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Influences of thermal dispersion on soil water flux estimates using heat pulse technique in saturated soils

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ABSTRACT

The heat-pulse technique (HPT) shows good potentials for in situ determinations of soil water flux (*J*), but its applications are limited because of *J* underestimates. This study aims to experimentally investigate the influences of thermal dispersion on *J* estimates using HPT in packed sand, silt loam, and sandy clay loam with one-dimensional saturated water flow, hypothesizing that *J* underestimates are caused by neglecting heat dispersion in heat transport model that arises from the heterogeneity of water velocities within and between water-filled soil pores. The results indicated that *J* estimates exhibited good linearity with the measurements ($R^2 > 0.95$). However, they were biased toward underestimates. The thermal dispersion's dependence on *J* was described by a power function. When heat dispersion was considered in the traditional heat conduction–advection model, the traditional ratio method yielded a higher accuracy with relative errors reduced by 45.0–74.3%, the bias reduced by 47.1–74.0% and the root mean square error reduced by 48.0–68.8%. In terms of the range of *J* herein, the maximum Keith Jirka Jan (*KJJ*) numbers obtained were 6.8%, 10.4%, and 13.4% for sand, silt loam, and sandy clay loam, respectively. Moreover, their corresponding *J* thresholds were 41.7, 21.1, and 12.3 $\mu m\ s^{-1}$, respectively.

1. Introduction

The accurate determination of soil water fluxes (*J*) remains an outstanding challenge in characterizing the subsurface transport of water, nutrients, and contaminants in the hydrology, environment, and ecosystem. The heat-pulse technique (HPT) has showed good potentials for in situ *J* estimations (Ren et al., 2000; Mori et al., 2003, 2005; Ochsner et al., 2005; Gao et al., 2006; Kluitenberg et al., 2007; Kamai et al., 2008; Lu et al., 2017). By using the HPT method, a heat pulse was introduced by passing electrical current through a central needle containing a resistance heater. The temperature responses in the flow direction at a distance from the heat source were monitored by thermocouples in the two outer needles, based on which the traditional heat conduction–convection equation was inversely solved to indirectly acquire the *J* estimates (Ren et al., 2000; Wang et al., 2002). Unfortunately, the preliminary results showed that HPT significantly underestimated *J* (Ren et al., 2000; Ochsner et al., 2005; Lu et al., 2017) and the deviations became larger as the water fluxes increased, especially for fine-textured soils, thereby hindering its practical application.

Researchers have long sought to better understand the reason for soil water fluxes being underestimated by HPT (Hopmans et al., 2002; Mori et al., 2005; Ochsner et al., 2005; Gao et al., 2006). However, the exact reasons remain unclear. Heat dispersion occurs because of the heterogeneity of water velocities within and between water-filled soil pores (De Marsily, 1986; Hopmans et al., 2002), leading to the mixing of pore-scale interstitial water in porous media. The role of the heat dispersion in *J* underestimation using HPT remains highly debated. Some studies theoretically showed that the *J* underestimates provide by Ren et al. (2000) mainly resulted from failures of the traditional heat transport model accounting for heat dispersion and the physical size of heater needles (Hopmans et al., 2002). They theoretically found that *J* could be determined accurately even at higher water velocities of 12–120 $\mu m\ s^{-1}$ if thermal dispersion was considered. Kamai et al. (2008) noted that the *J* underestimation was likely caused by neglecting the thermal dispersion and flow disturbance caused by the heater needle with water velocities > 1.2 $\mu m\ s^{-1}$. Similarly, the analysis by Bhaskar et al. (2012) highlighted that neglecting thermal dispersion affected the accuracy and interpretation of estimated streambed water fluxes using heat as a tracer. By contrast, some studies posed doubts on the effects of heat dispersion on water flux determination (Mori et al.,

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2005; Ochsner et al., 2005; Mortensen et al., 2006; Gao et al., 2006). Mori et al. (2005) demonstrated that thermal dispersion was insignificant and unrelated to water flux on saturated Tottori dune sand at rates ranging from 0.6 to 300 μm s^{-1} using a multi-functional heat pulse probe. Gao et al. (2006) and Mortensen et al. (2006) supported the conclusions reported by Mori et al. (2005). Gao et al. (2006) suggested that errors in J estimates could be reduced to under 5% by eliminating the wall flow on a soil–Plexiglas interface. Interestingly, Ochsner et al. (2005) evaluated the heat pulse ratio method for J determination and analyzed the sensitivity of J estimates in packed columns of sand, sandy loam and silt loam soil. They discovered that the predicted temperature signals from the reduced convection model agreed extremely well with the measurements which was in contrast to the original model and enhanced conduction. This result indicated that the water flux prediction errors could not be explained sufficiently by increasing the conduction term (equivalent to increasing thermal dispersion) in the traditional heat conduction–convection model. Instead, the errors could be attributed to reducing the convection term of the heat transport model. However, the abovementioned studies only theoretically or indirectly discussed the influences of heat dispersion on soil water flux determination using HPT. They did not discuss how to acquire the measured or estimated heat dispersive values. Noteworthily, the used dispersion values were mainly taken from a few empirical models available in literatures. These in turn, depended on specific experimental conditions, and had to be adjusted to realize a good agreement between the modelled and the experimental temperature responses. Moreover, little information is available on rigorously evaluating the effects of heat dispersion on the accuracy of water flux estimates from HPT. Therefore, the influences of heat dispersion on the water flux determination need to be studied experimentally.

The current study aims to (i) experimentally evaluate the performance of HPT in predicting J across a wide range of water fluxes (up to 58.9 μm s^{-1}) for different textured soils; (ii) determine the threshold of water fluxes at which thermal dispersion begins to significantly influence soil water fluxes; and (iii) characterize the role of thermal dispersion on the estimation of J.

2. Theory

Assuming that the magnitude of thermal dispersion along the x and y directions is similar and heat excitation is not z-dependent, the two-dimensional (2D) heat transport equation for a vertically uniform water flow along the x-direction in homogeneous and isotropic porous media combined with convective and dispersive transport (De Marsily, 1986; Hopmans et al., 2002) can be generally written as follows:

$$C_b \frac{\partial T}{\partial t} = \lambda_{eff}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - C_w J \frac{\partial T}{\partial x} \tag{1}$$

where x and y are the spatial coordinates (m); C_b represents the volume heat capacity of saturated soils (J m^{-3} K^{-1}); C_w represents the volume heat capacity of water (J m^{-3} K^{-1}); J represents the soil water flux densities (m s^{-1}); T represents the change of soil temperature (K); t represents time (s); and λ_{eff} represents the effective thermal conductivity along the x directions (W m^{-1} K^{-1}) analogous to solute dispersion, which is a combination of static thermal conductivity (λ_0) in a stationary fluid with the thermal dispersion coefficient (λ_d) linked to the heterogeneity of the water velocity within and between water-filled pores of the medium (Hopmans et al., 2002). λ_{eff} is expressed as:

$$\lambda_{eff} = \lambda_0 + \lambda_d \tag{2}$$

where λ_d is the thermal dispersion coefficient (W m^{-1} K^{-1}) resulting from the heterogeneous soil pore velocity and λ_0, the static thermal conductivity (W m^{-1} K^{-1}) in the absence of water flow.

The dimensionless Keith Jirka Jan (KJJ) number, defined by Hopmans et al. (2002), was used to quantify the contribution rate of thermal dispersion related to heat conduction.

$$KJJ = \frac{\lambda_d}{\lambda_0} \tag{3}$$

Assuming that thermal dispersion is related only to water flow velocities, an analytical solution of Eq. (1) can be obtained as follows for the case of pulse heating of an infinite line heat source normal to the x–y plane and located at (x, y) = (0, 0) (Ren et al., 2000)

$$T(x,y,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_0^t s^{-1}\exp\left(-\frac{(x-Vs)^2+y^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad 0 < t \le t_0 \tag{4a}$$

$$T(x,y,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_{t-t_0}^t s^{-1}\exp\left(-\frac{(x-Vs)^2+y^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad t_0 < t \tag{4b}$$

where s represents the time variable of the integration at time t', and it is a substitute for t-t'; t_0 represents heat pulse duration (s); q represents heat input per unit length per unit time during the interval $0 < t \le t_0$ (W m^{-1}); α_0 represents the static thermal diffusivity of saturated soil (m^2 s^{-1}); and V represents the convective pulse velocity (μm s^{-1}).

The temperature increases at the upstream (T_u) and downstream (T_d) positions directly from a linear source can be expressed as:

$$T_u(x,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_0^t s^{-1}\exp\left(-\frac{(x_u+Vs)^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad 0 < t \le t_0 \tag{5a}$$

$$T_u(x,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_{t-t_0}^t s^{-1}\exp\left(-\frac{(x_0+Vs)^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad t_0 < t \tag{5b}$$

$$T_d(x,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_0^t s^{-1}\exp\left(-\frac{(x_d-Vs)^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad 0 < t \le t_0 \tag{5c}$$

$$T_d(x,t) = \frac{q}{4\pi(\lambda_0+\lambda_d)}\int_{t-t_0}^t s^{-1}\exp\left(-\frac{(x_d-Vs)^2}{4\left(\alpha_0+\frac{\lambda_d}{C_b}\right)s}\right)ds \qquad t_0 < t \tag{5d}$$

3. Materials and methods

3.1. Soil column preparation and setup

Coupled soil water and heat transport experiments were conducted using a Plexiglas column (id: 0.08 m, height: 0.30 m) packed with soil samples at a constant room temperature (20 ± 1 °C). The inner surface of the Plexiglas column, which was the same as that used by Lu et al. (2009), was roughened to form a 1-mm frosting layer to minimize the wall effect induced by the air gap at the soil–column interface that is usually larger than the average pore size of bulk soil. Three types of soil textures were used: a sand from Fengning County, Hebei Province, China (a sandy, siliceous, mesic Ustic Quartzipsamment), a silt loam from Langfang City, Hebei Province, China (a coarse-loamy, mixed, mesic Ustic Eutrocryept), and a sandy clay loam from Dezhou City, Shandong Province, China (a fine-loamy, mixed, mesic Ustic Eutrocryept). Table 1 lists the particle-size distribution, organic matter content, and bulk density for each soil sample. The soil materials were air-dried, ground, and sieved through a 2-mm screen, wetted to a water