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Laboratory techniques to evaluate thermal conductivity for some soils

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Abstract The thermal conductivity of two soils was investigated through laboratory studies. These laboratory experiments used the single probe and dual probe methods to measure and compare thermal conductivities. The soils used were classified as sand and loam. Thermal conductivity measured using single probe method ranged from 0.95 to 2.11 for sand and from 0.49 to 0.76 W/m K for loam. Thermal conductivity measured using dual probe method ranged from 0.98 to 2.17 for sand and from 0.51 to 0.78 W/m K for loam. Finally, it was found that sand had higher values of thermal conductivity than loam for all soil conditions studied.

Nomenclature

d	constant perature during cooling after
$-Ei(-x)$	exponential integral
I	current in the line source, A
q'	energy input per unit length of heater per unit time, W/m
R	specific resistance of the wire, Ω/m
r	distance between electrodes, m
S	slope of the straight-line portion of the temperature rise or fall versus ln(t)
T	sensor temperature, C°
T_o	initial temperature, C°
t	time, seconds
t_h	heating time after which cooling would start, seconds
t_o	heat pulse duration, seconds
t_m	time at which ΔT_m is recorded, seconds
ΔT_m	maximum temperature change at a distance r from the heater, K
ρc	volumetric heat capacity, J/m^3 K

Greek symbols

λ	thermal conductivity of the material surrounding the line source, W/m K
κ	thermal diffusivity, m^2/s

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1 Introduction

Soil thermal properties are required in many areas of engineering, agronomy, and soil science, and in recent years considerable effort has gone into developing techniques to determine these properties. Thermal conductivity is considered one of the most important thermal properties of plant environment. It is considered as the property that controls heat flow through materials of different types.

The thermal conductivity of a soil depends on several factors. These factors can be arranged into two broad groups, those which are inherent to the soil itself, and those which can be managed or controlled, at least to a certain extent by human management. Those factors or properties that are inherent to the soil itself include the texture and mineralogical composition of the soil. Factors influencing a soil's thermal conductivity that can be managed externally include water content and soil bulk density. The way a soil is managed will play an important part in determining its thermal conductivity. Any practice or process which tends to cause soil compaction will increase bulk density and decrease porosity of a soil. This in turn will have a significant effect on thermal conductivity. A certain soil will not necessarily have a given value of thermal conductivity unless all of the factors are approximately the same whenever the measurements are taken.

Thermal properties can be determined indirectly by measuring the rise or fall of temperature in response to heat input to a line source at the point of interest [1, 2, 3, 4, 5]. De Vries [6, 7] developed models that allow estimation of thermal conductivity and volumetric heat capacity of soils from the volume fractions of their constituents and the shape of the soil particles. The dual-probe heat-pulse technique [8, 9, 10, 11] has also been used to make measurements of soil thermal properties. It consists of two parallel needle probes separated by a distance (r). One probe contains a heater and the other a temperature sensor. With the dual-probe device inserted in the soil, a heat pulse is applied to the heater and the temperature at the sensor probe is recorded as a function of time. Soil thermal conductivity can be determined from these data.

The purpose of this study was to determine thermal conductivity of sand and loam soils as affected by bulk density using the single and dual probe techniques. The results obtained using the single probe method will be compared with the results obtained for the same soil type but using the dual probe method. Furthermore, thermal conductivity of other soil types evaluated using both methods will be compared.

2
Theory

Due to the linear heat source and cylindrical geometry of the single probe dissipation sensors, sensor temperature (T) during heating is related to time (t) according to the theoretical solution for a line heat source [7, 8, 12, 13]

$$T - T_o = (q'/4\pi\lambda)\ln(t + t_o) + d \quad (1)$$

Where T_o is the initial temperature (C°), q' is the energy input per unit length of heater per unit time (W m^{-1}), λ is the thermal conductivity of the material surrounding the line source (W m^{-1} °C^{-1}), t_o is a time correction used to account for the finite dimensions of the heat source and the contact resistance between the heat source and the medium outside the source, and d is a constant. The corresponding equation for sensor temperature during cooling after t_h seconds of heating is given by [12, 13]

$$T - T_o = (q'/4\pi\lambda)[\ln(t + t_o) - \ln(t + t_o - t_h)] + d \quad (2)$$

Nonlinear least-squares regression is used to solve for λ. An alternative approach is to assume $t_o \ll t$ so that $\ln(t + t_o)$ approximately equals $\ln(t)$. With this assumption, linear regression can be used to calculate λ from heating data with Eq. (1) and ln(t) as the independent variable or from cooling data with Eq. (2) and $\ln[t/(t-t_h)]$ as the independent variable. Furthermore, if the relation between T and ln(t) is linear, then λ can be simply estimated from the change in sensor temperature between two times, t_1 and t_2, by

$$\lambda = (q'/4\pi)[\ln(t_2) - \ln(t_1)]/[T(t_2) - T(t_1)] \quad (3)$$

For cooling, the analogous to Eq. (3) is

$$\lambda = (q'/4\pi)\ln[(t_2/t_1)(t_1 - t_h)/(t_2 - t_h)]/[T(t_2) - T(t_1)] \quad (4)$$

Eqs. (3) and (4) can be approximated by substituting I^2R for q' as

$$\lambda = 0.0796\, I^2R/S \quad (5)$$

where λ is the thermal conductivity (W/m K), I is the current in the line source (A), R is the specific resistance of the wire (Ω/m), and S is the slope of the straight-line portion of the temperature rise or fall versus ln(t) during heating process (i.e. $S = \Delta T/\Delta\ln(t)$) and S is the slope of the straight-line portion of the temperature fall versus $\ln[t/(t-t_h)]$ during cooling process (i.e. $S = \Delta T/\Delta\ln[t/(t-t_h)]$).

The dual probe methodology is based on a solution of the radial heat conduction equation for an infinite-line heat source in a homogenous and isotropic medium at a uniform initial temperature. Volumetric heat capacity ρc (J/m^3 K) may be determined with a dual-probe heat-pulse method [7] as:

$$\rho c = (q'/4\pi\kappa\Delta T_m)[Ei(-r^2/4\kappa(t_m - t_o) - Ei(-r^2/4\kappa t_m)] \quad (6)$$

$$\kappa = (r^2/4)\{[1/(t_m - t_o) - 1/t_m]/[\ln(t_m/(t_m - t_o))]\} \quad (7)$$

where q' is the amount of heat input per unit time and unit of length of a probe (W/m), κ is the thermal diffusivity (m^2/s), r is the distance (m) between electrodes, ΔT_m is the maximum temperature change (K) at a distance r from the heater, t_m is the time (s) at which ΔT_m is recorded, t_o is a heat pulse duration (s), and $-Ei(-x)$ is the exponential integral. The exponential integral can be evaluated using formula 5.1.53 of Abramowitz and Stegun [14] for $0 \le x \le 1$ and formula 5.1.56 of Abramowitz and Stegun [14] for $1 \le x \le \infty$. Apparent thermal conductivity of soil λ (W/m K) is obtained by definition [11]

$$\lambda = \kappa\rho c \quad (8)$$

Substituting Eqs. (6) and (7) into Eq. (8) yields

$$\lambda = (q'/4\pi\Delta T_m)\{Ei[-\ln(t_m/(t_m - t_o))/(t_o/t_m)] - Ei[-\ln(t_m/(t_m - t_o))/(t_o/(t_m - t_o))]\} \quad (9)$$

in which r is eliminated.

3
Materials and methods

The dual-probe heat-pulse device used for making measurements in this study consisted of parallel heater and sensor needle probes made from thin stainless steel tubing 100 mm long and 2 mm in diameter. The needles were fixed on an acrylic plate by epoxy glue. The heater to sensor probe spacing was 5 mm. The diameter, length, and spacing of the needles were such that the assumptions of a probe of infinite length would produce negligible errors in the calculated thermal conductivity [15]. The line heater was made from enameled Evanohm wire (Wilbur B. Driver Co., Newark, NJ), which was pulled into the heater needle. The heater resistance (R) was 300 Ω m^{-1}. The temperature sensor consisted of copper-constantan thermocouple junction, which was pulled into and centered in the sensor needle. The needles were filled with high thermal conductivity epoxy glue to minimize radial temperature gradients through the probe and to provide a water-resistant, electrically insulated probe. Heat was generated by applying voltage from a 9-volt DC power supply to the heater for a fixed period of time. Lower power inputs were used to minimize the effects of heating on soil water movement and, hence, thermal conductivity. Actual current through the heater element was calculated with Ohm's law by measuring the voltage drop across a 10 Ω reference resistor in series with the heater wire. Heating power input to a sensor was calculated by multiplying the resistance per unit length of heating wire (300 $\Omega\ m^{-1}$) by the square of the applied current. Heating power inputs of 11–12 W m^{-1} was used in this study. During application of power to the heater, temperature of the thermocouple and the applied voltage were recorded with a datalogger (Model CR7X, Campbell Scientific Inc., Logan, UT). The single probe configuration consisted of a heater and a temperature sensor mounted together in a thin needle-like probe. With the heater and thermocouple pulled into the same needle, it was filled with thermal conductivity epoxy glue to provide a water-resistant, electrically insulated probe.

In our experiments rectangular steel boxes of dimensions 30 cm length, 20 cm width and 20 cm height were constructed in which the soil was packed. After packing the soil in the box to the desired bulk density, the single and dual probes were vertically inserted from the top of the box into the soil at the same time with about 20 cm between them. The electrical wire for both probes was then connected to the power supply unit. For single probe measurements, temperature was measured and recorded every 5 s for the first minute and then every 10 s till the end of the heating period (200 s). The power supply unit was then disconnected and cooling period was started immediately. The thermocouple continued to record the temperature after the battery was disconnected. The temperature was recorded every 5 s for the first 30 s and then every 10 s until the end of the cooling period. Temperature was plotted versus the logarithm of time. Slopes of the linear portions of these curves were determined, and these values were used to calculate thermal conductivity. Figure 1 shows an example of these plots. Thermal conductivity of the soil was calculated from the temperature-time record and power input according to Eq. (5). For dual probe measurements, power was applied to the heater for 6 seconds. During application and after termination of power to the heater, temperature changes of the thermocouple were recorded. The peak t_m and ΔT_m values were determined by inspection of the measured temperatures by time data. Figure 2 is an example of plots of measured temperature as a function of time at a sensor probe located 5 mm from the heater obtained using an 6-s heat-pulse. These data show a rapid increase in the temperature at the sensor probe to a maximum, and then a slow decrease back toward the original temperature value. These data, together with the values of t_o, q' and r were then used to determine the soil thermal conductivity by using Eq. (9).

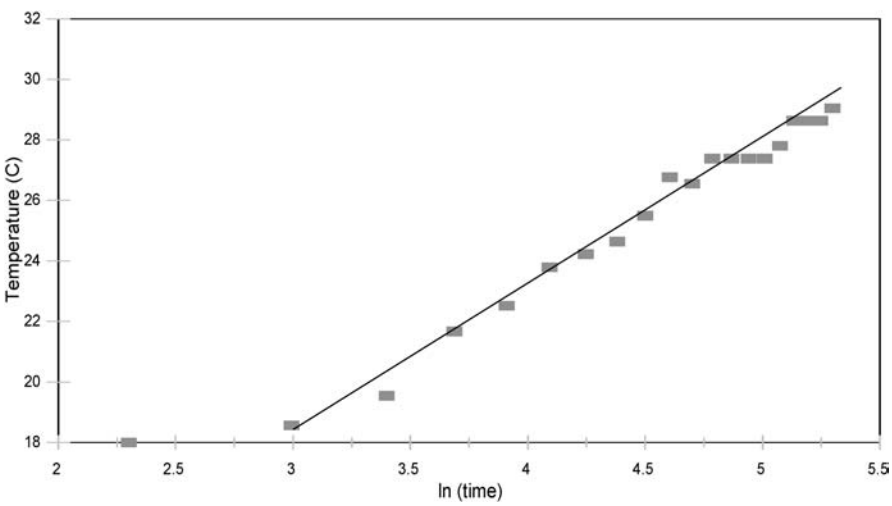

Fig. 1. Wire temperature as a function of ln t during heating for sand at a soil density of 1.25 g/cm^3

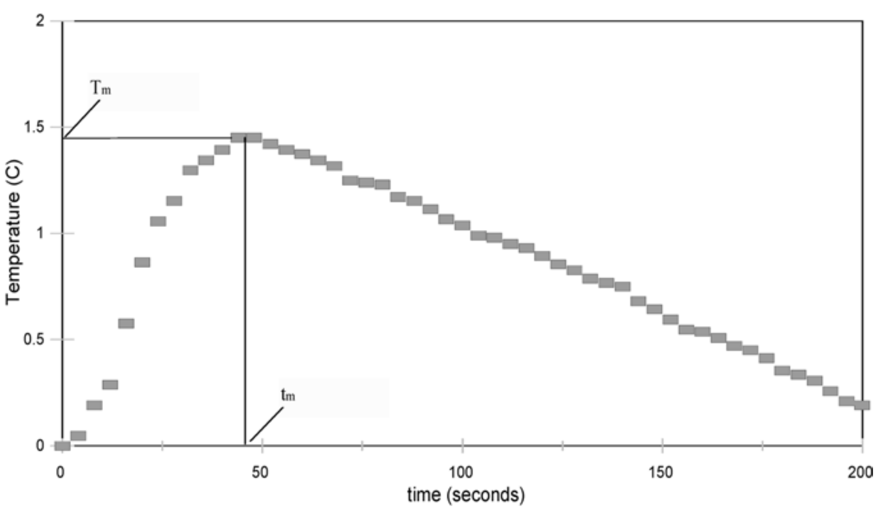

Fig. 2. Measured temperature as a function of time at a sensor probe located 5-mm from the heater for sandy soil at a soil density of 1.33 g/cm^3 (dual probe method)

The same procedure was repeated for different soil bulk densities for each soil type.

Measurements of thermal conductivity were made on two types of soils: sandy soil (95% sand, 4% silt, and 1% clay) and loam soil (40% sand, 35% silt, and 25% clay). Soils were air-dried and screened through a 0.2-cm sieve. Then the soil of known weight was packed to different known volumes marked on the box to bring the soil sample to the desired bulk density. Three levels of bulk density were used.

4 Results and discussion

The average of heating and cooling estimates of λ obtained using the single probe method was used in this study. A paired *t*-test was used to test the null hypothesis that λ obtained from heating data was not different than λ obtained from cooling data. The *P* value was 0.13, indicating that both the heating method and cooling method yield identical thermal conductivity values.

Thermal conductivities measured using single probe and dual probe methods of sandy and loamy soils as a function of bulk density are shown in Figures 3 and 4. As shown in the figures, thermal conductivity increased with increasing bulk density for the two soils using the two methods. It appears that thermal conductivity increased with increasing bulk density as a result of particle contact enhancement as porosity is decreased. The sandy soil had higher thermal conductivity values measured using the single and dual probes than the loam soil at all bulk densities. The decrease of effective thermal conductivity with decrease in grain size may be explained by the fact that as the grain size decreases, more particles are necessary for the same porosity, which means more thermal resistance between particles [16]. This suggests that loamy soils with low thermal conductivities would exhibit larger surface temperature changes, compared with sand under equal heat flux densities. Thermal conductivity values reported here lie well within the range of 0.15 to 0.79 W/m K for loamy soil as given by Ghuman and Lal [17], and within the range 0.50 to 2.25 W/m K obtained by Van Wijk [18] for sandy soil.

In general, the thermal conductivities determined using the single probe method were slightly lower and less accurate than those determined using the dual probe method for both soils. One possible reason is the density of the soil near the probe was not as uniform as intended. These small scale variations in soil density near the probes may

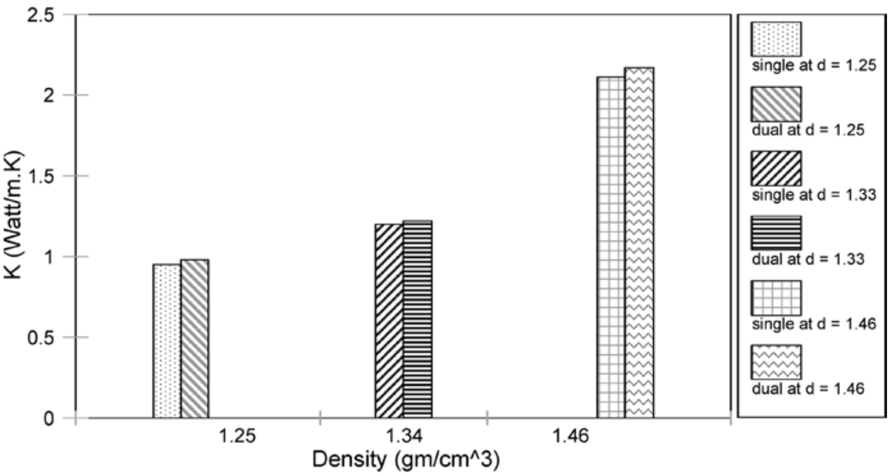

Fig. 3. Thermal conductivity for sandy soil at three soil densities using single and dual probe methods

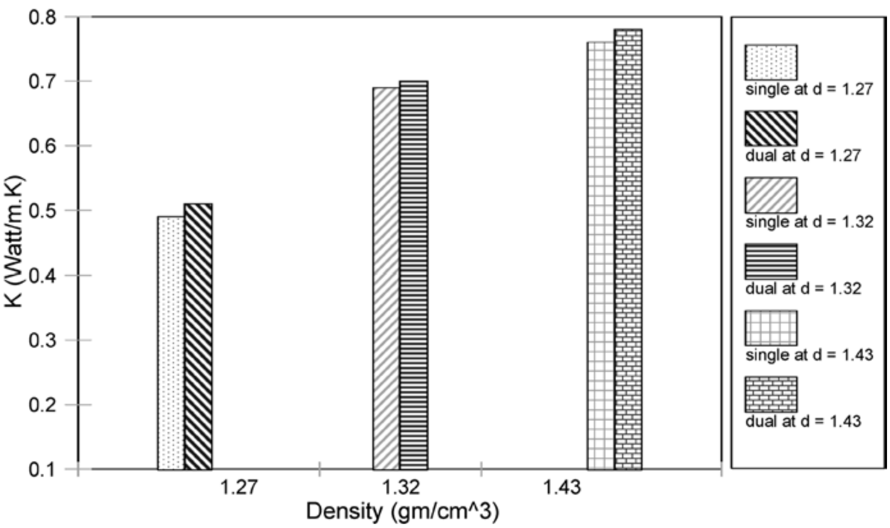

Fig. 4. Thermal conductivity for loamy soil at three soil densities using single and dual probe methods

yield differences in thermal conductivity for the two probes. Another possible error in determination of thermal conductivity may arise from poor contact between the probe and surrounding soil. Poor probe/soil contact, possibly from wobbling during probe insertion, may results in an air gap around the probe. This air gap decreases the conductance of the soil adjacent to the probe which produces errors in temperature readings and leads to errors in the determination of λ, so care is needed when inserting the probe into the soil. Also, the complicating factors arising from water movement in response to temperature gradients caused by heating is another source of errors in the determination of λ. Low power inputs were used since lower power inputs are preferable to minimize the effects of heating on soil water movement and hence thermal conductivity.

5 Conclusions

Thermal conductivities for sandy and loam soils at different bulk densities were measured and compared using single probe and dual probe methods. The results show that thermal conductivity varies with soil texture and bulk density. For the two soils studied, an increase in bulk density increased thermal conductivity. Loam soils exhibit slight increase in thermal conductivity beyond a certain bulk density. Loamy soil generally had lower thermal conductivity than sandy loam soil. In general, the dual probe method yielded thermal conductivities that were slightly higher and more accurate than those obtained using the single probe method. Since other soil thermal properties can be obtained from a single heat-pulse measurement, dual probe method is more useful and additional studies are needed to test the dual probe method for a range of soils at different conditions.

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