desirable to use a thermal non-equilibrium model when convective heat transport in porous media is quantified. This requires either knowledge of the solid-to-fluid heat exchange coefficient or separate measurements of the temperature within the solid and fluid phases.

In the context of earth sciences it is very difficult to measure the solid and fluid temperature separately, and the thermal non-equilibrium model is considered to be impractical [3]. Therefore, the separate energy equations for each phase are averaged over a representative elementary volume and expressed as a single energy equation, which is often referred to as thermal equilibrium model (TEM) (or one energy equation model) [11,18]. The thermal dispersion coefficient in the TEM quantifies the spread of heat in saturated porous media. The thermal dispersion coefficient describes the effects of diffusive heat transport through the solid and fluid phases, heat exchange between the phases, as well as thermal dispersion (fluid phase only) on the overall heat transport in saturated porous media [10,19]. The thermal dispersion coefficient is often expressed as a function of the thermal Péclet number (the ratio between convective to diffusive heat transport) or the thermal front velocity (convective heat transport taking into account diffusive heat transport through both the solid and fluid phases). The relationship between the thermal dispersion coefficient and the thermal Péclet number (or the thermal front velocity) must be known when the TEM is used to model convective heat transport in saturated porous media [e.g. 9, 20].

In order to determine the relationship between the thermal dispersion coefficient and flow velocity, laboratory experiments have been conducted. Green et al. [16] injected hot water at different velocities into uniform porous media consisting of 0.097, 0.41, 1.1, 3.0 mm diameter glass spheres. Levec and Carbonell [8] conducted similar experiments but with 5.5 mm diameter spheres made from urea formaldehyde. In other experiments, heat was added inside the porous media consisting of 2 mm glass spheres [9], three types of soils (sand, silt loam, sandy clay loam) [21], and uniform 2 mm sand [20]. All experiments found that the relationship between the thermal dispersion coefficient and flow velocity follows a power law. While previous experiments used differently sized particles, the effect of particle size on the thermal dispersion coefficient when it is correlated with the thermal Péclet number has not been reported to the best of our knowledge [16,22].

The physical process of thermal dispersion has often been considered in analogy to solute dispersion, despite the fact that heat propagates through both the solid and fluid phases whereas solute can be transported through only the fluid phase [19,20,23,24]. The characteristics of solute dispersion have been thoroughly investigated and reviewed [25]. For example, Carvalho and Delgado [26] showed that particle size does not affect solute dispersion.

While many previous studies have investigated thermal or solute dispersion separately, few studies have compared the difference in the transport mechanisms. This comparison could significantly improve our understanding of thermal dispersion phenomenon. For example, Rau et al. [20] conducted heat and solute transport experiments under the same experimental conditions. They illustrated that thermal and solute dispersion exhibit a similar non-linear velocity dependence when normalized and compared through the respective Péclet number.

The aim of this paper is to evaluate the effect of particle size on thermal and solute dispersion through water saturated porous media consisting of different particle sizes under the same experimental conditions. By fitting an analytical solution of a partial differential transport equation (DTE) to thermal and solute experimental data, we show that the thermal dispersion-velocity relationship in the TEM is indeed dependent on the particle size whereas solute dispersion is not dependent of the particle size. We further illustrate that this difference is caused by thermal non-equilibrium between the solid and fluid phases and that this has significant implications for quantifying convective heat transport using the TEM in natural porous media.

2. Materials and methods

2.1. Experimental method

2.1.1. Experimental setup

In order to investigate the particle size dependence of thermal and solute dispersion in saturated porous media, both heat and solute transport experiments under the same experimental conditions were separately performed. An insulated circular stainless steel column with 10 cm inner diameter and 50 cm length was used for the experiments (see in Fig. 1(a)). To ensure that the inside of the column was thermally insulated from the surrounding environment, the column was double-walled with a vacuum in between. Additionally, urethane foam was wrapped three times around the column to enhance the thermal insulation.

To uniformly distribute inflowing water, a lid featuring 7 outlets was used (see Fig. 1(b)). A gap between the lid and the top of the porous media in the column ensured that water could uniformly enter the materials. A metallic mesh was set at the top of the materials and the bottom of the column to prevent the materials from escaping. The overall schematic diagram of the experimental apparatus is shown in Fig. 1(a) and the photo can be seen in Fig. 2(a).

Different types of tanks were used to keep distilled hot water for heat transport experiments or sodium chloride solution (concentration: 0.01 mol L^{-1}, electrical conductivity (EC): 1.2 dS m^{-1}) for solute transport experiments. For heat transport experiments, a polypropylene foam box was used as a hot water tank (see Hot Water Tank in Fig. 1(a)). The temperature of the water in the hot water tank was controlled at a desired temperature (from 40 °C to 60 °C depending on the flow condition) using a temperature controlled water circulation device (Thomas Inc., USA). An agitator was installed into the hot water tank to maintain the uniform temperature distribution inside the hot water tank at all times. For solute transport experiments, an acrylic plastic tank was used to keep the sodium chloride solution. A plastic tank was also used to store distilled water to flush the column prior to both heat and