Theor. Appl. Climatol. 89, 109–114 (2007)
DOI 10.1007/s00704-006-0256-2
Printed in The Netherlands

Theoretical
and Applied
Climatology

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Accuracy of soil heat flux plate measurements in coarse substrates – Field measurements versus a laboratory test

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With 3 Figures

Received July 7, 2005; revised December 22, 2005; accepted May 8, 2006

Summary

The in-situ performance of heat flux plates within coarse porous substrates might be limited due to poor contact between plate and substrate. We tested this behaviour with a simple laboratory set-up. Two test substrates were placed above a reference material of known thermal conductivity between a warm and a cold plate to establish a vertical heat flux. The temperature gradients and the response of a soil heat flux plate were measured. By means of the Fourier law of heat conduction the thermal conductivity of each test substrate was calculated, thus incorporating all heat transfer within the volume and representing the "effective" conductivity. The laboratory method had an accuracy of up to ±7% (±13% for a smaller set-up). In comparison, heat flux plate-derived heat fluxes showed errors of up to 26%. Use of heat flux plates in coarse substrates is not recommended without additional measurements.

1. Introduction

Heat flux plates (HFP) offer a simple way to estimate soil heat flux (Q_G) but they are sensitive to a variety of influences including soil heterogeneity (Mayocchi and Bristow, 1995), deviation of thermal conductivity of the soil to that of the plate (Mogensen, 1970; Sauer et al., 2003) and blocked vapour flow (van Loon et al., 1998). Difficulties may arise especially in coarse substrates due to poor contact with the HFP and a non-negligible heat transfer through pore spaces. During two field experiments focussing on the surface energy balance at a Railway station in Osnabrück, Germany, and dew water availability on the volcanic Canary Island, Lanzarote, we measured the soil heat fluxes by HFP. Due to the porous substrates at both sites the need to investigate whether HFP measurements are reliable became evident (Graf et al., 2004; Weber and Kuttler, 2005; Weber, 2006). The intention of this study was to design a controlled laboratory set-up to test the applicability of HFP in porous substrates and compare their performance under field conditions by measuring the substrate thermal conductivity (λ) and obtaining alternative heat flux estimates from in-situ temperature profiles. This can be done by placing the soil volume between two differentially heated plates (e.g. van Loon et al., 1998). Here, a two-plate method is used that accounts for limited contact between particles as well as for possible heat transfer through pore air.

2. Theory

Heat flux is related to temperature gradient and thermal conductivity by the Fourier law of heat conduction

$$Q = \lambda \frac{\partial T}{\partial z} \tag{1}$$

with Q the heat flux density (W m^{-2}), λ the thermal conductivity (W m^{-1} K^{-1}), T temperature (K) and z depth (m). Here Q is defined as positive when directed towards the surface and depths are given as positive downwards from the surface.

If in a closed volume a vertical heat flux is established with two layers of different materials, there will be linear temperature profiles and equal heat fluxes in both substrates when equilibrium is reached. With one reference substrate of known λ, substitution of both Q according to Eq. (1) yields the unknown second λ:

$$\lambda_s = \lambda_r \frac{\left(\dfrac{\partial T_r}{\partial z_r}\right)}{\left(\dfrac{\partial T_s}{\partial z_s}\right)} \tag{2}$$

with λ_r the thermal conductivity of the reference material (W m^{-1} K^{-1}), λ_s the unknown thermal conductivity of the second substrate (W m^{-1} K^{-1}), $\partial T_r/\partial z_r$ and $\partial T_s/\partial z_s$ (K m^{-1}) the temperature gradients in the reference material and porous substrate, respectively.

3. Material and methods

3.1 Substrates

Two substrates were used in this study: lapilli, a volcanic substrate (Lanzarote field experiment, cf. Sect. 1) and ballast, a mix of shattered rock types (Osnabrück field experiment). The black, basaltic lapilli grains are highly porous. Samples taken from the field study site showed a bulk density of 854 kg m^{-3}, a porosity of 0.53 if intragranular pores are not taken into account, and a grain size median of 0.005 m. 17% mass of the lapilli are smaller than 0.002 m, and 1% larger than 0.01 m.

Ballast is used as a collective term for shattered rocks such as sandstone, greywacke and diabase used for construction applications, e.g. railway tracks. The ballast samples from the field site were characterised by an average diameter of $d = 4.7$ cm and a height of $h = 2.1$ which is defined normal to the diameter (median $d = 4.7$, median $h = 2.0$). The porosity was estimated to be 0.45, and the bulk density was 1500 kg m^{-3}. Both substrates were tested in a dry state (see Sect. 5). For laboratory experiments, the same samples as for bulk density determination were used.

3.2 Field campaigns

Heat flux was estimated in the field at two sites with a heat flux plate (HFP01, Hukseflux, Delft, Netherlands). Since these measurements are used to test HFP performance with the laboratory-derived λ, a brief description is given below (for details see Graf et al., 2004; Weber and Kuttler, 2005). The heat flux plate is 0.08 m in diameter and 0.005 m thick, its central sensitive part is 0.03 m wide. It has a thermal conductivity of 0.8 W m^{-1} K^{-1} and a sensitivity of 59.7 µV W^{-1} m^{2}. In Osnabrück, Germany, the HFP was placed at a depth of 0.05 m between ballast stones that were sliced so that the plane surfaces enhanced contact. Thermistors (Thies, Goettingen, Germany) were placed at depths of 0.05, 0.1 and 0.3 m within the ballast layer. In Lanzarote, Canary Islands, the HFP was placed at 0.04 m depth. The thermistor (Hygrotec, Titisee-Neustadt, Germany) measurement depths next to the plate were 0.02 and 0.06 m, all within the lapilli layer. In both experiments, the Philip's correction (Philip, 1961) had an effect of <5%.

3.3 Laboratory set-up

A measurement box was placed between two plates connected to heat exchangers (Colora Kryo-Thermostats Mod. WK 26-2 DS and KT 50). The upper exchanger was heated to a temperature of 50.7 °C while the bottom one was cooled to 0.86 °C (Fig. 1). The box was built of an insulating material ("Roofmate", for details DOW (2003); $\lambda = 0.035$ W m^{-1} K^{-1}; thickness 0.06 m). Interior box dimensions were 0.32 m × 0.34 m × 0.30 m (length, width, height) for ballast and 0.15 m × 0.15 m × 0.152 m for lapilli.

For the bottom (reference) layer, agar-gel was used. Only 0.4 mass percent agar-powder was added to water to suppress convection, leaving

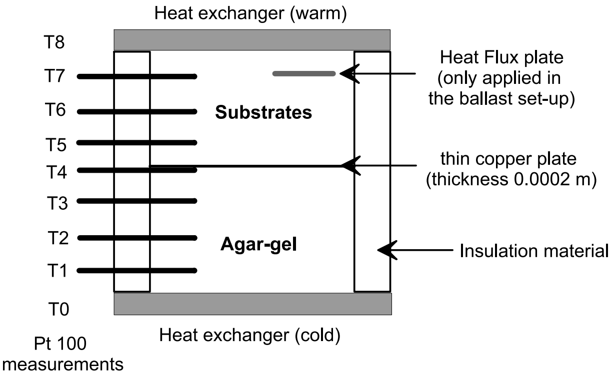

Fig. 1. Sketch of the experimental laboratory set-up

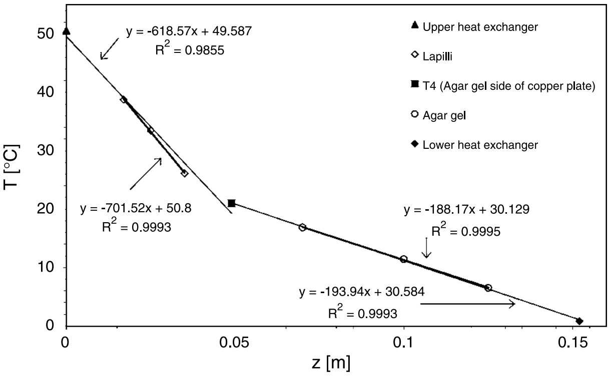

Fig. 2. Temperature profiles at the end of the lapilli experiment

the thermal conductivity of the water nearly unchanged (deviation <1%, van Haneghem, 1981). The λ of water varies between 0.561 W m^{-1} K^{-1} at 0 °C and 0.598 W m^{-1} K^{-1} at 20 °C (Lide, 1996). We used a λ_r of 0.57 W m^{-1} K^{-1} (Zmarsly et al., 2002; for possible errors see Sect. 4.2). A copper plate (thickness 0.0002 m) divided the upper (lapilli or ballast) layer from the agar-gel.

The temperature profile was measured with seven Pt100 probes (diameter 0.003 m, depths 0.0375, 0.075, 0.115, 0.1475, 0.190, 0.2275 and 0.2625 m for ballast, 0.027, 0.052, 0.082, 0.103, 0.117, 0.127 and 0.135 m for lapilli). The Pt100s were calibrated in water prior to the measurements and showed good agreement with a Pt100 serial no. 200, NIST traceable standard. Temperature probes T1–T4 were placed in the agar-gel, with T4 in direct contact with the copper plate. Probes T5–T7 were inserted within the lapilli and ballast substrates. The heat exchangers are termed T0 (bottom) and T8 (top).

The ballast set-up provided enough space to insert a HFP at 0.55 m below the upper heat exchanger. It was the same HFP, inserted in the same way, as in the field study in Osnabrück (cf. Sect. 3.2). All data were sampled at 1 Hz and stored as 2-minute averages.

4. Results

4.1 Thermal conductivity

A first estimate of λ is calculated from the temperature profiles at the end of each laboratory experiment. In the lapilli set-up, temperatures from probes T0–T4 and T4–T8 form approximately linear temperature gradients (Fig. 2). The ballast set-up exhibited similar characteristics except that T8 does not fit into a linear profile (data not shown here), an effect attributed to poor contact between the ballast and the heat exchanger.

In heat transfer through adjoining media, transition resistance can cause different gradients close to the interface. Furthermore, on top of the copper plate, small spots of water accumulated and may have increased conductivity. Therefore, we focus on the slopes of the linear least sum of squares fit to temperatures T1–T3 and T5–T7 for both substrates.

The thermal conductivity of the unknown λ was calculated according to Eq. (2). However, there was still some variation at the end of both experiments (measuring periods were 15 h for lapilli and 80 h for ballast), so this conductivity is referred to as apparent conductivity, and the time series have been extrapolated to test for further variation. A least sum of squares fit of the form

$$\lambda_{sa}(t) = a \cdot \exp(-bt) + \lambda_s \tag{3}$$

yields a final value for the unknown λ_s (W m^{-1} K^{-1}), with λ_{sa} the apparent conductivity (W m^{-1} K^{-1}) at time t, while a (–) and b ($[t]^{-1}$) are empirical constants. The extrapolated λ_s of 0.142 W m^{-1} K^{-1} for lapilli differs slightly from the apparent value of 0.153 W m^{-1} K^{-1} at the end of the experiment, while the values of 0.454 W m^{-1} K^{-1} and 0.458 W m^{-1} K^{-1} for the long-lasting ballast experiment are in good agreement (time series not shown here).

4.2 Error analysis

Using Eq. (2), the error of λ can be estimated by

$$\frac{\delta\lambda_s}{|\lambda_s|}=\sqrt{\left(\frac{\delta\lambda_r}{|\lambda_r|}\right)^2+\left(\frac{\delta\frac{\partial T_r}{\partial z_r}}{\left|\frac{\partial T_r}{\partial z_r}\right|}\right)^2+\left(\frac{\delta\frac{\partial T_s}{\partial z_s}}{\left|\frac{\partial T_s}{\partial z_s}\right|}\right)^2} \tag{4}$$

if $\delta x/|x|$ represents the relative error of each factor and input errors are independent from each other (Taylor, 1988). The possible error in λ_r results from the temperature dependence of the thermal conductivity of water (first term on the right hand side, see Sect. 3.3 for range of values) and the accuracy to which both gradients could be measured (second and third term). These contain sensor depth (assumed accuracy 0.0015 m) and temperature (<0.1 K, no significant contribution). These inputs yield a tolerant maximum error estimate on λ of 13% or 0.019 $\mathrm{W\,m^{-1}\,K^{-1}}$ for lapilli and 7% or 0.032 $\mathrm{W\,m^{-1}\,K^{-1}}$ for ballast.

This analysis only does account for an homogenous vertical heat flux. Deviations from these conditions in the central vertical box axis may be assessed qualitatively by the linearity of the temperature gradients. For the T1–T3 and T5–T7 values used to calculate λ, the lowest R^2 was 0.9993 (lapilli). The maximum deviation of a two-sensor gradient (T7–T6) from the regression gradient was 5%. The possible depth error in the above calculation would already be included in this figure. This indicates that with the current box design, accuracy is rather limited by depth and reference lambda than by inhomogeneity in the temperature and flux field.

For HFP measurement errors, conditions are vice versa: the manufacturer gives an accuracy of ±20%, explicitly including the influence of deviations between soil and plate thermal conductivity and resulting flux distortions. As this error is reduced to ±3% for a newer self-calibrating model (HFP01SC), flux inhomogeneities may be assumed to be more important than the accuracy to which thermopile distance, sensitivity and thermal conductivity of the plate are known.

4.3 HFP performance in the laboratory

To check the accuracy of the HFP in the laboratory set-up for ballast, heat flux estimates as measured by the plate at $z = 0.055$ m ($Q_{G\,(\mathrm{HFP})}$, $z = 0.055$ m) and by the temperature gradient method ($Q_{G\,(\mathrm{TG})}$, $z_{\mathrm{T7}} = 0.035$ m and $z_{\mathrm{T6}} = 0.070$ m) were compared.

During the course of the experiment, the heat flux $Q_{G\,(\mathrm{HFP})}$ showed higher values as compared to the heat flux $Q_{G\,(\mathrm{TG})}$. Under steady state conditions $Q_{G\,(\mathrm{HFP})}$ overestimated $Q_{G\,(\mathrm{TG})}$ by 38%.

4.4 HFP performance in the field

The laboratory-derived λ was compared with data obtained from the field campaigns in Lanzarote and Osnabrück. The HFP estimate ($Q_{G\,(\mathrm{HFP})}$) was tested against the heat flux calculated from temperature gradient and laboratory-derived λ ($Q_{G\,(\mathrm{TG})}$). $Q_{G\,(\mathrm{TG})}$ was calculated from temperature measurements in $z = 0.05$ m and 0.1 m for ballast and $z = 0.04$ and 0.06 m for lapilli (cf. Sect. 3.2).

Mean relative deviation of the HFP method against the temperature gradient method is determined by the slope of a least sum of squares fit of $Q_{G\,(\mathrm{HFP})}$ to $Q_{G\,(\mathrm{TG})}$ measurements. The regression for ballast shows a good determination of 94% variance but a systematic underestimation of 26% by the HFP method (Fig. 3). This is of interest since the HFP was placed slightly nearer to the surface at $z = 0.05$ m while the thermistors were centred at $z = 0.075$ m (temperature mea-

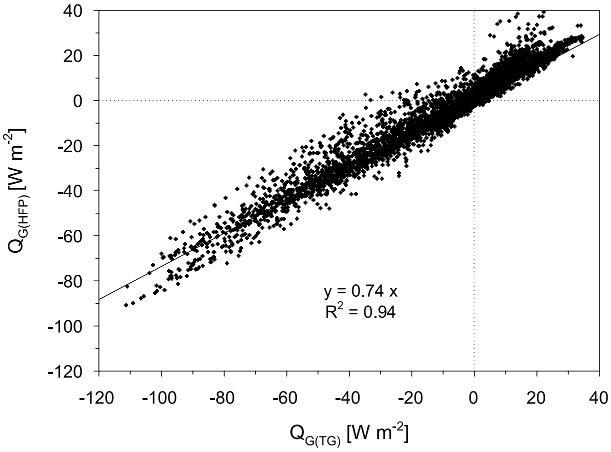

Fig. 3. Scatter diagram of the heat flux in ballast derived by HFP ($Q_{G\,(\mathrm{HFP})}$) and the heat flux calculated by temperature measurements and known λ ($Q_{G\,(\mathrm{TG})}$) for the study period 12 June–23 September 2002 in Osnabrück on the basis of 30-min averages

surements at $z = 0.05$ and 0.1 m). Due to flux divergence in the uppermost centimetres of the ballast bulk a larger heat flux from the HFP method would be expected. The regression for the lapilli underestimates the reference $Q_{G\,(\mathrm{TG})}$ by only 1%, but a R^2 of 76% indicates high random errors (data not shown here).

5. Discussion and conclusions

Significant errors can occur when deriving heat fluxes in coarse porous substrates by HFP. Underestimation of the soil heat flux might be one important contributor to the non-closure of the surface-energy-balance (e.g. Heusinkveld et al., 2004). Here, $Q_{G\,(\mathrm{TG})}$ would slightly reduce such gaps in the surface energy balance of the field experiments.

The fact that the heat flux $Q_{G\,(\mathrm{HFP})}$ both underestimated $Q_{G\,(\mathrm{TG})}$ in the field and overestimated $Q_{G\,(\mathrm{TG})}$ in the laboratory might be attributed to the sensitivity of HFP placement. Depending on the fraction of solid particles resting on the temperature-sensitive part of the HFP, the measured soil heat flux can vary significantly. Frequently, an ensemble of heat flux plates is used in the field to assess the uncertainty of deviation between different HFPs. The small systematic error of the HFP in the finer lapilli and better accuracy of HFPs in their intended media, i.e. typical soils, suggest that HFP performance decreases with increasing grain size. This would be in agreement to Fuchs and Hadas (1973) who found a doubling of thermal contact resistance between silty loam and coarse sand for HFPs with incompressible surfaces.

There are also limitations in the laboratory-derived λ. The method did not account for different moisture contents, which would have been beyond the scope of the paper. However, the moisture content was normally very low during field campaigns and the coarse substrates dried rapidly after precipitation.

The heat flow was established at a stable temperature stratification (warm plate on top). This does not represent nocturnal situations with free convection in the pore space, but daytime situations and therefore times of highest soil heat fluxes. In addition, van Donk and Tollner (2000) have shown that a fraction of heat transfer in coarse substrates is caused by wind-driven forced convection. All possible deviations of field to laboratory conditions, i.e. periods of moisture, unstable stratification at night, and wind, could only increase the effective λ and Q_G. Hence, $Q_{G\,(\mathrm{TG})}$ still represents a lower limit. Further accuracy improvements on the laboratory-derived λ could be achieved by lower temperature differences and by a taller measurement box. An additional assessment of HFP measurement accuracy with the present method could be achieved by inserting a second reference substrate of known lambda instead of the test substrate. Future research could be the establishment of a statistical relationship between substrate properties, substrate size distribution, and HFP performance.

In consequence of the presented results the use of heat flux plates in coarse substrates is not recommended without additional measurements.

Acknowledgements

Helpful comments by Simon Berkowicz (Hebrew University Jerusalem, Israel), Wilhelm Kuttler (University of Duisburg-Essen, Germany) and two anonymous reviewers are acknowledged.

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