### **Original Research**

### **Core Ideas**

- Heat loss is the main reason for water flux underestimation.
- Two methods were proposed to quantify the heat loss.
- More accurate hydraulic properties can be estimated with the addition of heat loss.

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## Improving the Estimation of Hydraulic and Thermal Properties of Heterogeneous Media via the Addition of Heat Loss

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Heat has been widely used to investigate water flow in soils and aquifers during the past few decades. However, heat loss as an important characteristic has not been well considered in laboratory heat-tracing experiments. To evaluate the impact of heat loss on the estimation of hydraulic and thermal properties, a laboratory experiment was conducted using a sandbox packed with heterogeneous silica sand under steady-state flow condition. Thermocouple probes were used to simultaneously measure the temperature inside and outside of the silica sand during the experiment. The measured temperature of the sand layer was used to estimate the hydraulic conductivities and longitudinal and transverse thermal dispersivities via curve fitting using HYDRUS software. We found that >50% of the sensible heat was dissipated into the shell of sandbox and the surrounding air rather than being absorbed by the sand. Two methods were then proposed to quantify the heat loss and to improve the accuracy of parameter estimation: (i) a conceptual heat balance method that accounted for the change in heat storage in different parts of the system and (ii) a physical process-based method that described the thermodynamic processes of heat transfer among different parts of the system. On combining these two methods, the relative error between the estimated and measured water flux significantly decreased from 19% to nearly 2%. The results imply that the heat-tracing method is capable of obtaining accurate hydraulic and thermal properties in a heterogeneous porous medium with the addition of heat loss.

Abbreviations: BTC, breakthrough curve; CM, conceptual heat balance method; LSH, loss of sensible heat; MRE, mean relative error; PPM, physical process-based method.

Heat as an environmentally friendly tracer has been widely used in hydrology and soil physics during the last several decades because of its advantages in describing water flow in porous media at different scales (Anderson, 2005; Constantz, 2008; Halloran et al., 2016; Rau et al., 2014; Wagner et al., 2014a). One of the major applications of the heat-tracing test is to estimate hydraulic and thermal properties that are critical for water and heat flow in porous media. However, as compared with the transport process of a conservative tracer, the heat transfer process is always accompanied by heat loss and heat retardation (i.e., the slower movement of the temperature front compared with the water flow because of the heat transfer from the liquid phase to solid phase) (Constantz et al., 2003; Giambastiani et al., 2013; Irvine et al., 2015), resulting in inaccuracy of parameter estimation using measured temperature data in porous media, particularly heterogeneous media.

Using heat-tracing-measured temperature data with additional information can produce more robust parameter estimation than using temperature data alone (Giambastiani et al., 2013; Nakhaei and Šimůnek, 2014; Steenpass et al., 2010; Su et al., 2004). The additional information includes groundwater level, water content, cumulative infiltration, solute concentration, etc. Steenpass et al. (2010) demonstrated that soil surface temperature was useful information in estimating soil hydraulic parameters of the van Genuchten model, which is a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters; however, the parameter uncertainties could be reduced by considering soil water content at different depths. Nakhaei and Šimůnek (2014)

conducted a single-ring infiltration test with relatively warm water (with an initial soil temperature of 17.5°C and an infiltration water temperature of 61°C) and estimated soil hydraulic and thermal parameters. They found that the confidence intervals of the optimized soil hydraulic and thermal parameters could be narrowed only with the known saturated water content and saturated hydraulic conductivity. Giambastiani et al. (2013) investigated the limits of the use of heat tracer to assess the aquifer properties via a large tank experiment and found that the uncertainty associated with the thermal longitudinal dispersivity was relatively large for the case of slow velocity only using temperature data. However, the thermal longitudinal dispersivity could be accurately estimated with the addition of a solute concentration. An experiment using an even larger tank packed with heterogeneous porous media conducted by Wagner et al. (2014b) proved that a borehole heat exchanger installed in an aquifer with significant horizontal groundwater flow can also be used for hydrogeological characterization of the penetrated subsurface. Recent studies have shown that the hydraulic conductivity field of heterogeneous porous media could be accurately obtained by integrating hydraulic tomography into a heat-tracing test (Saley et al., 2016; Somogyvari and Bayer, 2017).

Heat loss might also be considered as a type of useful information for parameter estimation of water flow and heat transfer in laboratory studies (e.g., sand tank studies). Because of the nonconservative nature of heat, heat loss is inevitable. The heat lost in porous media can be recovered over quickly, whereas the heat lost to the environment, such as evaporation and radiation into the ambient air, is difficult to be used for porous media. All thermal conduction (Yortsos, 1982), convection (Molz et al., 1983), and radiation (Schuetz et al., 2012) can be attributed to heat loss in transport processes. However, only a few studies have been conducted using heat loss as additional information to estimate the hydraulic and thermal properties of porous media.

Parameter estimations of water and heat transfer in porous media using a heat-tracing method are always performed by fitting the experimental data to the appropriate mathematical models. However, heat transfer in porous media is usually described by the convective-conductive equation without considering heat loss (Giambastiani et al., 2013; Klepikova et al., 2016). Heat loss can reduce the peak temperature and delay the arrival time of the temperature breakthrough curves (BTCs), causing an estimated bias of parameters in numerical modeling (Irvine et al., 2015; Palmer et al., 1992). Feng (2015) conducted a series of heat-tracing tests using packed homogeneous porous media in a small-scale sandbox and qualitatively determined that heat loss might be the major reason for the underestimation of water flux. For heterogeneous porous media, the parameter estimation bias may be more significant because less heat energy is recovered than that in homogeneous porous media (Ferguson, 2007) because significant preferential flow always occurs in heterogeneous media, resulting in larger temperature differences among materials. Thus, more energy might be dissipated accompanying the heat transfer at the same flux, and

less heat energy will be recovered. Therefore, it is important to account for the heat loss in numerical modeling to obtain accurate estimation of parameters.

To our knowledge, using the heat-tracing method with heat loss as a type of additional information to estimate hydraulic and thermal parameters, particularly in the heterogeneous porous media, has not been well studied. Therefore, our main objectives were (i) to evaluate the heat loss during heat-tracing experiments and its impact on the heat plume and (ii) to propose methods for calculating heat loss and improve hydraulic parameter estimation via the addition of heat loss.

## Experimental Setup

The experiment was performed using a horizontal twodimensional sandbox composed of 1-cm-thick Plexiglas plates. The two-dimensional tank consisted of three parts: an inflow chamber (15 by 2 by 2.5 cm) connected to the left side of the sandbox, a central part (50 by 40 by 2.5 cm) used for filling silica sand, and an outflow chamber (40 by 2 by 2.5 cm) connected to the right side of the sandbox. A sketch of the experimental apparatus design is shown in Fig. 1a. Two perforated partitions were separately inserted at the left and right sides of the central part to create a steady-state flow field, and a 5-cm layer of coarser sand material was packed around the partitions to prevent sand particles from blocking these holes and entering the outflow chamber. To minimize the wall flow effect at the Plexiglas-sand interface, epoxy resin was smeared on the inner surface of the Plexiglas in bandings at 5-cm intervals. The width of the epoxy resin bandings was 2 cm. Silica sand particles (diameter 0.5–1.0 mm) were placed on these bandings. After the epoxy resin bandings with silica sand particles were completely solidified, a heterogeneous structure was constructed within the sandbox.

Twenty T-thermocouple probes (Omega Engineering) were uniformly installed in the sandbox to record the temperatures of the silica sand in real time with an accuracy of  $\pm 0.01^{\circ}$ C (Fig. 1b). Two extra T-thermocouple probes were set in the inflow and outflow chambers. Three additional thermocouple probes were fixed on the outside surface of the sandbox to measure the temperature dynamics of the Plexiglas shell (Fig. 1a). All three probes were arranged in a line corresponding to the central axis of the sandbox, respectively. All of the thermocouple probes were connected to a CR3000 datalogger (Campbell Scientific) via data cables.

An overflow tank was connected to the inflow chamber to provide a constant water head for the sandbox. A micro-pump (Chengdu Xin Wei Cheng Technology Co.) with a flow rate of 1 to 3 L min<sup>-1</sup> was used to pump water from a large heated water tank to the overflow tank. A drainage tank was connected to the outflow chamber to collect water flowing out of the sandbox during the experiment. Piezometers with an accuracy of  $\pm 0.1$  cm were installed in the inflow and outflow chambers to measure the water pressure head.





Three silica sands ( $\sim$ 0.1 mm [fine], 0.5–1 mm [medium], and 1–2 mm [coarse]) in grain size were used to construct the artificial heterogeneous domain in the horizontal Plexiglas sandbox (Fig. 1a). The 50- by 40-cm domain was divided into 80 5- by 5-cm subregions. Thin stainless dividers were used to separate blocks of different types of silica sands, and some fine sand was filled into the gaps to eliminate preferred flow pathways after removing the dividers. The volumetric proportions of fine, medium, and coarse sands were 5, 80, and 15%, and the final bulk densities of the different sands were 1.90, 1.85, and 1.80 g cm<sup>-3</sup>, respectively. A Mariotte bottle was connected to the outflow chamber to saturate the sand layer by layer at depths of 5 cm until the top within 24 h. The layered saturation was perpendicular to the mean flow direction (the length of the sandbox). The sandbox was placed atop a horizontal experimental bench and leveled using a tubular spirit level.

Two hydraulic gradients were considered during the experiments. During Exp. 1, the difference in pressure head

between the inflow and outflow was  $\Delta H_1 = 42.6$  cm, whereas during Exp. 2 the pressure head difference was  $\Delta H_2$ = 48.9 cm. Prior to the injection of the heat tracer, water at a room temperature of  $26 \pm 0.2$  °C was pumped into the sandbox at a constant pressure head to maintain a steady-state flow field.

Once steady state-flow conditions were reached, warm water of a constant temperature (38°C) was switched on. A controlled heater was used to maintain a constant temperature. To ensure the warm water was immediately injected into the inflow chamber, the inflow chamber was connected to two overflow tanks: one for room-temperature water (not shown in Fig. 1a) and the other for the warm water. When the valve for the room-temperature water was switched off, the valve for the warm water immediately switched on. The heat-tracing experiments then began.

The CR3000 datalogger was set to acquire temperature data three times per minute, and the average value was recoded to show the movement of heat flow in the heterogeneous medium. The warm water supply system was stopped, and the experiment ended when the real-time temperatures at each observation point inside the sands approached constant values. The values of the piezometers at the inflow and out-

flow chambers and the cumulative volume of the effluents were recorded during the experiment. The durations of Exp. 1 and 2 were approximately 20 and 38 min, respectively.

# Theory Model Setup

In this study, HYDRUS-2D software (Šimůnek et al., 1999) was applied to simulate water and heat transfer processes in the porous medium under a steady-state flow condition. The water flow can be described as

$$\frac{\partial}{x_i} \left[ K_S \left( K_{ij}^{A} \frac{\partial h}{\partial x_j} \right) \right] = 0 \quad (i, j = 1, 2)$$
<sup>[1]</sup>

where *h* is the pressure head (cm),  $x_i$  is the coordinate along the *i*th direction (cm),  $K_{ij}^{A}$  are the components of a dimensionless

anisotropy tensor  $K^A$ , and  $K_S$  is the saturated hydraulic conductivity (cm min<sup>-1</sup>).

Neglecting the effect of vapor diffusion, the control equation for heat transfer can be described as (Sophocleous, 1979)

$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left[ \lambda_{ij}(\theta)\frac{\partial T}{\partial x_i} \right] - C_{w}q_i\frac{\partial T}{\partial x_i}$$
[2]

where  $\lambda_{ij}(\theta)$  is the apparent thermal conductivity of the silica sand (W m<sup>-1°</sup>C<sup>-1</sup>), and  $C(\theta)$  and  $C_w$  are the volumetric heat capacities of the porous medium and the water (J m<sup>-3</sup>°C<sup>-1</sup>), respectively. The first term on the right-hand side of Eq. [2] represents heat flow resulting from conduction, and the second term accounts for the heat transported by water flow. The volumetric heat capacity can be expressed as

$$C(\theta) = C_{\rm n}\theta_{\rm n} + C_{\rm w}\theta$$
<sup>[3]</sup>

where  $\theta$  is the volumetric content (cm<sup>3</sup> cm<sup>-3</sup>), and subscripts *n* and *w* are solid (nonwetting) and liquid (wetting) phases, respectively.

The apparent thermal conductivity  $\lambda_{ij}(\theta)$  is composed of the thermal conductivity  $\lambda_0(\theta)$  of the porous medium (solid and water) without water flow and the macrodispersivity, which is assumed to be a linear function of the velocity (de Marisly, 1986). The apparent thermal conductivity  $\lambda_{ij}(\theta)$  is provided by Šimůnek et al. (1999)

$$\lambda_{ij}(\theta) = \alpha_{\rm T} C_{\rm w} \left| q \right| \delta_{ij} + \left( \alpha_{\rm L} - \alpha_{\rm T} \right) C_{\rm w} \frac{q_j q_i}{|q|} + \lambda_0(\theta) \delta_{ij} \qquad [4]$$

$$\lambda_0(\theta) = b_1 + b_2 \theta + b_3 \theta^{0.5}$$
<sup>[5]</sup>

where q is the absolute value of the Darcian fluid flux density (cm min<sup>-1</sup>);  $\delta_{ij}$  is the Kronecker delta function;  $\alpha_{\rm L}$  and  $\alpha_{\rm T}$  are the longitudinal and transverse thermal dispersivities, respectively (cm);  $\lambda_0$  is the thermal conductivity (W m<sup>-1</sup> °C<sup>-1</sup>); and  $b_1$ ,  $b_2$ , and  $b_3$  are empirical parameters of  $\lambda_0$ .

Uniform triangular meshes with a side length of 1 cm were adopted for simulation of flow region (50 by 40 cm). Thus, the whole domain was divided into 4000 cells filled with three different sand materials (Fig. 1a).

An initial steady-state flow field was generated with a pressure head of 42.6 and 48.9 cm at the left boundary for Exp. 1 and 2, respectively, and a pressure head at the right boundary of 0 cm. A linear gradient of pressure head was assumed in those regions between the left and right boundaries. The room temperature of  $26^{\circ}$ C was set as the initial temperature of the domain. Sides bc and ef (Fig. 1b) were considered as prescribed constant pressure head boundaries. The third-type boundaries (i.e., the Cauchy type boundaries with the variable temperatures measured at the inflow and outflow chambers) were used for heat transfer at sides bc and ef. The boundaries for water flow and heat transfer at the other sides (i.e., ab, cd, de, and fa) were regarded as zero-flux boundaries.

### Model Calibration and Validation

Model Calibration without Considering Heat Loss

Several hydraulic and thermal parameters were determined prior to the simulation. The volumetric heat capacities of the solid and liquid phases were determined according to Nakhaei and Šimůnek (2014), and the effect of the organic phase was ignored. The empirical parameters of thermal conductivity  $(b_1, b_2, \text{ and } b_3)$ for each material were estimated using the inverse method of the HYDRUS-2D software on the basis of the homogeneous twodimensional sandbox experiment, which can be found in Feng (2015). Feng (2015) conducted the heat-tracing tests in homogeneous porous media using the same experimental apparatus and the same sand materials of the three diameters described in this work. The estimated results for the predetermined parameters are presented in Table 1.

The measured temperature data of Exp. 1 were applied for model calibration, and the saturated hydraulic conductivity  $(K_S)$ and longitudinal and transverse thermal dispersivities ( $\alpha_L$  and  $\alpha_T$ , respectively) as unknown parameters were then estimated by comparing the measured temperature data to the simulation results of HYDRUS-2D software. The  $R^2$ , RMSE, and mean relative error (MRE) were chosen as indicators to evaluate the simulation results

Table 1. Known hydraulic and thermal parameters for the fine, medium, and coarse sands used in these experiments.						
Parameter	Fine sand	Medium sand	Coarse sand			
Bulk density, g cm <sup>-3</sup>	1.85	1.80	1.75			
Saturated water content, $\rm cm^3  cm^{-3}$	0.40	0.38	0.36			
Heat capacity of the solid phase, J $m^{-3}^{\circ}C^{-1}$	1,920,000	1,920,000	1,920,000			
Heat capacity of water, J $\rm m^{-3}~^{o}C^{-1}$	4,180,000	4,180,000	4,180,000			
Empirical parameters of thermal conductivity						
$b_1$ , [M L T <sup>-3</sup> K <sup>-1</sup> ]	41,845,000	4,532,800	650,000,000			
$b_2$ , [M L T <sup>-3</sup> K <sup>-1</sup> ]	-50,810,000	-50,093,000	-7,436,800,000			
$b_3$ , [M L T <sup>-3</sup> K <sup>-1</sup> ]	29,152,000	90,388,000	3,466,900,000			
Thermal conductivity, W m <sup>-1</sup> K <sup>-1</sup>	1.85	1.91	2.45			

Table 1. Known hydraulic and thermal parameters for the fine, medium, and coarse sands used in these experiments.

in the calibration procedures. The values of  $R^2$ , RMSE, and MRE can be determined as

$$R^{2} = \frac{\sum P_{i}O_{i}\left(\sum P_{i}\sum O_{i}/n\right)}{\left[\sum P_{i}^{2} - \left(\sum P_{i}\right)^{2}/n\right]\left[\sum O_{i}^{2} - \left(\sum O_{i}\right)^{2}/n\right]}$$
[6]

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2}$$
[7]

$$MRE = \frac{1}{n} \sum_{i=1}^{n} \frac{P_i - O_i}{O_i} \times 100\%$$
[8]

where  $O_i$  and  $P_i$  are the measured and simulated values, respectively, and n is the number of the temperature pair values.

### Model Calibration and Validation Considering Heat Loss

Heat loss was not considered for parameter estimation, which might lead to inaccurate estimated results, particularly for the saturated hydraulic conductivity. Thus, we re-estimated the saturated hydraulic conductivity with the addition of heat loss. The measured temperature datasets of Exp. 1 and 2 as well as their heat loss rates were applied for parameter estimation and model validation, respectively. The  $R^2$ , RMSE, and MRE values were also used as indicators to evaluate the calibration and validation procedure performance.

Two methods based on heat balance were proposed to compute the heat loss during the experiment: (i) the conceptual heat balance method (CM) accounting for the heat loss of the whole experiment system and (ii) the physical process-based method (PPM) of heat loss.

#### **Conceptual Heat Balance Method**

Before the heat-tracing experiment began, temperatures of both the silica sands and Plexiglas shell were considered as room temperature ( $T_0$ ). After injection of the warm water (Fig. 2a), the conceptual heat balance of the sand box at different times was expressed as

$$Q_{\rm I}(t) - Q_{\rm O}(t) = Q_{\rm S}(t) + Q_{\rm P}(t) + Q_{\rm D}(t)$$
[9]

where  $Q_{I}(t)$  is the heat entering the sand box with the injected warm water (J),  $Q_{O}(t)$  is the heat transferred out of the sandbox with drainage (J),  $Q_{S}(t)$  is the heat stored in the sand layer (J),  $Q_{P}(t)$ is the heat absorbed by the Plexiglas shell (J), and  $Q_{D}(t)$  is the heat dissipated into the surrounding air (J).

Values for  $Q_{I}(t)$ ,  $Q_{O}(t)$ ,  $Q_{S}(t)$ , and  $Q_{P}(t)$  can be calculated using the heat capacity formula (Dence, 1972):

$$Q_x(t) = \sum_{j=1}^{N} C_x V_{xj} \Delta T_{xj}(t)$$
<sup>[10]</sup>

where  $Q_x(t)$  denotes the change in internal energy of the medium at different time (J); *x* represents *I*, *O*, *S*, and *P*;  $C_x$  is the volumetric heat capacity of the medium (J m<sup>-3</sup> °C<sup>-1</sup>), *N* is the number of subregions corresponding to the thermocouple locations,  $V_{xj}$  is



Fig. 2. Heat balance components of the sandbox for heat loss calculation: (a) for the conceptual heat balance method,  $Q_{\rm I}$  is the heat with water flow inside the sandbox,  $Q_{\rm O}$  is the heat with water flow outside the sandbox,  $Q_{\rm S}$  is the heat stored in the silica sand,  $Q_{\rm P}$  is the heat absorbed by the Plexiglas plates, and  $Q_{\rm D}$  is the heat dissipated into surrounding air; (b) for the physical process-based method,  $Q_{\rm CD}$  is the thermal conduction between the sand and Plexiglas,  $Q_{\rm R}$  is the effective thermal radiation from the Plexiglas shell to the air, and  $Q_{\rm CV}$  is the thermal convection at the Plexiglas–sand interface.

the volume of the *j*th subregion of the medium (m<sup>3</sup>), and  $\Delta T_{xj}(t)$  is the temperature difference relative to the initial temperature of *j*th subregion (°C).

For the heat balance calculation, the saturated silica sand layer was divided into 20 subregions (10 by 10 by 2.5 cm). The  $C_S$  value of each material was calculated using Eq. [3] with the parameters provided in Table 1, and a mean value of  $2.78 \times 10^6$  J m<sup>-3</sup> °C<sup>-1</sup> was applied in Eq. [10] because of the small variation in  $C_S$  values for the different sands. The top side of the Plexiglas shell was divided into three subregions (16.67 by 40 by 1 cm), with a  $C_p$  value of  $1.78 \times 10^6$ J m<sup>-3</sup> °C<sup>-1</sup> provided by the manufacturer. The bottom and lateral sides were treated in the same manner as the top side.

Newton's law of cooling (Davidzon, 2012) was used to describe the relationship between the rate of heat dissipation  $(Q_D)$  and the temperature difference between the sandbox and its surroundings, which is generally true in thermal conduction. In addition, the heat transfer coefficient (k) mediating between heat dissipation and temperature difference is a constant. It is only valid during the heating phase because the temperature difference between the heated area and room temperature gradually decreased until the whole sand layer reached the maximum temperature of the heat source.

Thus, the heat transfer coefficient can be described as

$$k = \frac{\mathrm{d}}{\mathrm{d}t} \left[ \frac{Q_{\mathrm{D}}(t)}{\beta \Delta S_{\mathrm{P}}(t) \Delta T_{\mathrm{mean}}(t)} \right]$$
[11]

where k denotes the heat transfer coefficient that should be fitted by the measured temperature, which is 1.46 J cm<sup>-2</sup> min<sup>-1</sup> °C<sup>-1</sup> for Exp. 1 and 1.35 J cm<sup>-2</sup> min<sup>-1</sup> °C<sup>-1</sup> for Exp. 2,  $Q_D(t)$  is the dissipated heat (J),  $\Delta T_{mean}(t)$  is the mean temperature difference between the inner and outer surfaces of the Plexiglas shell (°C), and  $\Delta S_P(t)$  is the heated area of the Plexiglas shell (cm<sup>2</sup>). Because the thickness of the sand layer was relatively small, the temperature at the inner surface of the Plexiglas shell was considered the same as that of the sand. The amplifying coefficient  $\beta$  represents the heat loss through the top and bottom sides and the lateral sides of the sandbox. If the area of the subregion on the top side is considered a unit, then a lateral side has an area of 0.06 (2.5/40 = 0.06); therefore, a value of 1.06 can be obtained for  $\beta$ .

During the experiment,  $Q_{\rm p}(t)$  and  $Q_{\rm D}(t)$  were assumed to be absorbed by the sand layer; thus, the equivalent temperature change caused by the heat loss of each subregion based on the conceptual heat balance can be described as:

$$\Delta T_j^{\rm CM}(t) = \varphi \frac{k \Delta T_{\rm meanj}(t)}{C_{\rm S} V_{\rm S}} + \frac{C_{\rm P} V_{\rm P} \Delta T_{\rm Pj}(t)}{C_{\rm S} V_{\rm S}}$$
[12]

where  $\Delta T_j^{\text{CM}}(t)$  denotes the temperature change because of the heat loss of the *j*th subregion (°C), and  $\varphi$  is an empirical parameter representing the ratio of the heated area of the Plexiglas shell to the sand layer ( $\varphi = 0.5$ ).

### Physical Process-Based Method

The physical processes of thermal transfer between silica sand and the Plexiglas shell are shown in Fig. 2b. Using this method, the heat balance at different times can be described as

$$Q_{\rm I}(t) - Q_{\rm O}(t) = Q_{\rm S}(t) + Q_{\rm CD}(t) + Q_{\rm CV}(t) + Q_{\rm R}(t)$$
 [13]

where  $Q_{\rm CD}(t)$  is the thermal conduction from the silica sand layer to the Plexiglas shell (J),  $Q_{\rm CV}(t)$  is the thermal convection at the Plexiglas–sand interface (J), and  $Q_{\rm R}(t)$  is the effective thermal radiation from the Plexiglas shell to the air (J). Because a preprocessing procedure was taken to enlarge the contact area between the sand particles and Plexiglas shell, we assumed  $Q_{\rm CV}(t)$  could be ignored during the calculation of the heat balance. The bottom and the lateral sides were treated in the same manner as the top side.

Fourier's law requiring a steady-state thermal conduction and one-directional heat flow were used to characterize  $Q_{\rm CD}(t)$ . Because of the isotropic and homogeneous nature of the Plexiglas shell, its thermal conductivity was constant. In our system, vertical heat exchange was dominant during the heat loss process, and the heat exchange in the Plexiglas shell along the longitudinal and transverse directions was ignored because of the relatively small temperature gradient compared with that vertically. Thus,  $Q_{\rm CD}(t)$ can be calculated by Fourier's law (Bear, 1972) as

$$Q_{\rm CD}(t) = \sum_{j}^{N} \beta \frac{\left[ T_{\rm Sj}(t) - T_{\rm Pj}(t) \right] \Delta S_{\rm P}(t)}{\delta/\lambda}$$
[14]

where  $T_{Sj}(t)$  is the temperature at the *j*th subregion of the sand layer (°C),  $T_{Pj}(t)$  is the temperature at the *j*th subregion of the

Plexiglas shell (°C),  $\delta$  is the thickness of the Plexiglas shell with a value of 1 cm, and  $\lambda$  is the thermal conductivity of the Plexiglas with a value of 0.6 W m<sup>-1</sup> °C<sup>-1</sup> as provided by the manufacturer.

According to the Stefan–Boltzmann law (Inagaki and Yoshizo, 1996),  $Q_{\rm R}(t)$  can be described as:

$$Q_{\mathrm{R}}(t) = \sum_{j}^{N} \beta \varepsilon_{\mathrm{P}} \sigma \left\{ \left[ K_{\mathrm{P}j}(t) \right]^{4} - \left[ K_{\mathrm{air}}(t) \right]^{4} \right\} \Delta S_{\mathrm{P}}(t)$$
[15]

where  $Q_{\rm R}(t)$  is the effective thermal radiation (J);  $K_{\rm Pj}(t)$  and  $K_{\rm air}(t)$ are the thermodynamic temperatures for the *j*th subregion of the Plexiglas shell and room temperature (K), respectively;  $\sigma$  is the Stefan–Boltzmann constant ( $\sigma = 5.67 \times 10^{-8}$  W m<sup>-2</sup> K<sup>-4</sup>); and  $\varepsilon_{\rm p}$  is the surface emissivity of the Plexiglas shell with a value of 0.94 provided by the manufacturer.

Similarly,  $Q_{CD}(t)$  and  $Q_{R}(t)$  were assumed to be absorbed by the sand layer during the experiment; thus, the equivalent temperature change caused by the heat loss of each subregion based on the physical process can be described as:

$$\Delta T_{j}^{\text{PPM}}(t) = \frac{\varepsilon_{\text{P}}\sigma\left\{\left[K_{\text{P}j}(t)\right]^{4} - \left[K_{\text{air}}(t)\right]^{4}\right\} + (\lambda/\delta)\left[T_{\text{S}j}(t) - T_{\text{P}j}(t)\right]}{C_{\text{S}}V_{\text{S}}}$$
[16]

where  $\Delta T_j^{\text{PPM}}(t)$  (°C) is the temperature change because of the heat loss of each subregion.

## Results and Discussion Temperature Spatial and Temporal Distributions

A similar trend in the heat plume was observed for Exp. 1 and 2. Figure 3 shows the measured temperature at typical observational points for Exp. 1. The temperature of the inflow chamber (Point A) significantly increased during the beginning of experiment and then gradually decreased instead of maintaining a constant value (Fig. 3a). The main reason for the temperature decrease was that a nonignorable amount of heat loss occurred on the water surface of the overflow tank and delivery pipe before the warm water was injected into the inflow chamber. It took approximately 5 min for the front of the heat plume to reach the drainage boundary after the injection of warm water. The temperature of the outflow chamber (Point B) gradually approached the temperature of the inflow chamber approximately 20 min later. The Plexiglas surface (PS1, PS2, and PS3) temperature also gradually increased a few minutes after the injection of warm water. The rate of the temperature increase measured on PS1, PS2, and PS3 decreased with increasing distance from the heat source.

Figure 3b shows the BTCs of the temperature measured via thermocouple probes for Group 2 (i.e., Points 2-1 to 2-5) along the flow direction. The measured temperature of Group 2 had a similar trend as that of the measured temperature of the inflow chamber. The temperature of Points 2-1 and 2-2 showed an earlier arrival time and a sharper increase than those of Points 2-3, 2-4, and 2-5 because Points 2-1 and 2-2 were closer to the heat source. The temperature of Points 2-4 and 2-5 showed a tendency to increase earlier



Fig. 3. Measured transient temperature during Exp. 1: (a) breakthrough curves (BTCs) of the temperature at the surface and boundary observational points, (b) BTCs of the temperature at typical observational group points along a longitudinal direction, and (c) BTCs of temperature at typical observational sections along a transverse direction. PS, Plexiglas surface.

compared with Point 2-3, which was attributed to the faster migration of heat resulting from the relatively larger flow rate in coarse sand compared with that in the medium and fine sands.

The thermal BTCs for the points of transverse Sections 2 and 3, which are perpendicular to the flow direction, are shown in Fig. 3c. All the points of Section 2 and Points 1-3 and 4-3 were in the medium sand zone, whereas Points 2-3 and 3-3 were in the fine sand zone. Because the heterogeneous domain was packed with a symmetric pattern along the direction perpendicular to the flow direction, the BTCs of the temperature at Points 1-3, 2-3, 1-2, and 2-2 were nearly the same as those at Points 4-3, 3-3, 4-2, and 3-2, respectively. Therefore, only those at Points 1-2, 2-2, 1-3, and 2-3 were plotted (Fig. 3c). The BTCs of Points 2-2 and 3-2 had an earlier arrival time and sharper increase than those of Points 1-2 and 4-2, indicating that higher velocities occurred in the central part of the sandbox at transverse Section 2. The fronts of the heat plumes arrived at Points 1-3 and 4-3 even faster than those reaching the points of Section 2, indicating that preferential flow in the coarse sand zone dominated the water flow compared with the flow in the medium sand. The temperatures of all of the points were approximately the same and approached a constant value around 19 min after the injection of warm water.

### Calibration without Considering Heat Loss

The measured and simulated BTCs of the temperature at typical observational points of Exp. 1 are shown in Fig. 4. The simulated temperatures agreed with the measured data ( $R^2 > 0.9$ ; MRE < 5%).

The estimated hydraulic and thermal parameters for the three sands of Exp. 1 are listed in Table 2. The saturated hydraulic conductivity increased as the particle size of the silica sand increased. The ratio of longitudinal to transverse thermal dispersivity was 21.3, 100.0, and 112.5 for the coarse, medium, and fine sand, respectively. The results were consistent with those of previous research (Hopmans et al., 2002; Rau et al., 2014), with a ratio in the range of 10 to 100.

Although the simulated thermal BTCs agreed reasonably well with the measurements, a significant difference was found between simulated and measured water flow. The estimated water flux was approximately 19% lower than the measured rate (Table 3); this might be because heat loss was not considered in the parameter estimation. The temperature of the sandbox surface significantly increased during the experiment (Fig. 3a), indicating a large amount of heat was absorbed by the Plexiglas shell and dissipated further into the surrounding air through the Plexiglas shell. Heat loss may reduce the peak temperature and delay its arrival time in silica sand, resulting in an underestimation of the saturated hydraulic conductivity. Because heat loss cannot be avoided, it is crucial to minimize the amount of heat loss from the medium to the environment when analyzing heat transfer in porous media (Mohammadzadeh and Chatzis, 2016). Therefore, numerical simulation with the addition of heat loss may be an alternative means to improve parameter estimation accuracy in the heat-tracing method.

### Calibration and Validation Considering Heat Loss Heat Loss Quantification

Heat loss during the heat-tracing experiment was calculated using the CM and PPM with the measured temperature in Exp. 1.



Fig. 4. Comparisons between the observed and simulated breakthrough curves of the temperature during Exp. 1 at four typical observational points (solid lines represent the simulated temperatures, and black dots represent the measured temperatures). MRE, mean relative error.

Figure 5 shows the heat stored in water  $[Q_{\rm I}(t) \text{ and } Q_{\rm O}(t)]$ , in the sand layer  $[Q_{\rm S}(t)]$ , and in the Plexiglas shell  $[Q_{\rm P}(t)]$  calculated using Eq. [10]. The results indicate that 46% of the loss of sensible heat  $[\text{LSH} = \int Q_{\rm I}(t) - \int Q_{\rm O}(t)]$  was stored in the silica sand, 16% of the LSH was absorbed by the Plexiglas shell, and 38% of the LSH dissipated into the surrounding environment at the end of the Exp. 1. This implied that more than 50% of the LSH was lost instead of being absorbed by the silica sands. The composition of the total heat loss  $[Q_{\rm L}(t) = Q_{\rm I}(t) - Q_{\rm O}(t) - Q_{\rm S}(t)]$  was estimated using the CM and the PPM. For the CM, the internal energy increase of the Plexiglas plates  $(Q_{\rm P})$  was 10.4%, and heat dissipation  $(Q_{\rm D})$  was 89.6%; for the PPM, thermal radiation  $(Q_{\rm R})$  was 20.8%, and thermal conduction  $(Q_{\rm CD})$  was 79.2%.

The results demonstrate that the main pathway for heat loss was via thermal conduction from the silica sand to the Plexiglas shell and then to the surrounding environment of the sandbox and

Table 2. Estimated hydraulic and thermal parameters for fine, medium, and coarse sands of Exp. 1.

Parameter	Fine sand	Medium sand	Coarse sand
Saturated hydraulic conductivity, cm min <sup>-1</sup>	0.55	8.5	20
Longitudinal thermal dispersivity cm	4.5	4.2	1.705
Transverse thermal dispersivity, cm	0.04	0.042	0.08

that the majority of the heat loss was heat that had dissipated from the sand box to the surrounding environment rather than heat stored in the Plexiglas shell at the end of the experiment.

The equivalent temperature changes estimated using Eq. [12] and [16] were different at different subregions. The average temperature changes based on the whole system caused by heat loss are shown in Fig. 6. The average temperature change using both the CM and PMM agreed with the result of the total heat loss calculated by placing  $Q_L(t)$  into Eq. [10]. This implied that these two methods can provide good approximations for heat loss during the heat-tracing experiment. The  $R^2$  value for the PPM was 0.954, which was higher than the value of 0.905 for the CM, indicating that the PPM can obtain better approximation of heat loss. This

			-
Experiment	Observed water flux	Estimated water flux	RE
	mI	_ min <sup>-1</sup>	%
1	726.75	587.50*	-19.27†
	726.75	743.25**	2.15‡
2	769.50	758.00**	-1.51‡

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

† Without considering heat loss.

<sup>‡</sup> With considering heat loss.



Fig. 5. Calculated heat balance components of the sandbox, where  $Q_{\rm I} - Q_{\rm O}$  is the sensible heat change of the system,  $Q_{\rm S}$  is the heat stored in the silica sand,  $Q_{\rm P}$  is the heat absorbed by the Plexiglas shell, and  $Q_{\rm D}$  is the heat dissipated into surrounding air.

result also showed that the thermal convection  $[Q_{CV}(t)]$  at the Plexiglas–sand interface was quite small and could be neglected during the heat loss calculation. Thus, using epoxy resin to enlarge the contact area between the Plexiglas shell and silica sand was a feasible means to avoid the wall flow effect during this experiment.

### Improving Parameter Estimation

The equivalent temperature change estimated using both the CM and PPM was used as additional information to improve the parameter estimation. For this purpose, the pseudo temperature (i.e., the summation of the equivalent temperature change and the measured temperature using the data of Exp. 1 for model calibration and Exp. 2 for model validation, respectively), was defined and then applied to re-estimate the hydraulic conductivity using the HYDRUS-2D software.

Figure 7 shows a comparison of the estimated pseudo temperatures using CM and PPM, with the simulated results of HYDRUS-2D during the calibration procedure. The data of the



Fig. 6. Actual total heat loss and average temperature change estimated using the conceptual heat balance method (CM) and the physical process-based method (PPM), respectively, in Exp. 1.

estimated pseudo temperature for the simulated results were distributed along the 1:1 line in both cases. Linear regression was then conducted between the estimated pseudo temperature and the simulated results. The  $R^2$  for both the CM and PPM estimation cases was 0.97, and the slope values of 1.045 and 1.053 were also close to unity. The BTCs of the pseudo temperature estimated using both the CM and PPM at Points 2-3 and 2-4 agreed well with the simulation results ( $R^2 > 0.95$ ; MRE < 2%) (Fig. 8). These results indicate that a reasonable calibration was obtained with the addition of heat loss estimated using both the CM and PPM. The re-estimated hydraulic conductivities of fine, medium, and coarse sand were 0.9, 11, and 23 cm min<sup>-1</sup>, respectively. The method accounting for heat loss could obtain a more precise estimation of water flux with a relative error of 2.15%, which was significantly less than that of the 19.27% for the method without considering heat loss (Table 3). The estimated saturated hydraulic conductivity for fine sand was approximately 1.6 times as large as the value estimated without considering heat loss.

The performance of the CM and PPM was validated by comparing the estimated pseudo temperature of Exp. 2 with that simulated by HYDRUS-2D. Linear regression between the



Fig. 7. Comparison of the simulated temperatures using HYDRUS-2D and the pseudo temperatures estimated using the conceptual heat balance method (CM) and the physical process-based method (PPM) accounting for the heat loss of Exp. 1.



Fig. 8. Comparisons of the simulated temperatures using HYDRUS-2D and the pseudo temperatures estimated using the conceptual heat balance method (CM) and the physical process-based method (PPM) accounting for heat loss at two typical observational points of Exp. 1. Solid lines represent the simulated temperatures, black dots represent the pseudo temperatures estimated using the CM, and circles represent the pseudo temperatures estimated using the physical process-based method. MRE, mean relative error.

estimated pseudo temperature and the simulated result showed that the  $R^2$  and the slope values were close to unity (Fig. 9). The relative error for water flux estimation during Exp. 2 was only -1.51%, which was significantly less than that of 19.27% for the method without considering heat loss. This again proved that the hydraulic properties could be reasonably estimated using the two proposed methods accounting for heat loss.

There was a clear difference between the simulated and pseudo temperature during the early stage (Fig. 7 and 9). The simulated results were obtained considering the overall optimal fitting, resulting in less bias for the plateau period and a in faster temperature increase during the rising period of the BTCs. Additionally, the simulated temperature increased faster than the measured value, which means the pore velocity was overestimated. The average porosity of the heterogeneous medium was



Fig. 9. Comparison of the simulated temperatures using HYDRUS-2D and pseudo temperatures estimated using the conceptual heat balance method (CM) and the physical process-based method (PPM) for Exp. 2.

0.378, and all the pore water could be replaced in 2.6 min for Exp. 1 ( $40 \times 50 \times 0.378/726.75 = 2.6$  min); thus, the temperature changed considerably over a very short time. Although the temperature values were measured three times per minute, the average temperatures per minute were used in this work, resulting in the measured temperatures being slightly lower than the real value, particularly for the rising period of the BTCs. Thus, it is helpful to more accurately estimate heat loss by more frequently monitoring the temperature.

### Discussion

Because of the nonconservative property of heat transfer, there was an inevitable loss of heat from sand to the Plexiglas shell and the surrounding air. Two methods were proposed to evaluate the influence of heat loss on the heat transfer process during the experiments. The CM is a lumped method accounting for the change in heat storage in different parts of the system. However, the PPM described the thermodynamic processes of the heat transfer among different parts of the system in detail, including the heat transfer from sand to shell, heat absorption by the Plexiglas shell, and heat dissipation to the air from a different perspective. The parameters of the PPM, such as surface emissivity and thermal conductivity of the sandbox, were usually known prior and were constant, but the heat transfer coefficient of the CM can only be obtained via linear regression analysis based on the measured data. Therefore, the PPM can be more easily applied in different experiments compared with the CM.

Figure 10 shows the sensitivity of heat storage and the BTCs of the temperature to saturated hydraulic conductivity  $(K_s)$  for Exp. 1. The simulated heat storage change in the sands increased with the increase in the  $K_s$  change (Fig. 10a). Because 80% of the domain was composed of medium sand, the  $K_s$  of the medium sand showed the largest effect on the simulated water flux, followed by the coarse sand (15%) and fine sand (5%). Thus, the sensitivity of the simulated heat storage to the  $K_s$  values of the different sands depended on the fraction of each material in the heterogeneous domain. Moreover, Fig. 10b shows the BTCs of the temperature with different  $K_s$  values of the medium sand at a typical observational point (Point 2-5); the larger  $K_s$  value produced a higher peak value and an increasing rate of temperature.

In general, heat transfer will show a retardation effect because of the adsorption of solid particles; however, if the time is sufficient, the heat absorbed by the particles will be recovered during the experiment, whereas the heat lost to the surroundings is difficult to recover. During laboratory experiments, the heat loss was strongly affected by the size of the experimental apparatus. Heat loss to the surroundings of an experimental device can be estimated using heat balance analysis. Our findings are that parameter estimation using a heat balance method considering heat loss in the vertical direction can be valid for two-dimensional laboratory experiments. For three-dimensional cases, heat losses in lateral directions should also be considered; otherwise, one can use devices with much greater horizontal scales to minimize the lateral heat loss (Wagner et al., 2014b).

Under field conditions, heat loss can be ignored if a heat plume is relatively small and the heat monitoring area is relatively large. In contrast, heat loss will be critical if the heat plume is relatively large and the heat monitoring area is relatively small. For example, Wildemeersch et al. (2014) conducted solute and heat-tracer experiments in a shallow alluvial aquifer. They estimated the average specific heat capacity and found that a heat energy balance approach considering heat loss from a saturated aquifer into unsaturated zones can improve parameter estimation to some extent.

In our sand tank test, we attempted to use some insulated materials, such as polyurethane boards, to reduce the heat exchange between the sand box and the air, but it remained quite difficult to create a completely thermally insulated environment. Moreover, the insulation could not be quantitatively evaluated for the sand box surrounded with insulated materials. It was very



Fig. 10. Sensitivity of heat storage and the breakthrough curves (BTCs) of temperature to the saturated hydraulic conductivity ( $K_S$ ) for Exp. 1: (a) heat storage change in fine, medium, and coarse sand and (b) BTCs of temperature with different  $K_S$  of medium sand at Point 2-5.

difficult to ensure the whole net heat could only be absorbed by the solid particles. Thus, we considered the heat loss and used it as additional information to obtain accurate parameter estimation. Our findings and proposed methods to estimate hydraulic properties are valid for small laboratory sand box studies. Research of the estimation of hydraulic properties using small insulated sand tank tests will be conducted in the future.

## Conclusions

A sandbox experiment was conducted to evaluate the impact of heat loss on water and heat transfer processes in repacked heterogeneous silica sand. Using the measured temperature data, hydraulic and thermal parameters were estimated using the HYDRUS-2D software. Additionally, two methods based on heat balance were proposed to improve the accuracy of the estimation of hydraulic properties. Two conclusions can be drawn:

- Significant heat loss occurred in the water flow and heat transfer processes in the sandbox with the heterogeneous porous medium. The main pathway for heat loss was via thermal conduction from the silica sand to the Plexiglas shell and then to the surrounding environment of the sandbox; the heat dissipated into the surrounding environment accounted for approximately 90% of the total heat loss, whereas 10% of the total heat loss was stored in the Plexiglas shell at the end of the experiment.
- 2. During laboratory tests (e.g., sand tank studies), heat loss was used as additional information to improve the accuracy of the estimated hydraulic and thermal properties as well as water flux. The CM and the PPM were proposed to calculate heat loss. Compared with methods without considering heat loss, the proposed methods accounting for heat loss could significantly reduce the estimated bias of water flux. Thus, more accurate hydraulic and thermal parameters were obtained by considering heat loss.

In this study, we only considered the heterogeneity of three sand materials; the effect of more complex heterogeneity on heat loss and parameter estimation will be the focus of a future investigation. Further research is needed to verify the proposed methods accounting for heat loss as additional information for the estimation of hydraulic and thermal properties in heterogeneous porous media.

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