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Calibration of soil heat flux sensors

W.K.P. van Loon[a,*], H.M.H. Bastings[a], E.J. Moors[b]

[a]*Department of Environmental, Agricultural and System Engineering, Wageningen Agricultural University, Bomenweg 4, 6703 HD Wageningen, Netherlands*

[b]*DLO Winand Staring Centre, P.O. Box 125, 6700 AC Wageningen, Netherlands*

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Abstract

Soil heat flux is difficult to measure accurately and soil heat flux plates are difficult to calibrate. In this research the reference heat flux was calculated from the temperature gradient and independent thermal conductivity measurements. Reference conductivities, as measured by the non-steady state probe method, have an error of about 2%, while the temperature gradient was measured to an accuracy better than 1%. This results in very reliable reference measurements. Compared with this reference, commercially available heat flux plates have significant inaccuracies. The 1 mm thin TNO PU 43 T sensor was the most accurate with an average relative error of only 4%. A promising new technique is the in situ self calibration, as performed by the Hukseflux HFP-01-SC disc sensor. With self calibration this sensor achieves an accuracy of 5% and confers several advantages for field use. The MIDDLETON CN3 and TNO WS 31S sensors had relative errors of about 20%. The ring shaped sensor Hukseflux SH1 gave relatively poor results, because it measured, in fact, the temperature gradient instead of the heat flux. The results of this sensor remained poor after correcting for the thermal conductivity of the sand. For all sensors the same conclusions hold for non-steady state conditions with evaporation.

The often used Philip (1961) correction factor is shown to be not very accurate: in only half of our experiments its use decreased the relative measuring error; and in some cases it made it worse. However, the correction remains useful as a tool for designing soil heat flux sensors; also a positive relation exists between the magnitude of the correction and the inaccuracy of the measurement. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Soil temperature is one of the most important growth factors of plants (Kirkham and Powers, 1972). Seeds will not germinate, until the soil temperature reaches a certain critical value and after that a normal growth rate also needs a certain soil temperature. Chemical reactions, that release nutrients to the plant, increase with soil temperature. The major cause of the variation of the temperature at the soil surface is the changing intensity of the solar radiation (van Wijk, 1966). A considerable fraction of this radiation reaches the soil surface if there is no dense vegetation covering the soil. The heat then flows through the soil mainly by conduction (the transfer of thermal energy on a molecular scale). Thus soil heat flux is an important parameter in models for energy balance,

*Corresponding author. Tel.: +31-317482980; fax: +31-317484819; e-mail: wilko.vanloon@user.aenf.wau.nl

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between air and soil, not only for plant growth models, but also for meteorological models.

The main practical use of measurements of soil heat flux is in meteorological stations that have the purpose to establish the energy balance at the surface. This energy balance is a part of soil vegetation atmosphere transfer models (SVATs), part of climatological studies or in general part of a far more accurate calculation of evaporation (Buchan, 1991; Franks et al., 1997).

The thermal conductivity of the soil and the temperature gradient determine the heat flux in the soil (Fourier's Law). The standard design of a soil heat flux sensor follows from this relationship. A thermopile embedded in a disc shaped resin measures the temperature gradient; the thermal conductivity of the sensor is usually known (it is mainly a material property of the insulating resin). This measuring set-up causes two kinds of measuring errors:

1. Because the thermal conductivity of the sensor differs from that of the soil, the soil heat flux by conduction is disturbed (Philip, 1961). This is known as the deflection error.
2. The plate itself impedes both liquid and vapour water flow, including the coupled (convective) heat transport (e.g., Buchan, 1991).

Soil heat flux plates are difficult to calibrate (Woodward and Sheehy, 1983). In dealing with the deflection error Watts et al. (1990) suggest a calibration for each sensor in two media with well-known thermal conductivities. A disadvantage is the extra measurement of the temperature gradient not only during calibration, but also in any (field) experiment.

In our research five commercially available sensors are tested under static and dynamic conditions in a well-controlled calibration set-up. The five sensors include: 1. Thick TNO disc, 2. Thin TNO disc, 3. Middleton plate, 4. Hukseflux disc and 5. Hukseflux ring. The fifth sensor cannot impede liquid and vapour flow, because it forms only a thin ring. All measured soil heat fluxes are compared with the in situ determined thermal conductivity (van Loon et al., 1989) and temperature gradient of the soil. The measuring errors of the four discs are evaluated and compared with the correction of Philip (1961) and qualitatively compared with the method of Watts et al. (1990).

2. Theory

Fourier's Law expresses the heat flux by conduction ϕ ($\mathrm{Wm^{-2}}$)

$$\phi = -\lambda \frac{\mathrm{d}T}{\mathrm{d}x} \tag{1}$$

with λ the thermal conductivity ($\mathrm{W\ m^{-1}\ K^{-1}}$) of the soil and $\mathrm{d}T/\mathrm{d}x$ the temperature gradient in the x (vertical) direction. It is the limit of the change in temperature ΔT over a small distance Δx.

The soil heat flux is assumed to be one dimensional in the vertical direction. Under steady state conditions we also assume that no convection or evaporation and condensation take place. Even under these idealised conditions two measuring errors can be distinguished according to van der Graaf (1990): the so-called one-dimensional distortion and the three dimensional distortion.

Philip (1961) described and solved analytically the deflection error for flat soil heat flux sensors. Because the soil heat flux sensor has a thermal conductivity which is usually smaller than that of the soil ($\lambda_{\mathrm{sen}} < \lambda_{\mathrm{s}}$), the heat flux through the sensor is smaller as well. In a large area of the sensor (not too close to the edge) the flux ϕ_{sen} is quite homogeneous. The undisturbed flux ϕ follows from the measured flux ϕ_{sen} (in the sensor) ($\mathrm{Wm^{-2}}$):

$$\phi = \phi_{\mathrm{sen}} \left(1 - F\left(\frac{h}{d}\right) \times \left(1 - \frac{\lambda_{\mathrm{s}}}{\lambda_{\mathrm{sen}}}\right)\right) \tag{2}$$

with h the height (thickness) of the sensor, d the diameter or length of the sensor and F a constant depending on the shape; for a disc $F \approx 1.92$ and for a square plate $F \approx 1.70$.

Based on this equation Watts et al. (1990) developed a two point calibration. At two different soil thermal conductivity's λ_1 and λ_2., the calibration coefficients ($\mathrm{Vm^{-2}\ W^{-1}}$) of the sensor (C_1 and C_2, respectively) are determined, using:

$$C = \mathrm{V}/\phi \tag{3}$$

with V is the voltage output of the sensor and ϕ the independently determined heat flux. The unknown heat flux ϕ_0 can only be calculated from the measured voltage output V_0 together with the measured temperature gradient $(\mathrm{d}T/\mathrm{d}z)_0$:

$$\phi_0 = \frac{C_2\lambda_1 - C_1\lambda_2}{(C_1 - C_2)/(\mathrm{d}T/\mathrm{d}z)_0 + (\lambda_1 - \lambda_2)/(\mathrm{V}_0)} \quad (4)$$

Another error is the edge error. Close to the edge of the sensor the flux is smaller, because the heat flux can go more easily through the soil. This causes also a larger heat flux in the soil close to the sensor, compared with that far away in the soil. van der Graaf (1990) showed that the use of a guard reduces the measuring errors due to edge. The guard has the same thermal properties as the rest of the sensor, but does not contain the temperature sensors.

3. Materials and methods

In this research, five different soil heat flux sensors are calibrated (see also Table 1)

- The Middleton CN3 sensor, manufactured in Australia, has a rectangular shape. The top and bottom consist of metal plates to minimise the edge errors. The corners of one metal plate end in pins, for fixing the probe's position. The effective thermal conductivity of the plate in vertical direction follows from the weighed average of the thermal conductivity of 2 mm×0.4 mm steel and 5.2 mm resin.
- TNO-thick or WS 31 S, manufactured by TNO Delft, is the standard disc shaped soil heat flux sensor in the Netherlands.
- A recent improvement of the last sensor is TNO-thin or PU 43T. Because of its 1 mm thickness the deflection error is theoretically very small.
- The Huksfluks SH1 has a very different concept (manufactured in Delft NL). It is a thin ring (0.25 mm) of flexible insulation material Kapton that contains the thermopile. The water and vapour can move freely through the big gap in the ring. The insulation contains besides the thermopile also a heating wire. In fact this sensor measures the temperature gradient in the soil. Only together with an independent estimation of the soil thermal conducutivity the soil heat flux can be calculated.
- The Huksefluks HFP-01 is a disc shaped sensor is manufactured from a well-conducting material. This sensor also contains a heater. By switching it on regurlary an in situ calibration can be performed. At the same time the condition of the sensor and data could be tested.

In general, the calibration set-up consists of temperature sensors in combination with a flat electrical heat source, whose dissipated heat is known (Biscoe et al., 1977; Buchan, 1991). From these data the thermal conductivity of the medium can be calculated. A disadvantage is measuring errors due to heat loss (this unknown heat loss must be subtracted from the dissipated heat to obtain the heat flux through the sensor). Our method using in situ measurements of thermal conductivity and temperature field is simpler and more accurate.

To calibrate the sensors a well insulated measuring box has been designed (see Fig. 1). Its dimensions are 0.36 m×0.31 m×0.20 m^3. The bottom of this box consists of a flat heat exchanger. One thermostat controls the temperature of the heat exchanger. A second thermostat controls the temperature in a

Table 1
Physical properties and calibration factors of the tested sensors: with h= thickness, d= diameter (or length × width), λ_{sen}= thermal conductivity, C= specific calibration factor, C_a= adjusted calibration factor determined with Van de Bos–Hoeksema method and np no determination possible

Name type	Middleton CN3	TNO-thick WS 31S	TNO-thin PU 43T	Huksefluks SH1	Huksefluks HFP 01
Shape	Rectangle	Disc	Disc	Ring	Disc
h [mm]	6	5	1	10	5
d [mm]	48×29	100	110	70	80
λ_{sen}[W m^{-1} K^{-1}]	0.30	0.25	0.25	0.25	0.8
C [W m^{-2} mV^{-1}]	38.5	13.2	6.4	8.3	13.5
C_a [W m^{-2} mV^{-1}]	np	14.0	6.2	np	13.5

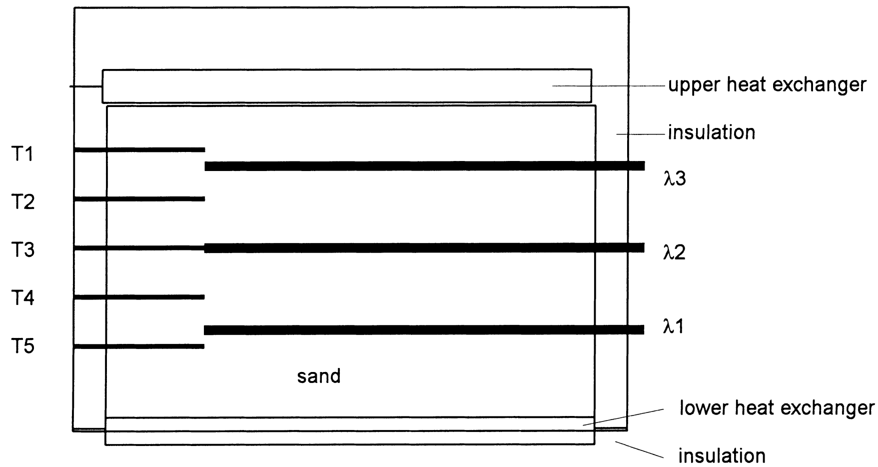

Fig. 1. Insulated measuring box with $\lambda1$, $\lambda2$ and $\lambda3$ thermal conductivity probes and T1.T5 thermocouple probes.

second flat heat exchanger, placed on the top. Together they control accurately a one dimensional temperature field. Five thermocouples (each separated 33 mm) measure the temperature field. Together with the thermal conductivity measurements, the soil heat flux can be determined independently. Thermal conductivity measurements have a long tradition in our laboratory (e.g. de Vries, 1952 and Haneghem, 1981). The thermal conductivity is measured with 200 mm long needle shaped probes, following the non-steady-state probe method as proposed by van Loon et al. (1989). This paper shows that for homogeneous, isotropic porous media the non-steady-state probe method provides thermal conductivity measurements with a measuring error of 1–3%. Measurements in the field are likely to be less accurate than these laboratory measurements. For real soils this measuring error increases to 3–5%. The thermal conductivity probes can also be seen in Fig. 1.

The measuring box contains Blokzijl sand (Wesseling and de Wit, 1966). An important parameter for soil is the water content, as it influences the thermal conductivity. The in situ determination of water content was performed with time domain reflectometry (TDR). From this method the dielectric permittivity follows, which mainly depends on the volumetric water content (e.g. Ledieu et al., 1994). The position of the soil heat flux sensors is mid plane, at the height of λ_2 and T_3. Because of space limitations not all sensors were tested at the same time.

4. Results and discussion

4.1. The steady state

First the accuracy of the calibration set-up has been tested. The linearity of the measured temperature profile is excellent: the deviation from the straight line is always less then 1% ($0.99<r^2<0.9996$, with r^2 the coefficient of determination). At four different moisture contents the steady state has been achieved, resulting in different thermal conductivities of the sand (see Table 2). The accuracy of the thermal conductivity is about 1–3%, resulting in an expected error in reference soil heat flux of 3% in this set-up. However, the relative deviation of the soil heat flux sensors is significantly larger: ranging from −40% to +20%.

To prevent the natural convection, the temperature at the top was always kept higher than the temperature at the bottom, during the steady state measurements. The most accurate sensor is TNO-thin: the average deviation is only 4%. This is in agreement with the configuration: this 1 mm thick sensor has both the smallest deflection and edge error. The TNO-thick and Huks-disc are qualitatively the same: an average deviation of about 15%. Among the plate sensors the Middleton sensor shows the largest deviation: about 25%.

The raw measurements performed by the Huks-ring, show an extremely large deviation: about 80%. In fact the temperature gradient in the soil is measured

Table 2
Soil heat flux measurement with and without Philip correction for five different soil heat flux sensors, with λ thermal conductivity of the soil, ϕ_{ref} the reference soil heat flux (i.e. thermal conductivity times temperature gradient)

λ ($m^{-1} K^{-1}$)	ϕ_{ref} (W m^{-2})	Philip correction	Middleton CN3 (W m^{-2})	TNO-thick WS 31S (W m^{-2})	TNO-thin PU 43T (W m^{-2})	Huks-ring (W m^{-2})	Huks-disc HFP01SC (W m^{-2})
0.17	16	no	18	19	16	2	15
0.17	16	yes	16	19	16	–	13
1.1	86	no	–	89	88	73	69
1.1	86	yes	–	118	93	–	72
1.4	111	no	79	92	101	90	84
1.4	111	yes	141	133	109	–	91
1.7	139	no	83	119	131	114	109
1.7	139	yes	165	185	145	–	124

with this sensor and not the heat flux itself. The sensor thermal conductivity (0.25 W m^{-1} K^{-1}) has no influence on the measured flux, because hardly any flux goes through the sensor (the thickness of the annulus is only 0.25 mm). So the edge error is large with this sensor. The calibration factor of this sensor is valid at a soil thermal conductivity of 0.20 W m^{-1} K^{-1}. To correct the flux for the measured thermal conductivity measurement λ_s it is multiplied with $\lambda_s/0.20$ (results see Table 2). These results are quite reasonable: the deviation is about 20%.

The measurements for the Middleton, TNO-thick and Huks-ring were also performed at two other temperature gradients: 209 and 23 K m^{-1}. About the same relative errors in measured soil heat flux were obtained. This is to be expected when only heat conduction takes place.

The correction for the difference between the thermal conductivity of soil and sensor as suggested by Philip (1961) does not improve the measurement significantly (see Table 2). Here the Middleton sensor is considered as a square plate with length of 48 mm. The Philip correction for all plates together results in only 8 out of 15 cases having a decrease in the relative error; in two cases the correction is in the good direction, but has a big overshoot; in two cases the correction is zero; and in three cases the correction is in the wrong direction. Thus quantitatively this correction, which can be found in many references (e.g., Woodward and Sheehy, 1983; Buchan, 1991), is not very accurate.

The two point calibration of Watts et al. (1990) gives accurate results. In our case the two extreme thermal conductivity's (0.17 and 1.70 W m^{-1} K^{-1}) were used to calibrate the sensors. So by definition the measuring error was made zero here. For the two other thermal conductivities used (1.10 and 1.40 W m^{-1} K^{-1}) the measuring error was in general less than 5%. In fact, following this procedure, the linearity of the sensor output as function of the heat flux was tested.

The heater mounted on top of the Huks-disc sensor, provides the opportunity to determine the specific calibration factor of the sensor, defined as $C=\phi_{sen}/V_{sen}$, with V_{sen} the voltage output of the sensor. With insulation on top of the heater and a metal block on the other side of the sensor almost all heat will flow towards the metal block (as long as the heat wave does not reach the far end of the metal block). When another truly flat soil heat flux sensor is located between the metal block and the heater also, the adjusted calibration factor C_a of this sensor could be determined. This method is referred to as the Van de Bos-Hoeksema method (Bastings, 1997; van den Bos, 1997). The C_a of the two TNO sensors has been measured this way. The calibration constants measured by this procedure are close to those given by the manufacturer (see Table 1). The Middleton CN3 and the Huksefluks ring don't have a really flat surface and therefor cannot be calibrated this way.

Another option of the heater on top of a flat disc sensor is an in situ calibration. Placed in the soil the heater of the sensor can also be used. Ideally half of this generated flux $\phi_{gen}/2$ is going upward and the other half is going downwards through the sensor. After about 5 minutes a new (quasi) steady state is reached, resulting in new output voltage of the sensor. From the change in measured voltage ΔV_{sen} the in situ

Table 3
Soil heat flux measured with Huks-disc using given calibration constant C and in situ determined calibration constant C_{insitu}, resulting in ϕ and ϕ_{recal}, respectively

λ (W m^{-1} K^{-1})	$\phi_{ref.}$ (W m^{-2})	C (W mV^{-1} m^{-2})	ϕ (W m^{-2})	C_{insitu} (W mV^{-1} m^{-2})	ϕ_{recal} (W m^{-2})
0.17	15.9	13.5	14.7	15.3	16.7
1.1	86	13.5	69	17.5	89
1.4	111	13.5	84	17.9	111
1.7	139	13.5	109	20.5	157

calibration coefficient can be calculated: C_{insitu}= $0.5\phi_{gen}/\Delta V_{sen}$. The soil heat flux values following this in situ recalibration procedure ϕ_{recal} are presented in Table 3. They are compared with the reference soil heat flux (ϕ_{ref}) and the standard values (ϕ) measured with the given calibration constant of 13.5 [W mV^{-1} m^{-2}]. Table 3 shows that the recalibration improves the results significantly: the relative error decreases from about 20% to about 5%.

4.2. Non-steady-state

Under field conditions, the thermal conductivity of the soil is likely to change due to rainfall, evaporation, etc. Therefore, tests under changing thermal conductivity have been carried out. With the previous experimental configuration, temperature increased with height; in these non steady state experiments the temperature profile was inverted. To improve evaporation the top heat exchanger has been removed. As an example one drying test from water content of 0.37 to 0.29 (vol. water/volume bulk) is given in Fig. 2. (A second test with sensors Middleton CN3, TNO thick and Hukseflux ring give similar results (Bastings, 1997) and were therefore not graphically presented in this paper). The decrease in water content resulted in a decrease in thermal conductivity from 1.7 to 1.4 W K^{-1} m^{-1}. Every ten minutes a datalogger auto-

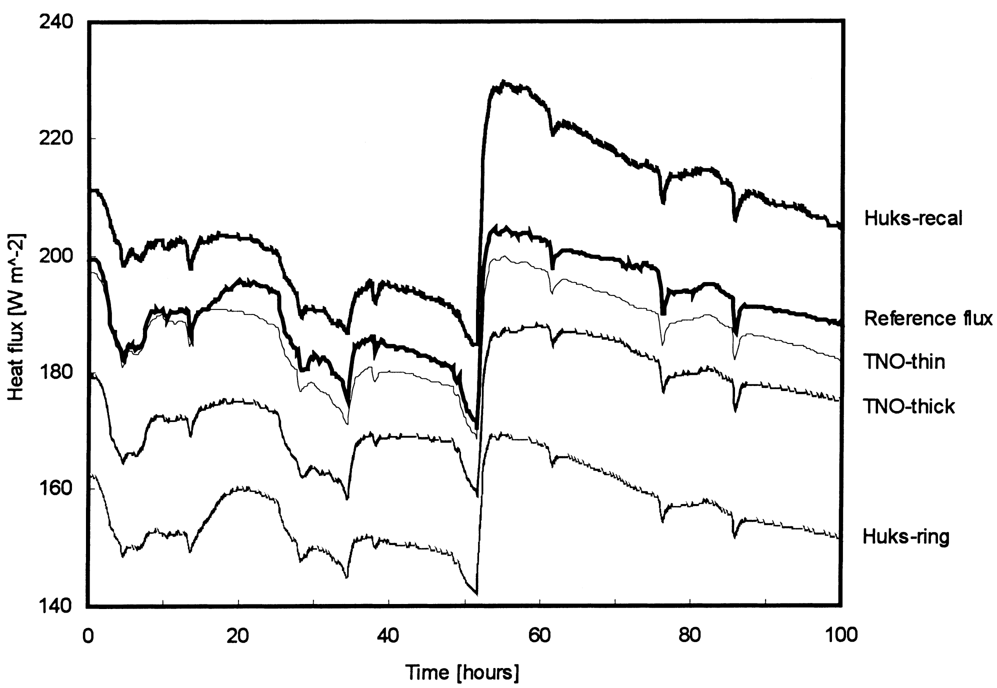

Fig. 2. Non-steady state soil heat fluxes measured with four different sensors compared with the reference flux during drying of sand.

matically registered the output of all soil heat flux and temperature sensors. So this experiment (shown in Fig. 2) lasted 100 h. Switching off the thermostat for a few minutes caused sudden dips in soil heat flux. All measured fluxes reacted similarly to this event. After 50 hours a fan above the sand surface was switched on, to improve the water evaporation. This caused the sudden increase in flux, registered by all sensors.

The TNO-thin sensor is most accurately measuring the reference soil heat flux, which is also true under steady state conditions. The relative error increases roughly over time from 2–4%, which is very acceptable. The TNO-thick sensor gives an underestimation of about 5–10%, while the recalibrated Huks-disc gives an overestimation in the same range. The Huks ring, designed for a good water (vapour) transmission, does not give better results than under steady state conditions: the relative error is still about 20%. In other tests we observed similar results; for the Middleton sensor an underestimation of about 35% was found.

5. Conclusions

Soil heat flux plates are difficult to calibrate accurately. Woodward and Sheehy (1983) advise to compare the output of a calibrated, commercially available plate with new uncalibrated plates. However from this research it follows that the commercially available plates have a large error also .

Even with a well-calibrated soil heat flux sensor it is difficult to measure the correct soil heat flux, because the heat and moisture fluxes in the soil are disturbed. Quantitatively the heat deflection correction, as suggested by Philip (1961) and found in many references (e.g., Woodward and Sheehy, 1983 and Buchan, 1991) is not very accurate. However, the 1DD correction equation is valuable as a designing tool for soil heat flux sensors: the thickness diameter ratio should be as small as possible. There is also a positive relation between the magnitude of the 1DD correction and the inaccuracy of the measurement.

The two point calibration of Watts et al. (1990) gives accurate results. In our case the measuring error was in general less than 5%. A disadvantage is the requirement for an extra measurement of temperature gradient in any (field) experiment.

According to the present research the TNO-thin sensor, with a thickness of only 1 mm, is the most accurate: an average relative error of only 4% was achieved. A promising new technique is the in situ calibration of the sensor, as performed with the Huks-disc. With the recalibration the relative error in the measured flux decreased from 20–to 5%. The ring sensor gives relatively poor results, even after correcting for the thermal conductivity of the sand. The same conclusions hold for non steady state conditions, when high evaporation takes place. In this Blokzijl sand the condensation and evaporation of water do not increase the measuring errors.

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