Soil Heat Flux Plates: Heat Flow Distortion and Thermal Contact Resistance

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ABSTRACT

Persistent concern regarding surface energy balance closure encourages increased scrutiny of potential sources of error. Laboratory and field experiments addressed heat flow distortion and thermal contact resistance errors during measurement of soil heat flux (*G*) using the flux plate technique. Steady-state, one-dimensional heat flow experiments determined flux plate thermal conductivities (λ_m) and measured the effect of air gaps and thermal heat sink coatings on plate performance. Use of measured instead of manufacturer-specified λ_m and plate dimensions in a heat flow distortion correction improved the consistency but not the average disagreement between imposed sand *G* and corrected plate heat flux density (G_m). Consistent underestimates of *G* in dry sand by 20 to 25% after heat flow distortion correction was attributed to thermal contact resistance effects. A convex air gap 0.1 to 1.32 mm thick across 5.9% of the plate face area reduced G_m by up to 9.7%. A thin layer of a thermal heat sink compound with λ 0.18 W m^{-1} K^{-1} greater than the plate λ_m (1.0 W m^{-1} K^{-1}) did not increase G_m in a clay soil but increased G_m by ~6% in quartz sand. A 6.5% increase in G_m was also observed for plates treated with the same heat sink compound in a silt loam soil under field conditions. Thermal contact resistance errors are probably <10% in moist, medium-textured soils and can be minimized by careful plate installation. Relatively greater errors in G_m may occur due to thermal contact resistance in dry sand and due to heat flow distortion when soil $\lambda >> \lambda_m$.

Soil plays an integral role in affecting crop canopy microclimate and the surface energy balance. Properties of the surface soil layer affect the partitioning of incident radiation and the amount of energy used to evaporate water, warm the air in and above the plant canopy, and warm the soil. The magnitude of the soil heat flux density (*G*) as a component of the surface energy balance varies with soil properties (texture, density, water content, color, and mineralogy), surface cover, and solar irradiance. Most recent studies have used sensors composed of a thermopile encapsulated in a thin disk, called a *heat flux plate* or *heat flow transducer*, to measure *G* (Sauer, 2002). The popularity of this method is due to its simplicity; however, several potentially significant errors may occur when using soil heat flux plates in the field. These include heat flow distortion and thermal contact resistance (Philip 1961; Fuchs and Hadas, 1973; Mayocchi and Bristow, 1995).

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Heat flow distortion occurs near flux plates because soil thermal conductivity (λ) varies with static (particle size and mineralogy) and dynamic (density and water content) soil properties while the plates are constructed of materials with a λ that can be considered constant across typical environmental temperature ranges. Philip (1961) developed a method to correct the plate *G* (G_m) for heat flow distortion based on plate dimensions, λ, and the plate thermal conductivity (λ_m). Mogensen (1970) presented a generalized form of Philip's equation to describe the ratio between heat flow through the plate to heat flow in the surrounding soil:

$$G_m/G = 1/[1 - \alpha r(1 - \lambda/\lambda_m)] \qquad [1]$$

where α is an empirical factor related to plate shape and r is a dimensionless factor equal to the plate thickness divided by the square root of the area of the plate facing heat flow. In laboratory and field experiments, Sauer et al. (2003) found that Eq. [1] often improved plate estimates of *G*, especially when $\lambda > \lambda_m$, but *G* was still often underestimated. They concluded that uncertainty in λ_m along with other sources of error not accounted for in the Philip correction, including thermal contact resistance, might have limited the effectiveness of the correction. Although Philip's correction did not consider thermal contact resistance, he recognized that it could lead to "serious errors" in flux plate measurements.

Thermal contact resistance is the resistance to heat transfer at an interface due to poor physical contact between adjoining objects of differing shapes or roughness. Philip (1961) estimated that flux plates having an air gap on both plate faces equal to 5% of the plate thickness would cause *G* underestimates of up to 54%. Fuchs and Hadas (1973) conducted laboratory and field experiments with an Al and glass flux plate and a resin heat flow disk (610, C.W. Thornthwaite Assoc., Pittsgrove, NJ) using several soils with λ from 0.28 to 0.89 W m^{-1} K^{-1}. Estimates of *G* with the Al and glass flux plate (λ_m = 1.03 W m^{-1} K^{-1}) were within 7% of the known *G*. The 610 disc (λ_m = 0.33 W m^{-1} K^{-1}), however, produced an average *G* that was 35% less than the known value. Fuchs and Hadas (1973) estimated the thermal contact resistance for both types of plate from the difference between measured and theoretical *G*. Like Philip (1961), Fuchs and Hadas (1973) expressed the contact resistance as an equivalent air gap thickness, which ranged between 5 and 14% of the Al and glass plate thickness (0.127–0.379 mm) and between 18 and 22% of the 610 heat flow disk thickness (0.527–0.648 mm).

Persistent concern regarding surface energy balance closure (Twine et al., 2000; Wilson et al., 2002) encourages increased scrutiny of potential sources of errors. Previously, Sauer et al. (2003) evaluated the Philip (1961) correction for heat flow distortion errors and found that uncertainty in λ_m may contribute to its ineffectiveness.

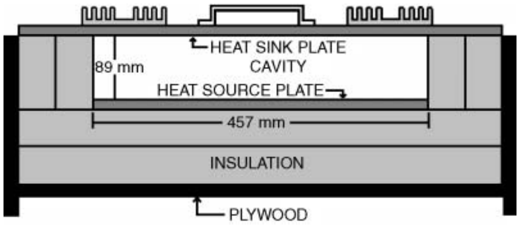

Fig. 1. Cross-section of laboratory heat flow chamber.

The first component of this study involved measuring λ_m for four flux plate designs and comparing Philip corrections using measured and manufacturer λ_m values. The second component of this study involved laboratory and field experiments to quantify thermal contact resistance errors and to evaluate a technique for its reduction.

MATERIALS AND METHODS

Laboratory Experiments

Laboratory measurements were completed using the same approach as reported in Sauer et al. (2003). A heat flow apparatus consisting of a 510 by 457 by 89 mm (length by width by height) cavity with 102-mm-thick polystyrene insulation surrounded by 19-mm-thick plywood was used to complete one-dimensional heat flow experiments (Fig. 1). An anodized Al plate under the cavity had heater windings through which current was passed to develop a uniform plate temperature and the desired temperature gradient through the medium filling the cavity. An anodized Al heat sink plate on top of the cavity had cooling fins attached to promote heat dissipation. Both source and sink plates had five chromel–constantan thermocouples to monitor plate temperature.

Dry sand or dry clay soil was placed in the cavity along with heat flux plates and thermocouples in various arrangements. The sand used was a quartz sand composed of 20.5, 68.9, 10.2, and 0.4% coarse, medium, fine, and very fine sand (USDA classification system). The dry sand had a volumetric water content (θ) of 0.0003 and a bulk density after packing of 1.75 Mg m^{-3}. The soil used was from a field site near Ames, IA, and was mapped as a Canisteo series (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll). The soil contained 32% sand, 25% silt, and 43% clay, which is a clay by the USDA classification system. The clay soil had been ground and passed through a 2-mm screen, had a θ of 0.05, and a bulk density after packing of 1.39 Mg m^{-3}. At the beginning of an experiment, sand or soil was added to the cavity in thin layers and packed in place by tapping the side of the box. Flux plates were placed in the medium when the midpoint level was reached, after which medium was added as before until the cavity was filled.

Thermocouples (0.254-mm-diam. Cu–constantan) were placed in the center of the cavity 1.5, 3, 4.5, 6, and 7.5 cm above the source plate to measure the temperature profile within the medium. Thermal conductivities of the sand and clay soil were determined using Fourier's Law:

$$G = -\lambda \, dT/dz \qquad [2]$$

where dT/dz is the average temperature gradient (K m^{-1}) across the medium as measured by the source and sink plate temperatures and G is calculated from the energy input to the source plate. Measured values of λ for all runs were 0.31 $\pm$ 0.01 and 0.26 $\pm$ 0.01 W m^{-1} K^{-1} (means $\pm$ SD) for the dry quartz sand and clay soil, respectively. All flux plate and thermocouple signals were recorded at 1-min intervals using a data logger (CR7, Campbell Scientific, Logan, UT). Hourly averages of the raw data were computed and stored for analysis.

The first experiment involved measurement of λ_m for four flux plate designs. The four plates evaluated were the CN3 (Carter-Scott Manufacturing Pty. Ltd., Brunswick, Victoria, Australia), GHT-1C (International Thermal Instrument Co., Del Mar, CA), HFT1.1 (Radiation and Energy Balance Systems, Seattle, WA), and the 610 (C.W. Thornthwaite Assoc.). Table 1 lists the dimensions and λ_m supplied by the manufacturer for each plate. For comparison, plate thickness (at five locations) and diameter or length of each side were measured using a micrometer (0.0127-mm precision). Thermocouples (0.254-mm-diam. Cu–constantan) were cemented to the top and bottom of three plates of each design with adhesive (380, Henkel Loctite Corp., Rocky Hill, CT). The plates were placed in the cavity filled with quartz sand and runs completed at flux densities of 86 and 172 W m^{-2} for 7 d. Values of λ_m for each plate were determined from Eq. [2] using uncorrected individual plate G_m values and the temperature gradient across the plate measured by the thermocouples and plate thickness for dT/dz. Uncorrected G_m values were determined by multiplying the thermopile voltage output by the manufacturer's calibration coefficient.

The second experiment used nine HFT1.1 plates to determine the effect of an air gap on G_m. Rigid gas permeable (RGP or "hard") contact lenses 9.25-mm diameter and 1.5 mm tall were used to create an air gap of known dimensions on the plate surfaces. The lenses were composed of 0.28-mm-thick fluorosilicon acrylate with a λ of ~0.2 W m^{-1} K^{-1}. Three fine sand grains were cemented under the outer rim of each lens and the bottom of the sand grains were attached to the flux plates using Loctite 380 adhesive. The sand grains were used to limit heat conduction between the rim of the contact lens and the plate surface. Three plates had a contact lens cemented to one side of the plate (facing the heat source), three plates had a contact lens cemented to both sides, and three plates had no contact lens attached. The plates were placed in both quartz sand and clay soil in the heat flow apparatus for 7 d at each flux density of 43, 86, and 172 W m^{-2}.

The third experiment used the same nine HFT1.1 plates. In this instance, the contact lenses were removed and the plates were coated with a thin layer of a thermal heat sink compound to determine whether the presence of this thermally conductive grease on the plate surface would decrease the thermal contact resistance. The heat sink compound used (10–8132,

Table 1. Manufacturer-specified and measured physical characteristics of heat flux plates. Measured values are means $\pm$ SD.

Plate	Face area		Thickness		Thermal conductivity	
	Manufacturer	Measured	Manufacturer	Measured	Manufacturer	Measured
	mm^2		mm		W m^{-1} K^{-1}	
CN3	1392	1411 $\pm$ 11	7	5.5 $\pm$ 0.35	0.4	0.60 $\pm$ 0.14
GHT-1C	2704	2597 $\pm$ 6	5.7	4.8 $\pm$ 0.06	0.26	0.63 $\pm$ 0.10
HFT1.1	1134	1154 $\pm$ 5	3.9	3.8 $\pm$ 0.06	1.0	1.26 $\pm$ 0.12
610	491	507 $\pm$ 5	2.6	4.0 $\pm$ 0.06	0.33	0.21 $\pm$ 0.04

GC Thorsen, Rockford, IL) was water soluble with a ZnO base and a λ of 1.18 W m^{-1} K^{-1}. Three plates had the heat sink compound applied to one side (facing the heat source), three plates had heat sink compound applied to both sides, and three plates had no heat sink compound. As in the contact lens experiment, the plates were placed in both quartz sand and clay soil in the heat flow apparatus for 7 d at each flux density of 43, 86, and 172 W m^{-2}.

Field Experiments

A field experiment was conducted at the University of Minnesota Rosemount Research Center to assess the effectiveness of thermal heat sink compounds under field conditions. The soil at the field site is mapped as a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll). Six of the same nine HFT1.1 plates used in the laboratory experiments were used, three plates with heat sink compound applied to both sides and three plates with no heat sink compound. In June 2004, the plates were installed in a strip-till soybean [*Glycine max* (L.) Merr.] field with a rye (*Secale cereale* L.) cover crop. The rye had been shredded and sprayed with glyphosate [*N*-(phosphonomethyl)glycine] in mid-May. The plates were installed at a depth of 4 cm in the soybean interrow in a transect parallel with the rows. All residue was removed from the surface above the plates. The soil was excavated to 8 cm and sieved to pass an 8-mm sieve. Four centimeters of soil was placed back into the trench, the plates were placed on top, and then the remaining 4 cm of soil was placed on top of the plates. Plates treated with the same heat sink compound used in the laboratory experiments (10–8132) were used from 28 June to 16 July 2004. On 16 July, all plates were excavated, the heat sink compound was removed from the treated plates and replaced with a silicone-based heat sink compound containing Ag with a λ of 8.89 W m^{-1} K^{-1} (Arctic Silver 5, Arctic Silver, Visalia, CA), and the plates reinstalled as before. Heat flux density was measured every minute, and the average for the previous 30 min was recorded every 0.5 h.

Data Analysis

For each of the laboratory experiments, data from one continuous 24-h period after thermal equilibration was reached (>48 h) were selected for analysis. Confidence intervals (95%) about the regression slope estimates were used to determine whether heat flow distortion-corrected G_m values were significantly different from the known sand *G*. Differences among G_m values for plates with and without air gaps or heat sink compound were analyzed using one-way ANOVA and Fisher's protected LSD (Steel and Torrie, 1980). All statistical analyses were completed at the $P = 0.05$ confidence level.

RESULTS

Measured flux plate face areas were within ±4% of the manufacturer specifications; however, measured plate thicknesses ranged from 21% less to 54% greater than the plate specifications (Table 1). Similar discrepancies were observed for the measured λ_m, which varied from 36% less to 26% greater than the manufacturer specifications. Only the 610 plates had measured λ_m less than the plate specifications. Each of the other plates had measured λ_m from 0.2 to 0.26 W m^{-1} K^{-1} greater than their specified λ_m. The measured λ_m values in Table 1 are the means of the 48 1-h values at the two flux densities in the quartz sand.

The measured values of plate area and plate thickness (to determine *r*) and λ_m were used with Eq. [1] to compute heat flow distortion corrections to compare with corrections obtained using the manufacturer specifications (Fig. 2). An α of 1.7 was used for the CN3 and GHT-1C plates; an α of 1.92 was used for the HFT1.1 and 610 plates (Philip, 1961). Computed and manufacturer-specified heat flow distortion corrections were evaluated using data from Sauer et al. (2003) for flux plates in dry and saturated sand. They used the same apparatus, quartz sand, and fluxes as reported in the current study. For dry sand, use of measured plate values resulted in improved corrections only for the 610 plates. Using manufacturer specifications with the Philip correction, all plates underestimated *G* by an average of 23.0% (range 15.2% for the GHT-1C to 37.4% for the 610). Corrected heat flux densities using the measured plate dimensions and λ_m also underestimated the sand *G*, averaging 23.4% lower, but were much more consistent, ranging only from 20.9 to 25.7%. By contrast, for saturated sand ($\lambda = 2.25$ W m^{-1} K^{-1}), use of the measured plate dimensions and λ_m improved corrections for three out of four plates (GHT-1C, 610, and HFT1.1). The G_m for the HFT1.1 and 610 plates were the only cases in either dry or saturated sand where corrected plate G_m was not significantly different from the sand *G* as determined by the 95% confidence interval of the regression slope estimate. The consistent pattern of corrected plate G_m < sand *G* for dry sand suggests that another systematic error equivalent to a 20 to 25% underestimate of *G* is not accounted for by the Philip correction.

For all flux densities in both quartz sand and clay soil, an air gap created by a contact lens on one or both faces of the HFT1.1 plates significantly decreased the plate

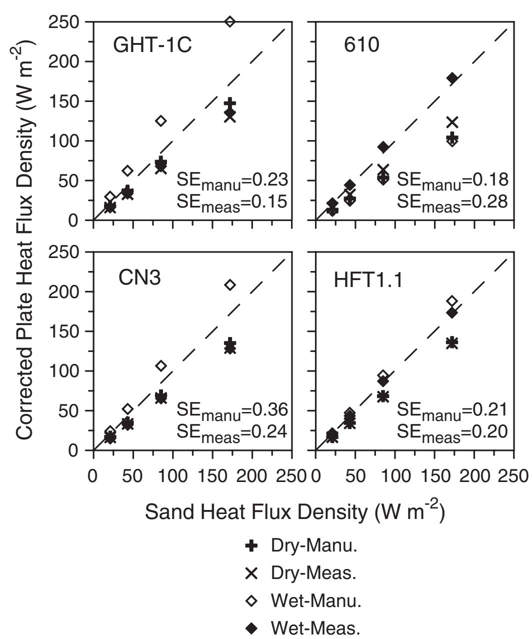

Fig. 2. Corrected plate heat flux density (G_m) for four plate designs vs. known heat flux density (*G*) in dry and saturated quartz sand using manufacturer-specified and measured plate dimensions and thermal conductivities (λ_m). Original flux plate data taken from Sauer et al. (2003).

G_m compared with control plates without an air gap (Table 2). In the clay soil, there was no significant difference in plate G_m between plates with a lens on one or both sides of the plate. For the quartz sand, G_m for plates with a lens on both sides was significantly lower than for those with no or one lens. The presence of a contact lens created a convex air gap of 1.32-mm maximum thickness (1.5-mm lens + 0.1-mm sand grains − 0.28-mm lens thickness) to 0.1-mm minimum thickness across an area equivalent to 5.9% of the flux plate face area (67.2 mm^2). The presence of one lens reduced G_m an average of 8.3 and 9.7% and two lenses reduced G_m an average of 9.5 and 11.7% compared with the control plates in clay soil and sand, respectively.

Less consistent and smaller differences in G_m were observed for plates with and without the water-soluble heat sink compound (Table 2). For the clay soil across all flux densities, plates with heat sink compound on one plate face had G_m within 1% of the control plates. Plates with heat sink compound on both sides had slightly lower (2.1%) G_m than the control plates. Contrary to the clay soil results, the expected effect of the heat sink compound was observed for the quartz sand, as the treated plates had values of G_m that were consistently 6% greater than the control plates. This result was attributed to reduced thermal contact resistance induced by the heat sink compound.

Field data for HFT1.1 plates with and without the water-soluble heat sink compound showed varying effects on plate G_m (Fig. 3). The lower graph in Fig. 3 shows the ratio of G_m for plates with and without heat sink compound for time intervals with $|G_m| > 10$ W m^{-2} (selected to avoid imprecision at very small G_m). For several days after installation on Day 180, the heat sink compound decreased or had no consistent effect on G_m (not all data shown). After Day 187, however, plates with heat sink compound had consistently greater G_m. This change appears to be linked to the first significant rain (13.6 mm) on Day 185 and further rain of 9.4 mm on Days 187 and 188. From Days 186 to 194, plates with the heat sink compound had G_m that was on average 6.5% greater than the control plates. There were, however, no

Table 2. Measured plate (G_m) and media (G) heat flux density from laboratory contact lens and heat sink compound experiments using HFT1.1 flux plates.

Experiment	Media G	Control G_m	Lens or heat sink on one side G_m	Lens or heat sink on both sides G_m
	W m^{-2}			
Contact lens—soil	43	39.0a†	35.7b	35.1b
	86	84.1a	77.0b	75.9b
	172	171.1a	157.5b	155.9b
Contact lens—sand	43	42.8a	38.6b	37.7b
	86	85.4a	77.1b	75.4c
	172	173.0a	156.7b	153.2c
Heat sink—soil	43	41.1a	41.0b	40.2c
	86	83.6a	83.3a	81.6b
	172	169.3a	169.6a	166.3b
Heat sink—sand	43	40.5b	43.0a	43.2a
	86	83.1b	87.8a	88.3a
	172	168.4b	177.7a	178.4a

† Means followed by the same letter within rows were not significantly different as determined by the Fisher's protected LSD ($P = 0.05$).

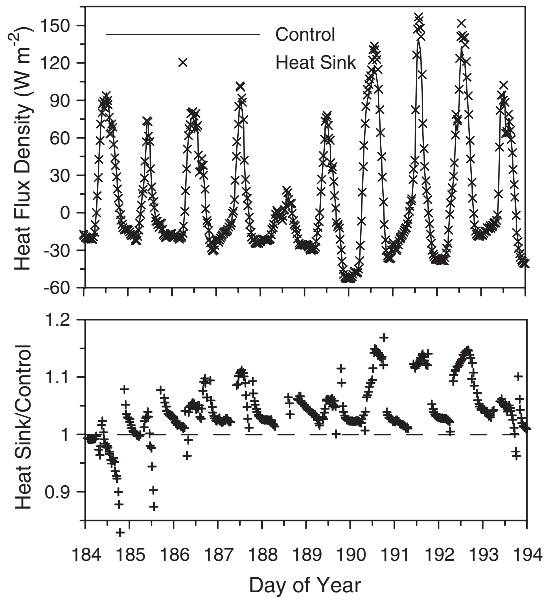

Fig. 3. (Top) mean heat flux density of triplicate control and heat sink compound-coated flux plates in Waukegan silt loam and (bottom) the ratio of plate heat flux density (G_m) for plates with and without water-soluble heat sink compound.

statistically significant differences in daily G_m between plates with and without heat sink compound. Coating plates with the high-λ Arctic Silver 5 heat sink compound was expected to increase the magnitude of G_m for treated plates compared with the control plates. Instead, plates treated with Arctic Silver 5 always had a lower daily average G_m (Fig. 4). For a similar 10-d interval as presented for plates with the water-soluble heat sink compound, plates treated with Arctic Silver 5 had G_m that averaged 7.6% less than the control plates.

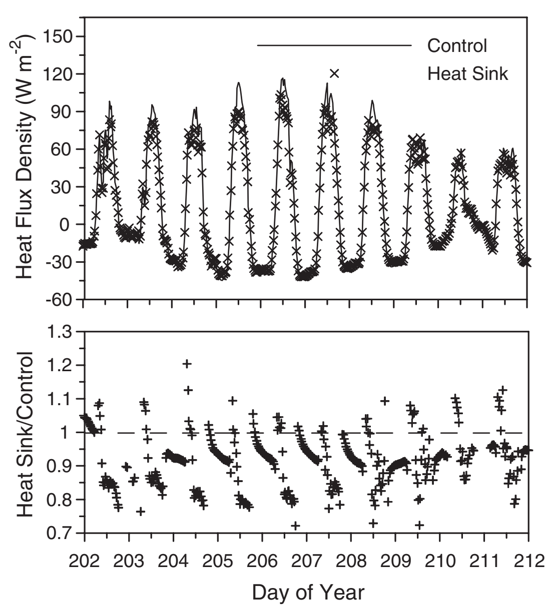

Fig. 4. (Top) mean heat flux density of triplicate control and heat sink compound-coated flux plates in Waukegan silt loam and (bottom) the ratio of plate heat flux density (G_m) for plates with and without Arctic Silver 5 heat sink compound.

DISCUSSION

The significant discrepancies between manufacturer specifications and actual plate dimensions were unexpected. Relaxed tolerances for plate dimensions are probably acceptable given that plate dimensions are not critical to plate performance and each plate receives a unique calibration. Accurate values of the plate dimensions, however, especially plate thickness, are very important to the Philip correction. Not all manufacturers measure λ_m directly; some only provide an estimate of λ_m based on the λ of the component materials. Again, an accurate λ_m is not critical for individual plate performance but is essential for accurate application of the Philip correction.

Use of measured plate parameters in the Philip correction improved the consistency of the corrected flux densities, especially in dry sand, but failed to improve all G_m estimates. For the dry sand runs, all plates had corrected G_m that were 23.4 ± 2.5% underestimates of the sand G. The magnitude and consistency of this G underestimate suggests that some mechanism other than heat flow distortion is limiting heat flow through the plates. The most likely source of error in this controlled laboratory system with dry sand, where latent heat transfer does not occur, is thermal contact resistance. For saturated sand, corrected G_m for the HFT1.1 and 610 plates were not significantly different from the sand G. It is perhaps serendipity that, as for the dry sand, corrected G_m for the CN3 and GHT-1C plates underestimated the sand G by the same amount (23.6 ± 2.8%). Under saturated conditions, thermal contact resistance is assumed ≅0 (van Haneghem et al., 1983) as water bridges the particle–plate interface. This would explain the performance of the HFT1.1 and 610 plates. Assuming the contact resistance is = 0, however, requires that the λ_m for the CN3 and GHT-1C plates must be ~0.35 W m^{-1} K^{-1} for the corrected G_m to agree with the saturated sand G. There is, therefore, an unexplained inconsistency in plate performance in the saturated sand. Plate construction may be a factor as the CN3 and GHT-1C plates both have metal sheaths while the HFT1.1 and 610 have epoxy resin construction. Fuchs and Hadas (1973) observed similar differences in performance between resin and metal-sheathed plates, although it is not clear how these differences affect plate performance under saturated conditions.

Uncorrected plate G_m values based on the manufacturer's calibrations were used in determining the plate λ_m values. Accuracy of the measured λ_m values are thus dependent on the accuracy of the original manufacturer's calibration. There is no standard method for calibrating soil heat flux plates. For example, plates used in this study were calibrated sandwiched between metal plates (GHT-1C), in dry sand (CN3), and in saturated sand (HFT1.1). The calibration method for the 610 plates is unknown. It is probable that some thermal contact resistance and heat flow distortion occurred during calibration and, if so, the plate calibration factors may already partially compensate for these effects. If sand G instead of plate G_m were used to calculate λ_m, values of λ_m would increase by an average 0.053 ± 0.020 W m^{-1} K^{-1}. Use of these slightly greater λ_m values increases disagreement between the corrected G_m and sand G by ~3% with the exception of the 610 plate in saturated sand, for which the corrected G_m increases by >20% and is now significantly different than the saturated sand G. It was concluded that use of the plate G_m values to determine λ_m is reasonable and does not change the conclusions but produces slightly smaller corrections.

The uniform air gap thickness analysis used by Philip (1961) and Fuchs and Hadas (1973), while useful in illustrating the magnitude of thermal contact resistance, is not physically realistic in well-structured soils where the pattern of soil particle-to-plate contact is probably quite heterogeneous, with air gaps of varying thickness. Particle and aggregate size distribution, aggregate stability, bulk density, soil structure, and plate installation procedure may all influence the degree and spatial pattern of soil particle-to-plate contact. In this study, an air gap on one side of a flux plate equivalent to 5.9% of the plate face area and average thickness of ~0.6 mm (15.8% of the plate thickness) reduced total heat flow through the plate by 8.3 and 9.7% in clay soil and sand, respectively. Heat flow reduction was, therefore, 40 to 64% greater than the proportion of the plate face covered by the air gap. The presence of a second air gap on the opposite plate face reduced the flux only an additional 1.2% in the clay soil and 2.0% in the quartz sand. These results indicate that an air gap on just one plate face effectively decoupled that portion of the plate from conductive heat transfer and any localized cooling on the plate surface was not compensated for by lateral heat conduction.

A thin layer of water-soluble heat sink compound on one plate face had no significant effect on G_m in the clay soil but had a significant effect (average 5.7% increase) on G_m in the quartz sand. This result is consistent with the anticipated lower thermal contact resistance for finer textured soils. For the clay soil, however, G_m for plates with the heat sink compound on both plate faces was slightly (1–3 W m^{-2}) lower than for the control and single-coated-face plates. This suggests that the heat sink compound failed to enhance heat flow across the soil–plate interface. For the quartz sand, there was no decrease nor a significant increase in G_m with heat sink compound applied to the second "cold" plate face, suggesting that, while thermal contact resistance was restricting heat conduction to the plate, it did not limit heat transfer from the plate.

Results from the field experiments with heat sink compounds provide additional insight into their potential for improving heat flux plate measurement accuracy. Placing the heat flux plates in dry, disturbed soil with relatively large aggregates was intended to highlight the potential benefit of the heat sink compound. After 13.6 mm of rainfall, the water-soluble heat sink compound increased G_m by ~6.5%, but this effect began to decay after an additional 30 mm of rainfall on Day 193. By the end of the experiment on Day 198, daily average G_m for the treated plates was steadily decreasing and was only 3.4% greater than the control plates. This trend suggests improved thermal contact with the control plates, removal of the water-soluble heat sink compound from the treated plates, or both. Use of the high-λ Arctic Silver 5 heat sink compound was expected to result in optimal plate performance for extended periods. Instead, plates treated with this compound always had lower G_m than the control plates. A possible explanation is that the hydrophobic Arctic Silver 5 actually inhibited the establishment of good thermal contact at the liquid water–heat sink compound interface and also increased water flow diversion around the treated plates.

Porous media like soils are relatively poor heat conductors. The limited points of contact between particles and the thermal contact resistance at these contact points severely restrict heat conduction. For example, a sandy loam soil may consist of quartz particles with a λ of almost 9 W m^{-1} K^{-1} but the effective soil λ might range from <0.4 W m^{-1} K^{-1} when dry to ~2.5 W m^{-1} K^{-1} at saturation (Campbell, 1985). When a soil is dry, the pores become filled with air, which has a very low λ (0.025 W m^{-1} K^{-1}). With increasing soil water content, the soil particles are covered with water films of increasing thickness until, at saturation, all pores are filled with water. Although water has a much greater λ (0.57 W m^{-1} K^{-1}) than air, its λ is still much less than common soil minerals (3–9 W m^{-1} K^{-1}). Heat conduction between soil particles and the flat surface of a flux plate is similarly limited by the area of the contact points. The number and total area of contact points increases with decreasing particle size. The thermal contact resistance at the plate–soil interface is, therefore, expected to decrease with increasing water content and decreasing particle size (Fuchs and Hadas, 1973; Hadas, 1974; van Haneghem et al., 1983).

Particle-to-particle thermal contact resistance has received significant attention by engineers studying heat transfer in fluidized, packed bed systems (Cheng et al., 1999; Siu and Lee, 2000; Vargas and McCarthy, 2001). Even in designed systems with known particle dimensions, uniform thermal properties, and controlled flux densities, however, accurate estimation of thermal contact resistance is still difficult and often involves empirical relationships (Ofuchi and Kunii, 1965; Gloski et al., 1984). In soils, the circumstances are significantly more complex, as particle dimensions, arrangement, and surface roughness are not well known. In addition, in many medium- and fine-textured agricultural soils, soil particles exist as components of aggregates whose extent and properties are dynamic and depend on soil management practices. All of these interacting factors make development of a practical correction for thermal contact resistance effects on soil heat flux plates under field conditions very challenging.

CONCLUSIONS

The flux plate method is the most popular method for measuring G even though systematic errors are known to affect the accuracy of plate measurements. We showed that measured plate dimensions and λ_m produced corrections for heat flow distortion that resulted in more consistent performance of four different plate designs. Nonetheless, an underestimate of G by >20% in dry sand persisted. Accurate knowledge of soil λ dynamics is required to complete the Philip heat flow distortion correction, making it of questionable utility, especially under field conditions. The consistent underestimation of G observed in dry sand was attributed primarily to thermal contact resistance. Creation of a small air gap on the plate surface resulted in a significant decrease in G_m, clearly demonstrating the potential consequences of poor thermal contact resistance at the macroscopic scale.

Application of a thermal heat sink compound to the plate surface increased G_m by ~6% in dry sand but not in dry clay. Field experiments were also inconclusive, as the heat sink compound increased G_m by ~6.5% in a moist silt loam soil but this effect was temporary, probably due to the water solubility of the compound or improved contact with the untreated plates with time. The benefit of the heat sink compound was small and, given the transitory effect in the field, problematic for long-term field installations. Use of a silicone-based heat sink compound decreased heat flux through the plates, possibly due to heat flow distortion induced by a layer of hydrophobic material on the plate surface.

Any correction procedure for thermal contact resistance at soil heat flux plate surfaces in structured soils will require characterization of soil particle dimensions, shape, and arrangement at a level of detail that will be very difficult to achieve for field soils. Fortunately, thermal contact resistance errors are probably <10% in moist, medium-textured soils and can be minimized by careful plate installation that prevents air gaps on the plate surface. The exact magnitude of contact resistance errors, however, is very difficult to assess under field conditions and will probably remain an area of persistent uncertainty.

Heat flow divergence and thermal contact resistance errors will be minimal if the calibration medium and the soil in which the plates are buried have similar physical properties or the plates are calibrated in situ as advocated by Fuchs and Hadas (1973). Field calibration, however, requires an independent and accurate measure of G using the calorimetric, gradient, or some other technique (Sauer, 2002). Flux plates are, therefore, often calibrated in fine sand under controlled conditions but used in soils of varying texture, density, and water content with heat flow distortion and contact resistance errors of varying and unknown magnitude. Further advances would be required to accurately correct for these errors under field conditions. Given these limitations and the lack of straightforward solutions, an increasingly attractive alternative is to use a different method for measuring G. Due to recent improvements in sensor technology and comparative ease of measurement, the gradient method (Cobos and Baker, 2003) has become a viable alternative for G measurement.

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