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A dual-probe heat pulse-based sensor that simultaneously determines soil thermal properties, soil water content and soil water matric potential

Yuki Kojima [a,*], Tomoyuki Kawashima [b], Kosuke Noborio [c], Kohji Kamiya [a], Robert Horton [d]

[a] Department of Civil Engineering, Gifu University, 1-1 Yanagido, Gifu City, Gifu 501-1193, Japan
[b] Graduate School of Natural Science and Technology, Gifu University, 1-1 Yanagido, Gifu City, Gifu 501-1193, Japan
[c] School of Agriculture, Meiji University, 1-1-1 Higashimita, Tama-Ku, Kawasaki City, Kanagawa 214-8571, Japan
[d] Department of Agronomy, Iowa State University, Ames, IA 50011, USA

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ABSTRACT

A dual-probe heat pulse (DPHP) sensor is a robust tool that can measure soil thermal properties and associated soil physical properties and processes. A new DPHP based sensor was developed to simultaneously measure soil thermal properties, soil water content and soil water matric potential. A series of experiments were performed to evaluate the sensor performance. The new sensor was able to measure each soil property with acceptable accuracy. The accuracy of the matric potential determinations was approximately 10% in log scale. The effective range for ψ measurements was −1000 to −2.5 m of water, and the accuracy of the ψ determinations was best between −350 and −2.5 m of water, which included values of field capacity and wilting point for most soils and crops. The sensor design included a single heater wire to provide simultaneous heat inputs to two different materials, i.e., the soil and the sensor porous medium. The single heater wire did not influence sensor accuracy as long as the soil and the sensor porous medium thermal conductivity values were not significantly different. The new DPHP based sensor effectively measured various soil properties, including soil water matric potential, soil water content, and soil thermal property values.

1. Introduction

In-situ measurements of soil thermal properties are essential for many studies associated with soil heat transfer and surface energy balance (e.g., Ochsner et al., 2006), crop germination and growth (e.g., Abu-Hamdeh, 2000), and soil freezing and thawing (e.g., Ochsner and Baker, 2008). In recent years, the dual-probe heat pulse (DPHP) sensor has been widely used to measure soil thermal properties. The DPHP sensor was initially introduced by Campbell et al. (1991) to measure soil volumetric heat capacity, C (J m^{-3} °C^{-1}), and it was later extended by Bristow et al. (1994) to simultaneously measure C, soil thermal diffusivity, α (m^2 s^{-1}), and soil thermal conductivity, λ (W m^{-1} °C^{-1}).

An advantage of the DPHP sensor is the determination of soil thermal properties and several other soil physical properties and processes (He et al., 2018). It is well known that C and soil volumetric water content (θ) have a linear relationship for a given soil at a fixed bulk density (ρ_b). Therefore, θ values can be estimated from measured C values (Campbell et al., 1991; Bristow et al., 1993; Tarara and Ham, 1997; Song et al., 1998). Ochsner et al. (2006) and Heitman et al. (2010) determined ground heat fluxes with DPHP sensors, because a DPHP sensor can measure λ and vertical temperature distributions, i.e., temperature gradients. Heitman et al. (2008a, 2008b) and Xiao et al. (2011) reported that latent heat sinks associated with water evaporation in subsurface soil layers could be quantified by sensible heat balance calculations based on DPHP sensor measurements. Kojima et al. (2014, 2016) used the same sensible heat balance concept and DPHP measurements to determine changes in partially frozen soil ice contents. A DPHP sensor also can be used to determine soil water fluxes based on downstream and upstream temperature responses to heat pulse inputs (Ren et al., 2000; Wang et al., 2002; Mori et al., 2005; Gao et al., 2006). Noborio et al. (1996) and Ren et al. (1999) combined the DPHP technique and time domain reflectometry (TDR) method to develop a thermo-TDR sensor. This sensor can simultaneously determine soil thermal properties with the DPHP measurements and soil electrical properties, i.e., dielectric

Abbreviations: DPHP, dual-probe heat pulse; TDR, time domain reflectometry.

* Corresponding author.
E-mail addresses: kojima@gifu-u.ac.jp (Y. Kojima), kwsm_tmyk1124@yahoo.co.jp (T. Kawashima), noboriok@meiji.ac.jp (K. Noborio), kkamiya@gifu-u.ac.jp (K. Kamiya), rhorton@iastate.edu (R. Horton).

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constant (ε) and electrical conductivity, with the TDR measurements. The measured ε can be converted to θ with empirical equations. Ochsner et al. (2001) used thermo-TDR measurements of ε and C to determine ρ_b and air-filled porosity. Lu et al. (2016) used ε and λ instead of C to determine ρ_b. Liu et al. (2014) and Tian et al. (2018) performed in-situ determinations of transient ρ_b with thermo-TDR sensors. Thermo-TDR sensors were also used to determine ice contents in partially frozen soils. Liquid water content and ice content were determined from ε and either C or λ measured with thermo-TDR sensors (Liu and Si, 2011; Zhang et al., 2011; He et al., 2015; Tian et al., 2015, 2017, 2019). A comprehensive review of DPHP measurements and their applications was provided by He et al. (2018).

Although DPHP sensors have been applied to measure several soil physical properties and processes, one valuable soil property, soil water matric potential (ψ), has not yet been measured. The ψ represents the energy state of soil water associated with capillary and adsorptive forces. It is important for soil water transfer and plant water availability (e.g., Bittelli, 2010; Vereecken et al., 2008). Kojima et al. (2017) developed a ψ sensor that used DPHP measurements in the sensor porous medium made of Kaolinite, which was equilibrated with surrounding soil. The DPHP technique determines thermal properties by analyzing heat pulse induced temperature changes at a temperature sensing needle located at a known distance from the heater needle. The Kojima et al. (2017) sensor had a pair of stainless steel tubes embedded into the Kaolinite porous medium (Fig. 1(a)). One of the tubes contained a resistance heater wire, and the other tube held a thermistor temperature sensor. The DPHP technique was used to determine the porous medium thermal property values. When the sensor was buried in the soil and the porous medium and soil ψ values were equilibrated, the DPHP thermal property measurements were used to determine ψ. They showed that ψ values could be estimated by using either the ψ-C or ψ-λ relationships of the porous medium. This is similar to the approach used by heat dissipation ψ sensors (e.g., Phene et al., 1971; Reece, 1996). The Kojima et al. (2017) sensor could not measure soil thermal properties. However, a re-design of the Kojima et al. (2017) sensor may provide a new sensor with the capability of simultaneously determining soil thermal properties, soil water content and ψ. Such a new sensor that can connect the hydraulic properties and the thermal properties is important to improve our understanding of soil processes (He et al., 2020). Therefore, the objectives of this study are to develop a new DPHP based sensor that simultaneously measures soil thermal properties, ψ, and θ, and to evaluate the performance of the new sensor.

2. Materials and methods

2.1. Sensor development

In this study, the Kojima et al. (2017) DPHP sensor was re-designed by extending the length of the stainless steel tubes so they projected outside of the porous medium. Also, two thermistors were placed in the temperature sensing tube (Fig. 1(b)). When the new sensor is placed in the soil, the porous medium body contacts the soil and the extended stainless steel tubes are also in contact with the surrounding soil. This sensor structure makes it possible to simultaneously measure heat pulse induced temperature changes at two different locations, i.e., one in the soil and one in the sensor porous medium. The temperature changes in the soil are used to determine soil thermal properties and to estimate θ, and the temperature changes in the sensor porous medium are used to determine the thermal properties of the porous medium. The porous medium thermal property values are used to estimate ψ.

Construction of the new sensor involves several steps. First, the porous medium was made by sintering a mixture of Kaolinite (Kaolin, Cat. No.23000-02; Kanto Chemical, Tokyo, Japan), charcoal bone powder (Cat. No.07205-02; Kanto Chemical), activated carbon powder (Cat. No.01085-02; Kanto Chemical), and water. The mass ratio of Kaolinite, charcoal bone powder, activated carbon powder, and water was 4:2:1:7. The mixture was first air-dried at room temperature for one week in a cylindrical plastic column to shape the dough into a cylinder with a 26 mm diameter and 40 mm height. Following the air-dry process, the mixture was oven-dried at 105 °C for 24 h to remove residual water. The mixture cylinder was sintered in a muffle furnace at 500 °C for 8 h and at 1150 °C for 12 h (Abu-Hamdeh, 2000). These drying steps maintained the shape of the mixture cylinder. The sintering resulted in the sublimation of charcoal bone powder and activated carbon powder to form many pores. Two different carbon powders were used to create a range of pore sizes.

Two stainless steel tubes whose inner and outer diameter were 1.6 mm and 2.1 mm, were installed into the porous medium spaced 8 mm apart. The installation was made by drilling a 2.2 mm hole into the porous medium. The spaces between the stainless steel tubes and the porous medium were filled with high thermal conductivity silicone adhesive. The porous medium covered half of the tubes (40 mm from the base), and the other half was exposed. Two NTC 10 kΩ thermistor temperature sensors (NXFT15XH103FA2B090; Murata Manufacturing, Kyoto, Japan) were embedded in the temperature sensing tube. The thermistors were located at 20 mm and 60 mm from the head of the sensing tube so that the thermistor locations were the middles of the exposed part and the porous medium embedded parts of the tubes, respectively. The heater wire embedded in the heating tube was a 75 μm diameter Evanohm wire doubled over twice to produce a heater resistance of 1120 Ω m^{-1}. The inside spaces of the stainless steel tubes were filled with the high thermal conductivity silicone adhesive. The joints between the extension conductor wires and the heater wire/thermistor were encased in epoxy. A photograph of the new sensor is shown in Fig. 2.

2.2. Relationships between thermal properties and matric potential of the porous medium

It is necessary to establish the relationships between thermal properties and ψ of the porous medium to be able to determine soil ψ with the newly developed DPHP sensor. Therefore, laboratory experiments were performed. A 46 cm inner diameter and 8 cm long cylindrical container was filled with an Andisol soil. The texture of the Andisol soil was sandy

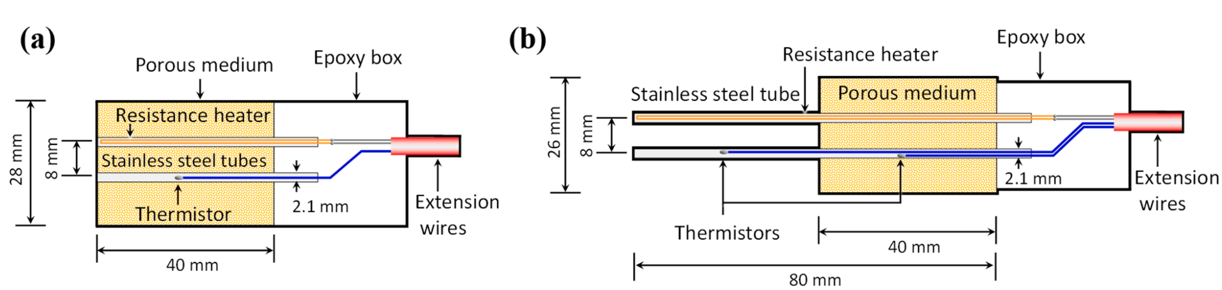

Fig. 1. Schematics of (a) a dual-probe heat pulse (DPHP)-based matric potential sensor developed by Kojima et al. (2017) and (b) the newly developed DPHP sensor that simultaneously measures soil thermal properties, water content and matric potential.

Fig. 2. A photograph of the newly developed dual-probe heat pulse sensor that can simultaneously measure soil thermal properties, water content and matric potential.

loam (60% sand, 34% silt, and 6% clay), organic matter content was 21.9 kg kg^{-1}, and bulk density was 840 kg m^{-3}. Five of the newly developed DPHP sensors (No. 1–5), two MPS-6 ψ sensors (METER Group, Pullman, WA), two 5TE θ sensors (METER Group), and one ML-2600AES tensiometer (mol, Tokyo, Japan) were installed at a depth of 4 cm in the container. The Andisol soil was initially saturated, and then it was allowed to dry for approximately one month in a 25 °C constant temperature room. During the drying process, an electric fan was used to blow air across the soil surface in order to encourage soil water evaporation.

A datalogger, CR1000 (Campbell Scientific, Logan, UT), and two multiplexers, AM16/32 and AM416 (Campbell Scientific), were used to obtain heat pulse measurements with the new DPHP sensor. The heat intensity and duration of the heat pulse produced with the experimental setup were 10 W m^{-1} and 60 s, thus, the applied total heat quantity was 600 J m^{-1}. The DPHP temperature changes at the sensing tubes were recorded for 180 s. The temperature changes associated with heat pulse inputs were analyzed to determine the soil thermal properties and the porous medium thermal properties. The temperature changes at the sensing tube can be described by the pulsed infinite line source solution (de Vries, 1952; Kluitenberg et al., 1993);

$$\Delta T(r,t) = \begin{cases} -\dfrac{q}{4\pi\alpha C} & \mathrm{Ei}\left(\dfrac{-r^2}{4\alpha t}\right) & \text{for } t \leqslant t_0 \\ \dfrac{q}{4\pi\alpha C} & \left[\mathrm{Ei}\left(\dfrac{-r^2}{4\alpha(t-t_0)}\right) - \mathrm{Ei}\left(\dfrac{-r^2}{4\alpha t}\right)\right] & \text{for } t \geqslant t_0 \end{cases} \quad (1)$$

where ΔT is temperature change (°C) at elapsed time t (s) and distance r (m), which is equivalent to tube spacing, q is heat intensity applied at the heater tube (W m^{-1}), and t_0 is the heating duration (s). Equation (1) was fitted to temperature change data to determine the best combination of C and α values. The λ value was determined as the product of C and α. A datalogger, EM50 (METER Group), was used to collect data from the 5TE and MPS-6 sensors. It is known that the factory-supplied functions used to convert 5TE sensor output to θ values are not applicable for some soils, including Andisol soils (Kassaye et al., 2019). Therefore, 5TE calibration equations were established based on measurements made in the Andisol soils at known θ values. Tensiometer data were collected with the CR1000 at a 6 h interval.

Kojima et al. (2017) expressed the relationships between logarithm values of −ψ, log −ψ, and the thermal properties as two intersecting linear functions. Here we adapt a soil water characteristic model to describe these relationships, because the relationships between the ψ and the thermal property values of the sensor porous medium were similar to the soil water retention curves. The model proposed by Durner (1994) to describe water retention curves of soils having heterogeneous pore size distributions was chosen for this study. The model was modified by replacing water content with a thermal property, C or λ:

$$x = (x_s - x_r)\left[w_1(1+|\alpha_1\psi|^{n_1})^{1/n_1-1} + w_2(1+|\alpha_2\psi|^{n_2})^{1/n_2-1}\right] + x_r \quad (2)$$

where x represents a thermal property of the porous medium, i.e., C or λ, x_s and x_r are thermal property values corresponding to the saturated and residual water contents of the porous medium, w_1 and w_2 are weighting coefficients, α_1 and α_2, and n_1 and n_2 are empirical parameters determining the curve shape. The parameters, x_s, x_r, w_1, w_2, α_1, α_2, n_1, n_2, were determined by fitting Eq. (2) to the observations by using the Solver code in Microsoft Excel. The Durner (1994) model was selected due to its relatively simple equation form and its ability to express the complicated curve shape. Some other water retention curve models such as the van Genuchten (1980) model could not capture the slight changes in thermal property values as they approached their minimum values, i.e., x_r in Eq. (2). The Durner (1994) model described well the relationships with a relatively simple equation form and parameters.

2.3. Accuracy of the new DPHP sensor to determine matric potential, thermal property values, and volumetric water content

A second experiment was performed, which included five new DPHP sensors, three MPS-6 sensors, one tensiometer, and three thermo-TDR sensors. Andisol soil was packed into the same box at the same ρ_b (840 kg m^{-3}), and sensors were placed in the soil at the 4 cm depth. The initially saturated Andisol soil was allowed to dry for a month with a fan at a constant temperature room (25 °C). The thermo-TDR sensors measured θ, λ, and C as reference values to compare to values determined with the new DPHP sensors. The thermo-TDR sensors used in this study followed the design of Ren et al. (1999). The thermo-TDR sensors had three 40 mm long, 1.3 mm outer diameter stainless steel tubes with 6 mm spacing. Each tube held a type-T thermocouple, and the center tube held 533 Ω m^{-1} resistance heater wire. A CR1000 was used to collect heat pulse data from the thermo-TDR sensors. Applied heat intensity and duration were 66 W m^{-1} and 8 s, thus, the total heat quantity applied was 528 J m^{-1}. To determine λ and C values, Eq. (1) was fitted to the temperature changes measured with the thermo-TDR sensor. A CR1000, TDR100 (Campbell Scientific), and SDMX-50 multiplexer (Campbell Scientific) were used to collect the thermo-TDR waveforms. Measured ε values were converted to θ values with an empirical equation for Andisol soil proposed by Miyamoto et al. (2001);

$$\theta = -0.0356 + 4.35\times10^{-2}\varepsilon - 1.23\times10^{-3}\varepsilon^2 + 1.48\times10^{-5}\varepsilon^3 \quad (3)$$

The EM50 was used to collect MPS-6 sensor data, and a CR1000 was used to collect tensiometer data. Data collection occurred every 6 h.

The first experiment focused on establishing the sensor porous media ψ and thermal property relationships. The relationships were established by connecting the porous media thermal property values and the MPS-6 ψ values. The second experiment determined the accuracy of the new sensor to measure ψ, thermal property values (λ and C), and θ. We used the same soil (Andisol) for the first and second experiments. We should note that the new sensor determines soil ψ from the relationship between ψ and thermal properties of the sensor porous medium. Thus, the soil ψ estimation performance with the new DPHP sensor is relevant to other soil types as long as the water in the sensor porous medium and the soil is in equilibrium. The new DPHP sensor measured soil C values which were converted to θ values with the following equation (Campbell et al., 1991):

$$\theta = \frac{C - \rho_b c_s}{C_w} \quad (4)$$

where c_s is the specific heat of soil solids (J kg^{-1} °C^{-1}), and C_w is the volumetric heat capacity of water (4.18 × 10^6 J m^{-3} °C^{-1}). The c_s was assumed to be 0.8 × 10^3 J kg^{-1} °C^{-1} based on literature values (Kasubuchi, 1975; Maeda et al., 1983). The ψ, λ, C, and θ values determined by the new DPHP sensor were compared to those determined by MPS-6 and thermo-TDR sensors. The accuracy of the new sensor was characterized as root mean square error (RMSE) and mean absolute percentage error (MAPE) (Yilmaz and Kaynar, 2011).

$$\mathrm{RMSE} = \sqrt{\frac{\sum \left[X_{(DPHP)} - X_{(reference)}\right]^2}{m}} \tag{5}$$

$$\mathrm{MAPE} = \frac{1}{m}\sum\left|\frac{X_{(reference)} - X_{(DPHP)}}{X_{(reference)}}\right| \times 100 \tag{6}$$

where X is a sensor measured property, m is the number of data points, and the subscripts of X, DPHP and reference, represent data obtained from DPHP sensors and the reference values are measured with MPS-6 or thermo-TDR sensors. Because the ψ values ranged over several orders of magnitude, we evaluated the sensor accuracy of ψ based on log −ψ, which is known as pF.

2.4. Influence of the single heater wire on the soil and the sensor porous medium properties

The new DPHP sensor used a single resistance heater wire to produce temperature changes in both the soil and the sensor porous medium. When the λ values of the soil and the sensor porous medium differed, there were different heat applications into the soil and into the porous medium. Such a heterogeneous heat application could be a source of measurement error. Therefore, the following experiment was performed to evaluate the influence of using a single heater wire for the soil and porous medium measurements. The experimental setup is shown in Fig. 3. The new DPHP sensor was placed in a plastic box whose dimensions were 102 mm long, 30 mm wide, and 38 mm tall. The inside of the box was partitioned into two chambers by a 2 mm thick plastic sheet placed between the porous medium and the exposed stainless steel tubes of the sensor. The chamber holding the porous medium portion was filled with dry (θ = 0.10 m^3 m^{-3}) or wet (θ = 0.45 m^3 m^{-3}) Andisol soil. This procedure resulted in a dry and wet condition of the porous medium. The other chamber for the exposed tubes was initially filled with dry Andisol soil. The thermal property values of the Andisol soil and porous medium were measured with the DPHP sensor five times with two-hour intervals. Then, water was added to the dry Andisol soil in the chamber with the exposed tubes such that θ = 0.45 m^3 m^{-3}, and DPHP measurements were performed five times. During the measurements, the surface of the soils was sealed with plastic. The thermal property values of the porous medium before and after adding water to the Andisol soil were compared. A single shared heater was deemed to be acceptable, if there was no significant difference in the porous medium thermal property values with dry and wet conditions of the Andisol soil into which the exposed stainless steel tubes were inserted.

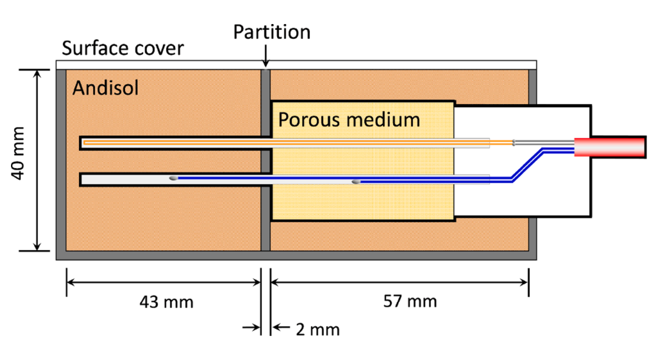

Fig. 3. A schematic of the experiment designed to evaluate the influence of the single shared heater wire on the soil and porous medium properties.

2.5. Time required for the sensor porous medium to equilibrate with surrounding soil

Equilibration time is a general concern for all porous media ψ sensors. The equilibration time depends on the dimension and pore size distribution of the porous media (e.g., Noborio et al., 1999). Thus, we performed an experiment to evaluate the equilibration time for this sensor. Andisol soil was packed into three plastic boxes (160 mm long, 90 mm wide, 60 mm tall) with ρ_b = 840 kg m^{-3}. The Andisol soil included three θ values (0.15, 0.30, and 0.45 m^3 m^{-3}), and each box was used for each θ. The new DPHP sensors were inserted into the center of each box. The porous medium portion of each DPHP sensor was air-dry when it was inserted into the soil. Immediately after inserting a sensor into a box, DPHP measurements of λ and C were started, and the temporal values of λ and C were recorded. Measurements were performed every hour for one week. The experiment was performed in a constant temperature room at 20 °C. The times required for the porous medium to equilibrate with surrounding soils were evaluated based on the times it took for property values to become stable. This experiment assumed situations that mimicked dynamic θ changes due to precipitation (air-dry porous media placed in wet soils). The conditions imposed in this experiment were relatively extreme compared to actual field conditions, thus, the results indicated the sensor's maximum equilibration times.

3. Results and discussion

3.1. Relationships between thermal properties and matric potential of the sensor porous medium

Fig. 4 shows soil θ measured with 5TE sensors, soil ψ measured with tensiometers and MPS-6 sensors, and C and λ of the sensor porous medium measured with the new DPHP sensor. The tensiometer and the MPS-6 sensor measure different ψ ranges. The tensiometer measured ψ from 0 to −1.5 m of water (see Fig. 4), and the MPS-6 sensor measured ψ values smaller than −1.5 m of water (see Fig. 4). The θ values displayed in Fig. 4a represent the average values of two 5TE sensors, and the ψ values smaller than −1.5 m of water displayed in Fig. 4b are the average values of two MPS-6 sensors. The C and λ values measured with the five new DPHP sensors are shown in Fig. 4c and 4d. The Andisol θ values decreased from 0.66 to 0.24 m^3 m^{-3}, and the ψ values decreased from −0.03 to −2,640 m of water due to evaporative drying of soil during the 30 day (720 h) experiment. The porous medium C values decreased from 3.1 to 1.3 MJ m^{-3} °C^{-1} on average, and the porous medium λ values decreased from 0.76 to 0.32 W m^{-1} °C^{-1}. Dynamic decreases in C and λ were observed after 100 h, corresponding to the air entry value of the porous medium. Decreases in C became quite small after 450 h, while λ kept decreasing until the end of the experiment. The decrease in C after 450 h was 0.03 MJ m^{-3} °C^{-1} (2% on average), and the change in λ after 450 h was 0.05 W m^{-1} °C^{-1} (13% on average). Thus, λ was more sensitive than C to small changes in porous medium θ. A possible reason was that the changes in θ significantly influenced solid particle contacts when θ was small. The λ was in part controlled by the particle contacts (e.g., Jury and Horton, 2004). Although all five sensors estimated similar C values through the experiment, the sensors estimated slightly different λ values, because λ was sensitive to minor differences in the internal structure of the porous medium or to contacts between the stainless steel tubes and the porous medium.

The relationships between ψ and the thermal properties for sensor No. 1 are presented in Fig. 5. The other sensors had similar relationships. Both C and λ changed very little in the ψ range from 0 to −2.5 m of water, and they decreased in the ψ range from −2.5 to −10 m of water. These trends of the thermal properties were associated with the air entry value of the porous medium. At ψ values smaller than −10 m of water, C

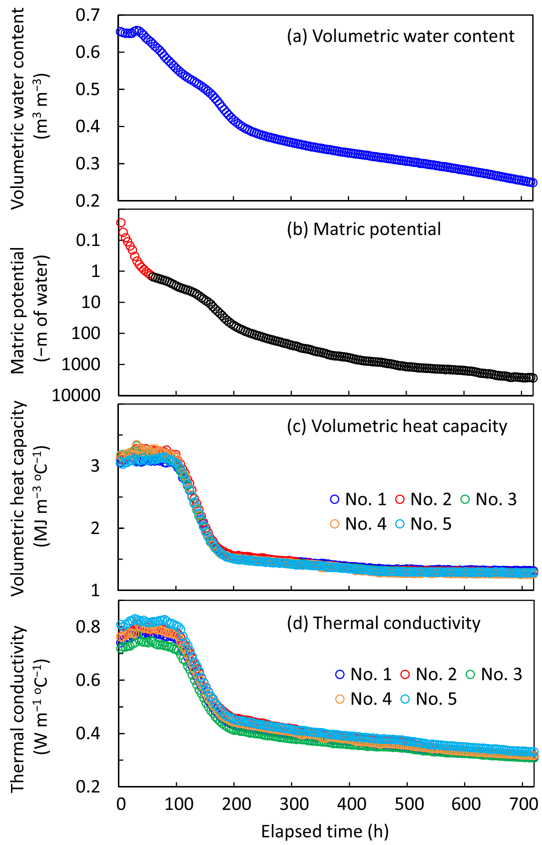

Fig. 4. Time dependent values of (a) volumetric water content, (b) matric potential, (c) volumetric heat capacity and (d) thermal conductivity of the sensor porous media. The red and black symbols in (b) represent matric potential values measured with tensiometers and MPS-6 sensors, respectively. The volumetric heat capacity and thermal conductivity panels include all values measured with five different dual-probe heat pulse sensors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

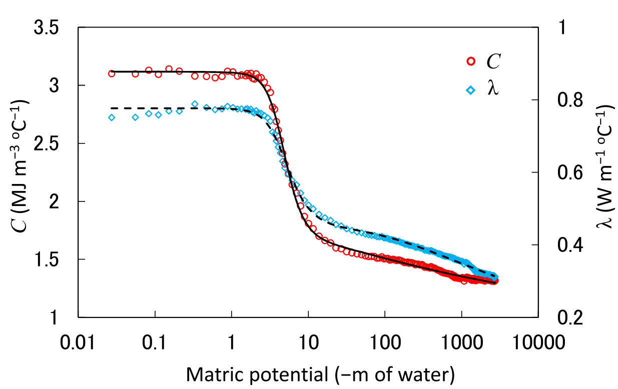

Fig. 5. Sensor porous media relationships between volumetric heat capacity (C) and matric potential and thermal conductivity (λ) and matric potential (sensor no.1). Solid and broken lines indicate the modified Durner (1994) type models fitted to the observed C and λ versus matric potential values.

and λ gradually decreased, although changes in C at ψ values smaller than −1000 m of water was quite small. Eq. (2) was fitted to these observed relationships (black solid and broken lines in Fig. 5). The fitted parameters for the five sensors are presented in Table 1. Adjusted coefficients of determination R^2_{adj} were > 0.99 for all of the fitted curves. Each parameter had only small variation, because the relationship between ψ and the thermal properties of the five sensors were similar. The x_r values for λ converged to zero, which was not a realistic value, however, we used the zero values, because we prioritized the optimization of the model. ψ values could be derived from Eq. (2) using the fitted parameters and measured thermal property values. Both C and λ were constant as ψ ranged from 0 to −2.5 m of water. Therefore, this sensor was not able to determine ψ values larger than −2.5 m. The C values became almost constant for ψ values smaller than −1000 m of water, while λ values decreased until the end of the experiment. The smallest ψ value was −2600 m of water. Therefore, the measurable ψ range for the new DPHP sensor was −2.5 to −1000 m when ψ was estimated from C, and it was −2.5 to −2600 m of water when ψ was estimated from λ (this range might be larger if the experiment was performed for a longer duration). The fact that the λ based determination had a wider range of measurable ψ was consistent with that reported by Kojima et al. (2017).

3.2. Accuracy of the DPHP sensor estimated matric potential, thermal property, and volumetric water content values

Fig. 6 displays comparisons between MPS-6 ψ values and the new DPHP sensor ψ values obtained in the second experiment. The new DPHP sensor-based ψ values were determined with Eq. (2), which used the parameters shown in Table 1. Only ψ values smaller than −2.5 m of water were included, because the DPHP sensor could not determine ψ values larger than −2.5 m. All five sensors had similar trends with only slight variations in the observed values. The variations could have been caused by minor differences in the sensor properties. The DPHP sensor ψ values were consistent with the MPS-6 values when ψ was between −2.5 and −400 m of water. For ψ values less than −400 m of water, the DPHP values tended to be smaller than the MPS-6 values. The reason in part for the difference was that the room temperature fluctuated by 3 °C partway through the measurements, which caused the MPS-6 measured values to suddenly decrease.

Although the room temperature change may have affected the accuracy of the MPS-6 ψ measurements, we decided to evaluate the performance of the DPHP sensor by setting the MPS-6 ψ values as the reference values. The five RMSE values for the sensors ranged from 0.26 to 0.44 for log −ψ estimated from C, and from 0.34 to 0.47 for log −ψ estimated from λ. The MAPE values had similar trends. The MAPE values ranged from 10.3 to 14.4% when log −ψ was estimated from C, and from 11.0 to 16.4% for log −ψ estimated from λ. The RMSE and MAPE values indicated that ψ values estimated from C were more accurate than those estimated from λ, although λ was more sensitive to ψ changes at the dry end. Kojima et al. (2017) showed that C was less sensitive to temperature variation than λ, so regarding temperature effects, C may be a more favorable property than λ to determine ψ. It is known that DPHP C determinations are sensitive to the r value in Eq. (1) and deflection of stainless steel tubes causes errors in C determinations (e.g., Kluitenberg et al., 1993). However, the tubes inside the porous media are fixed by the silicone adhesive so that the tube deflection does not occur. The relative errors between DPHP-based ψ and reference ψ tended to increase for all of the sensors as ψ decreased. In particular, there was a dynamic increase in relative error when ψ values were smaller than −350 m of water, which corresponded to the possible room temperature induced errors for the MPS-6 sensor measurements. The relative errors for ψ values between −2.5 and −350 m were mostly less than 10%. Dry soil conditions were associated with small C and λ values of the porous media, and the slopes of the Eq. (2) relationships were also small, i.e., small errors in C and λ during dry soil conditions led to relatively large errors in ψ. Even with this shortcoming, the sensor showed good accuracy, within 10%, for the range in ψ values. The new DPHP sensor is able to measure ψ of other soils with this same accuracy as long as the sensor porous medium and the soil have an adequate hydraulic connection. For coarse-textured soils, such as quartz sand, the sensor may not perform as well, due to limited hydraulic connectivity between the sensor porous medium and the soil (Noborio et al., 1999). The measurement accuracy

Table 1
Empirical parameters for the modified Durner (1994) type of model to describe the relationship between matric potential (ψ) and volumetric heat capacity (C) or ψ and thermal conductivity (λ).

Thermal properties	Sensor number	x_s	x_r	w_1	w_2	α_1	α_2	n_1	n_2
		J m^{-3} °C^{-1} or W m^{-1} °C^{-1}				m^{-1}			
C	1	3.12×10^6	0.96×10^6	0.661	0.339	0.225	0.064	3.81	1.15
	2	3.24×10^6	1.21×10^6	0.788	0.212	0.223	0.012	3.66	1.51
	3	3.22×10^6	0.84×10^6	0.646	0.354	0.240	0.073	3.67	1.13
	4	3.25×10^6	0.84×10^6	0.656	0.344	0.235	0.044	3.86	1.15
	5	3.12×10^6	1.10×10^6	0.700	0.300	0.222	0.068	4.04	1.24
λ	1	0.777	0.000	0.428	0.572	0.219	0.007	3.06	1.12
	2	0.795	0.000	0.406	0.594	0.214	0.007	3.02	1.13
	3	0.744	0.000	0.425	0.575	0.228	0.010	3.03	1.10
	4	0.794	0.000	0.423	0.577	0.226	0.008	3.08	1.12
	5	0.827	0.000	0.435	0.565	0.218	0.008	3.11	1.11

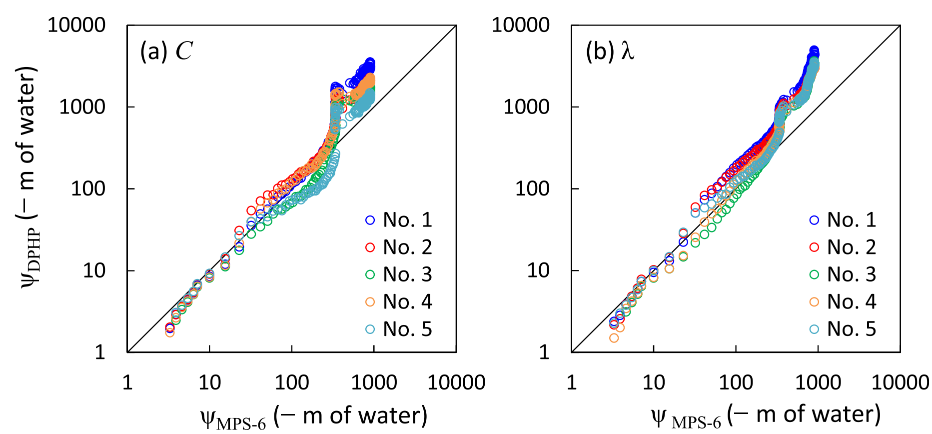

Fig. 6. Comparisons between matric potential values measured by the new dual-probe heat pulse sensor (ψ_{DPHP}) and those determined with MPS-6 sensors ($\psi_{MPS\text{-}6}$). The ψ_{DPHP} values were determined from (a) volumetric heat capacity (C) values and (b) thermal conductivity (λ) values.

and measurable range of ψ could be further improved by developing a more robust sensor porous medium.

The new DPHP sensor determined C values of the soil were converted to θ values. Thus, we evaluated the sensor performance of C determination by comparing θ values converted from C with Eq. (4) and reference θ values measured with the TDR function of the thermo-TDR sensors. Fig. 7 shows the θ values determined with TDR are consistent with values estimated from DPHP-based C measurements. Sensors 2, 3, and 4 provided accurate estimations of θ, and RMSE values for the three sensors were 0.018 m^3 m^{-3}, while sensors 1 and 5 gave under/overestimations of θ. The RMSE values for sensors 1 and 5 were 0.028 and 0.052 m^3 m^{-3}, which were larger than those for sensors 2, 3, and 4. A possible reason for these errors was deflections in the exposed stainless steel tubes. There was a possibility that the r values for sensors 1 and 5 changed slightly from the calibrated values caused by packing soil around the tubes in the container. Another possibility for the under/overestimation, could have been non-homogeneous soil moisture distributions in the container. Even with the over/underestimations, the differences in DPHP-based and TDR-based θ values were within 0.05 m^3 m^{-3} on average. These results are similar to the heat pulse sensor results reported in earlier studies (e.g., Basinger et al., 2003), indicating that the new DPHP sensor determines C and θ quite accurately.

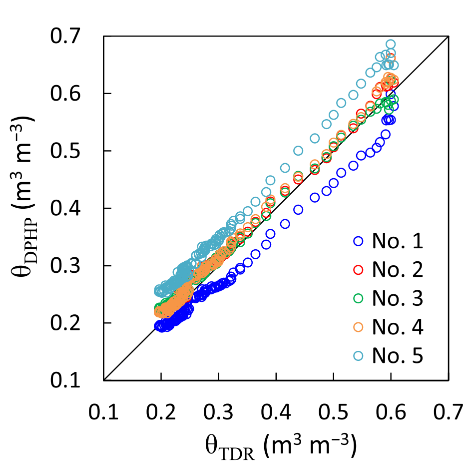

Fig. 7. Comparisons between volumetric water content values estimated from the new dual-probe heat pulse sensor (θ_{DPHP}) measured volumetric heat capacity values and those measured with the time domain reflectometry (TDR) function of the thermo-TDR (θ_{TDR}) sensor.

Fig. 8 shows comparisons between λ values measured by the thermo-TDR sensors and λ values measured by the new DPHP sensors. The λ values from the different sensors were consistent, although the new DPHP sensor-based λ values tended to be slightly smaller than the thermo-TDR values. The RMSE of the DPHP sensor λ values was 0.026 W m^{-1} °C^{-1}. Thus, the new DPHP sensor measured λ quite accurately. The slight underestimation of λ might be caused by sensor configuration, i.e., using one heater wire to heat both porous medium and soil, or to the 60-s long heating duration. The influence of sharing one heater wire will be discussed in section 3.3. Most DPHP measurements performed by other investigators had a short-duration heat pulse application, such as 8 s, but the new DPHP sensor required a relatively long heating duration, due to the unusually long heater tube length. Thus, the heater wire resistance in the new DPHP sensor was larger than those used in earlier DPHP sensors, i.e., the heat flux produced by a 12 V power supply from the datalogger was smaller than the heat flux produced in the thermo-TDR. The long heating duration could cause three-dimensional heat

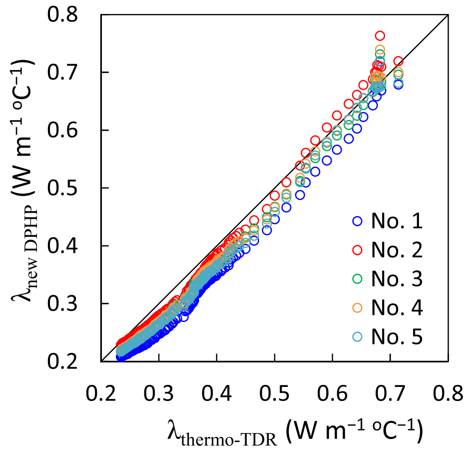

Fig. 8. Comparisons between soil thermal conductivity values measured with the new dual-probe heat pulse sensor ($\lambda_{\text{new DPHP}}$) and those measured with a thermo-time domain reflectometry ($\lambda_{\text{thermo-TDR}}$) sensor.

conduction, which could cause minor errors in the λ values.

3.3. Impact of sharing a single heater wire on the soil and the sensor porous medium measurements

Table 2 shows the *C* and λ values of the sensor porous medium with dry and wet Andisol soils into which the exposed tubes of the new DPHP sensor were inserted. Only small changes in the sensor porous medium *C* and λ values were caused by the different water content conditions of the Andisol soil. The measured porous medium *C* value increased from 1.20 to 1.22 MJ m^{-3} °C^{-1} (a 2% increase), and the λ value increased from 0.25 to 0.26 W m^{-1} °C^{-1} (a 4% increase) when the soil was wet and the porous medium itself was dry. The measured porous medium *C* value decreased from 3.45 to 3.34 MJ m^{-3} °C^{-1} (a 3% decrease), and the λ value increased from 0.75 to 0.76 W m^{-1} °C^{-1} (a 1% increase) when the soil was wet and the sensor porous medium itself was wet. Wetting the Andisol soil caused its λ value to increase from, on average, 0.17 to 0.55 W m^{-1} °C^{-1}. Differences in soil and sensor porous medium thermal properties appeared to only have a minor impact on the heat dissipation that occurred from the exposed part of the heating tubes. Thus, differences between λ of the porous medium and λ of the soil did not cause significant errors in the new DPHP sensor measurements. It should be noted that the λ ranges of the Andisol soil and the porous medium were similar, approximately 0.1 to 0.8 W m^{-1} °C^{-1} for the Andisol soil and 0.2 to 0.8 W m^{-1} °C^{-1} for the porous medium. Sharing one heater tube could possibly cause some measurement errors if the sensor was used in high λ soils, such as wet sandy soils.

Table 2
Volumetric heat capacity and thermal conductivity values of the dual-probe heat pulse sensor porous medium placed in dry and wet Andisol soil. Each value is the mean of five repeated measurements. The standard deviations are not shown because they are quite small for all cases (<0.01).

	Volumetric heat capacity of sensor porous medium		Thermal conductivity of sensor porous medium	
	MJ m^{-3} °C^{-1}		W m^{-1} °C^{-1}	
Initial sensor porous media condition	Andisol soil condition			
	Dry	Wet	Dry	Wet
Dry	1.20	1.22	0.25	0.26
Wet	3.45	3.34	0.75	0.76

3.4. Time required for the porous medium water to equilibrate with the soil water

Fig. 9 shows thermal property temporal variations for an initially air-dry sensor porous medium after it is placed in soils at θ = 0.30 and 0.45 m^3 m^{-3}. The data for the porous medium placed in θ = 0.15 m^3 m^{-3} soil were not shown because there was no apparent change. Variations of *C* and λ occurred quickly within the first hour. It took only 1 h for *C* to be within 5% of the final value in both θ = 0.30 and 0.45 m^3 m^{-3} soils, and it took 16 and 17 h for λ.

The results of this experiment indicated that the new DPHP sensor can follow the small change in soil water content relatively fast. It is expected that the ψ between the two materials is similar in field condition so that the equilibrating time in the field must be much shorter. It was found that equilibrating times for *C* were shorter than those for λ. So, compared to λ, the determination of ψ from *C* has an advantage of shorter equilibration time.

4. Conclusions

A new DPHP based sensor was developed to simultaneously measure soil thermal properties, ψ, and θ, and its performance was evaluated. The new sensor was able to measure each property with acceptable accuracy. The effective range of ψ measurements was −1000 to −2.5 m of water, and the accuracy of the ψ measurements was particularly good in the range of −350 to −2.5 m of water. This covered the ψ range critical for plant water availability, i.e., field capacity and wilting point (−3.3 and −150 m of water). Although the sensor used a single heater wire to produce heat input to two different materials, i.e., the soil and the sensor porous medium, this did not influence sensor accuracy as long as the λ values of the soil and the porous medium were not significantly different. The equilibration times between the senor porous media and the soil were insignificant for most real world type of conditions.

It was found that the new DPHP based sensor is promising, and the next challenge is to evaluate its performance in field studies. The use of the new sensor in the field may have some challenges, such as the electrical power supply and the influence of soil temperature variations. The power consumption of the new DPHP sensor was about twice that of conventional DPHP sensors. DPHP sensors have been used in the field with a battery and a solar panel (e.g., Ochsner and Baker, 2008; Xiao

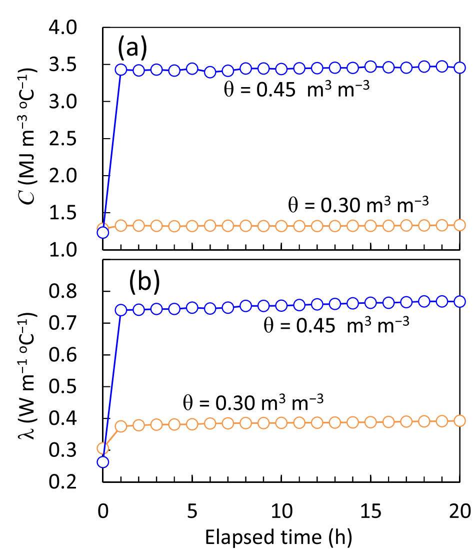

Fig. 9. Time dependent values of (a) volumetric heat capacity (*C*) and (b) thermal conductivity (λ) of an initially air-dry dual-prpbe heat pulse sensor porous media while the sensor is equilibrating with the surrounding soil. The volumetric water content (θ) labels in the figure represent the water content values of the surrounding soil.

et al., 2011), so the new sensor can be deployed in the field. The portable devices to control the DPHP sensors developed by Ravazzani (2017) may help in places where it is challenging to use battery power. The temperature dependence of the thermal property measurements may impact the accuracy of the ψ estimates. Kojima et al. (2017) report that the temperature dependence of the *C* is smaller than that of the λ. Thus, ψ determinations based on *C* may be preferred in the field. Alternatively, measurements can be made at times with the same temperature. The new DPHP sensor will be further examined under actual field conditions.

CRediT authorship contribution statement

Yuki Kojima: Conceptualization, Methodology, Data curation, Writing – original draft. **Tomoyuki Kawashima:** Methodology, Data curation. **Kosuke Noborio:** Conceptualization, Methodology, Writing – review & editing. **Kohji Kamiya:** Conceptualization, Methodology. **Robert Horton:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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