Theor. Appl. Climatol. 42, 263–272 (1990)

Theoretical
and Applied
Climatology

551.508:551.525

USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX, U.S.A.

Calibration of Soil Heat Flux Transducers*

T. A. Howell and **J. A. Tolk**

With 4 Figures

Received May 23, 1989

Summary

Soil heat flux transducer calibration, according to theory, is influenced by the thermal conductivity difference between the transducer and the calibration medium and the geometry of the transducer. This study was conducted to compare the influence of these parameters on the calibration factors of two types of commercial soil heat flux transducers with different material thermal conductivities and different geometries. A theoretical calibration equation was developed and evaluated. Calibrations of 14 transducers representing two commercial types were conducted in the laboratory using steady-state conductive methods over a range of heat fluxes from 40 W/m^2 to 200 W/m^2. The calibration medium was dry and saturated sand with a thermal conductivity varying from 0.3 to 3 $W m^{-1} {}^\circ C^{-1}$. The mean calibration factor for one type of transducer was 12% lower than the mean manufacturer's calibration factor instead of the 26 to 36% lower value predicted by theory. The other type of transducer had a mean calibration factor 7% greater than the mean manufacturer's calibration factor in contrast to the 1 to 11% larger value predicted from theory. The computed geometric factors were 1.07 and 0.89 for the circular and square transducers, respectively. These factors were less than the theoretical value of 1.70 for each shape of transducer but similar to experimental values of 1.02 to 1.31 from previous studies reported in the literature. The thermal conductivity of the calibration medium and the geometry of the transducer affects the calibration factors of soil heat flux transducers, basically according to theory.

Introduction

Vertical flux of heat into the soil is one of the components of the total surface energy balance. Heat flux in the soil may be small and even negligible when integrated over 24-h cycles (days or weeks), but over shorter time periods (minutes or hours) it is an important part of the partitioning of the total net radiation into the various energy balance components. During night-time, soil heat flux is one of the dominate sources of energy driving the evaporative process. Traditional surface energy balance studies have used methods similar to those described by Tanner (1960) in which soil heat flux is computed by the sum of the heat flux measured at some depth (Z) with soil heat flux transducers and the calorimetrically estimated heat storage in the layer above the transducer (0 to Z).

Soil heat flux is most often measured using heat flux transducers which are thin plates in which the temperature difference across the plate is measured with thermopiles (Fritschen and Gay, 1979). Deacon (1950) and Hatfield and Wilkins (1950) described the construction of early soil heat flux transducers and cited previous work back to the 1930's. Fuchs and Tanner (1968) described the construction and calibration of soil heat flux transducers. Fritschen and Gay (1979) described nine methods (7 conductive and 2 radiative) for calibrating soil heat flux transducers.

Portman (1958) and Philip (1961) investigated the effects of transducer geometry (thickness, diameter, etc.) and transducer thermal conductivity on the performance of soil heat flux transducers as influenced by the soil thermal conductivity.

---

* Contribution from USDA-Agricultural Research Service, Southern Plains Area.

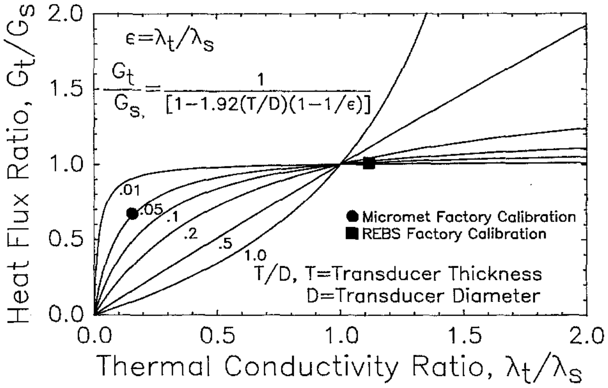

Fig. 1. Illustration of the effect of soil heat flux transducer geometry and soil heat transducer thermal conductivity on heat flux divergence around or through a soil heat flux transducer in relation to the thermal conductivity of the soil surrounding the soil heat flux transducer. This illustration is similar to Fig. 4.1 in Fritschen and Gay (1979) and is based on the theory of Philip (1961) using an α value of 1.70

Philip (1961) emphasized that 1) thin transducers were desirable, 2) thermal conductivity of the calibration medium should equal the arithmetic mean of the extremes of the soil thermal conductivity to which the transducer is intended to be used, 3) thermal conductivity of the transducer material should be as large as possible, and 4) real accuracy of soil heat flux transducers was likely limited by the thermal contact between the transducer and the soil. Philip (1961) proposed the equation

$$F = G_t/G_s = \varepsilon/[1 + (\varepsilon - 1)H] \tag{1}$$

where F is the ratio of the soil heat flux in W/m^2 going through the transducer (G_t) to that going through the soil (G_s), ε is the ratio of the transducer thermal conductivity (λ_t) in W m^{-1} °C^{-1} to that of the soil (λ_s) and H is a dimensionless constant that depends on the transducer geometry and is given as

$$H = 1 - (\alpha\, r) \tag{2}$$

where α is a dimensionless geometric constant and r is $T_t/[(A_t)^{1/2}]$, where T_t is the transducer thickness in m and A_t is the transducer area in m^2. Philip (1961) proposed that the value of α should be 1.70 based on theory but computed a value of 1.31 from electrical analog data presented by Portman (1958). Mogensen (1970) reported that α based on his analysis of Portman's data should be 1.83, and computed an α value of 1.02 for the transducer he calibrated. Solutions of equations [1] and [2] for a circular heat flux transducer with various thickness/diameter ratios (T_t/D_t where D_t is transducer diameter in m) and an α value of 1.70 are illustrated in Fig. 1 similar to Fig. 4.1 in Fritschen and Gay (1979). This diagram illustrates the significant errors associated with soil heat flux measurements with 1) thick transducers (large T_t/D_t ratios) and 2) transducers with low thermal conductivities (small λ_t/λ_s ratios).

The soil heat flux transducer sensitivity (or calibration factor) following Fritschen and Gay (1979) is given as

$$K = \lambda_t/(N E T_t) \tag{3}$$

where K is the transducer calibration factor in W m^{-2} mV^{-1}, N is the number of thermoelectric junctions in the thermopiles, and E is the thermoelectric potential in mV/°C of the thermocouple junctions. Fuchs and Hadas (1973) described K as the "ideal sensitivity". The soil heat flux at the measurement depth Z is then given as

$$G_Z = (V_t K)/F \tag{4}$$

where G_Z is soil heat flux in W/m^2 and V_t is the transducer analog output signal in mV.

We combined these four equations (Eq. 1–4) into the following soil heat flux transducer calibration equation given as

$$G_c/V_t = K[1 - (\alpha\, r)] + [(K \alpha\, r)/\lambda_t]\lambda_c \tag{5}$$

where G_c is the heat flux in W/m^2 in the calibration medium, G_c/V_t is termed the "apparent" calibration factor in W m^{-2} mV^{-1}, and λ_c is the thermal conductivity in W m^{-1} °C^{-1} of the calibration medium. Equation (5) contains three parameters [K, α, and λ_t] that describe the calibration sensitivity of a soil heat flux transducer. If λ_t, T_t, and A_t are assumed to be known values for each transducer, then unique values of K and α for each transducer define its calibration and can be determined by linear regression with G_c/V_t as the dependent variable and λ_c as the independent variable.

The purposes of this paper are to 1) demonstrate the utility of equation (5) for soil heat flux transducer calibrations, 2) to present calibration results for two types of commercial soil heat flux transducers with different thermal conductivities, and 3) to evaluate the experimental values of α for the two types of transducer geometry.

Table 1. *Characteristics of the Soil Heat Flux Transducers Used in the Calibration Experiments*

Number	Shape	Transducer characteristics serial					
		D_t, L_t [a] mm	T_t [a] mm	N [a]	λ_t	λ_c [b]	K
					W m^{-1} °C^{-1}		W m^{-2} mV^{-1}
406[c]	circular	60	2.8	22	0.15	1.092	100.5
412	circular	60	2.8	22	0.15	1.092	105.0
431	circular	60	2.8	22	0.15	1.092	110.4
432	circular	60	2.8	22	0.15	1.092	119.0
434	circular	60	2.8	22	0.15	1.092	103.7
435	circular	60	2.8	22	0.15	1.092	113.9
88078[d]	square	32	3.5	31	1.05	0.94	35.0
88079	square	32	3.5	31	1.05	0.94	33.1
88080	square	32	3.5	31	1.05	0.94	38.1
88081	square	32	3.5	31	1.05	0.94	36.8
88082	square	32	3.5	31	1.05	0.94	32.2
88083	square	32	3.5	31	1.05	0.94	32.9
88084	square	32	3.5	31	1.05	0.94	37.8
88085	square	32	3.5	31	1.05	0.94	38.0

[a] Manufacturer's nominal values.

[b] Reported thermal conductivity of the calibration medium.

[c] Micromet Instruments, Inc., Bothell, WA.

[d] Radiation Energy Balance Systems (REBS), Seattle, WA.

Materials and Methods

Characteristics of the heat flux transducers used in this study are listed in Table 1. The circular transducers (Micromet Instruments*, P.O. Box 486, Bothell, WA 98011) have a manufacturer reported thermal conductivity of 0.17 W m^{-1} °C^{-1}, and the square transducers (Radiation Energy Balance Systems, P.O. Box 15512, Seattle, WA 98115, Model HFT-1) have a manufacturer reported thermal conductivity of 0.69 W m^{-1}°C^{-1}. Fritschen (1989, personal communciation) reported thermal conductivity of 1.05 W m^{-1} °C^{-1} for the REBS transducers and indicated that the reported thermal conductivity for the Micromet transducers may be about 9% high. Figure 1 illustrates the F values for these transducers based on the reported manufacturer's calibration medium thermal conductivity (Table 1). Fritschen (1989, personal communication) indicated that the thermal conductivity of the calibration medium for Micromet and REBS was about 0.905 W m^{-1} °C^{-1}. Soil heat flux transducer characteristics used in these experiments are compared to several types of transducers used in previous studies in Table 2. The thermal conductivity of the Micromet transducers is quite low in comparison to those from the previous studies, although the one used by Mogensen (1970) is only about twice as conductive. The Micromet transducers were several years old while the REBS transducers were new.

Calibrations were conducted in a temperature controlled laboratory (20 °C ± 1 °C). A one-dimensional conductive heat source similar to that used by Fuchs and Tanner (1968) was employed, and the calibration box is shown in Fig. 2. The heating mat (Cole Parmer, model J-3125-62) used NiChrome wire spiraled around glass string that was laminated between two cloth pieces and coated with silicone rubber and all air was removed during vulcanization. The heating mat was 152 by 508 mm in size and had a resistance of 24 ohms. The heating mat was located vertically in the calibration box and 48 mm equidistant from the sides as shown in Fig. 2. The bottom and ends of the box were insulated with 25-mm thick styrofoam and 19-mm thick plywood. The top was insulated with 25-mm thick styrofoam. Aluminum

---

* Mention of trade names does not imply endorsement by the United States Department of Agriculture.

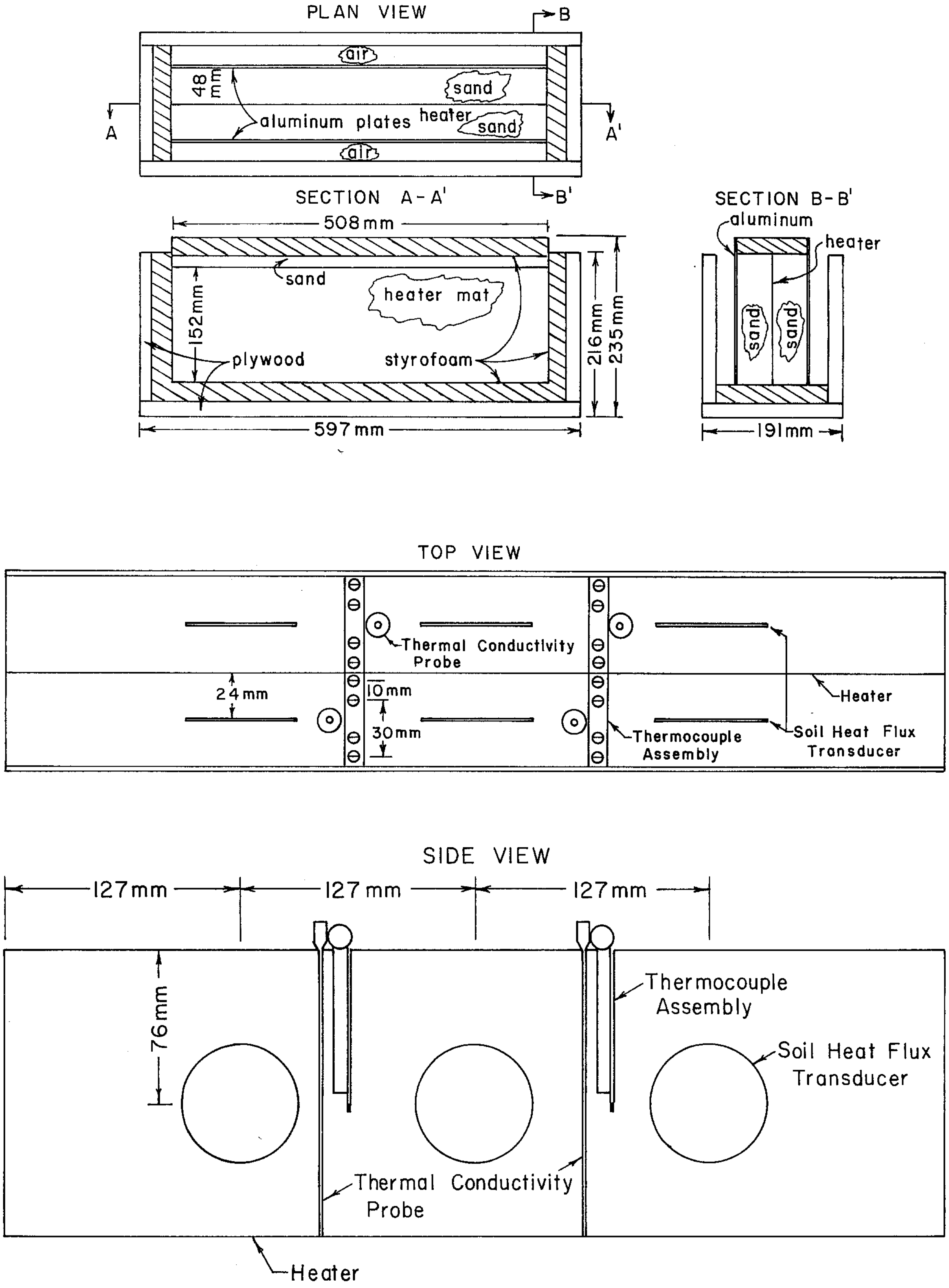

Fig. 2. Soil heat flux calibration box construction details and instrumentation arrangements

Table 2. *List of the Soil Heat Flux Transducer Characteristics from Past Studies*

Reference	Shape	Transducer characteristics			
		D_t or L_t mm	T_t mm	r	λ_t $\mathrm{W\,m^{-1}\,°C^{-1}}$
Fuchs and Tanner (1968)	rectangular	83 × 33	1.7	0.032	2.55
Mogensen (1970)	circular	13	2.5	0.217	0.37
Fuchs and	rectangular	80 × 30	1.2	0.025	1.03
Hadas (1973)	circular	25.4	2.9	0.129	0.335
Micromet	circular	60	2.8	0.053	0.15
REBS	square	32	3.5	0.109	1.05

plates, 3-mm thick, were placed on either side of the sand medium and 25 mm from the outside of the plywood box to dissipate the heat. A commercial grade sand was used as the calibration medium. Sand particle size characteristics were 87.5% coarse to medium sand (0.6 to 0.25 mm), 11.8% fine sand (0.1 to 0.25 mm), and 0.7% very fine sand (0.06 to 0.1 mm). The sand was carefully packed into the box in shallow layers, and the instruments were installed. The sand was packed by tapping on the outside of the box with a rubber mallet, and the final packed density was $1.66\,\mathrm{Mg/m^{-3}}$.

Four thermocouple assemblies were constructed with 6-mm wooden dowel rods with the Cu-Co thermocouples extended about 6 mm beneath the end of each dowel. Thermocouples were located 10 and 20 mm from the heat flux transducers shown in Fig. 2. This permitted thermal gradients to be measured across both 20- and 40-mm increments centered on the heat flux transducer. A thermal conductivity probe (Decagon Devices, Inc., P.O. Box 835, Pullman, WA 99163, Model TC-1) was inserted vertically and centered with respect to each thermocouple assembly as shown in Fig 2. Six circular soil heat flux transducers (Micromet) or eight square soil heat flux transducers (Radiation Energy Balance Systems) were installed in the box with one-half in each side of the box. Signals from the thermocouples and the soil heat flux transducers were recorded by a Campbell Scientific CR-7 data logger. The thermocouple signals were converted to temperature using the internal compensation program of the CR-7. Thermocouple signals were manually monitored until steady-state conditions were reached (usually 48 hours or longer). Thermal gradients and soil heat flux transducer signals were then averaged using a 0.2 Hz sampling frequency for a 15-minute time period.

At the end of a measurement sequence, the thermal conductivity probes were excited (5 V-d.c.) and data were recorded by a separate Campbell Scientific CR-21 X data logger. Probe temperature (T_p) and heater resistance measurement samples (32 samples power measurement) were logarithmically spaced over the time interval of 0.2 s to 201 s. Thermal conductivity was determined by 1) visually inspecting a plot of T_p vs ln (t) to determine the number of data points to disregard (de Vries and Peck, 1958), 2) then determining the slope of the linear regression between T_p and ln (t), and 3) then computing the thermal conductivity with the theoretical relationship for heat flow from a line source in an infinite uniform medium (de Vries and Peck, 1958), [$\lambda = Q/(4\pi S\,Lp)$ where Q is the applied power in W, L_p is the probe length in m, and S is slope of the linear regression between T_p and ln (t) with t in s].

A range of heat flux through the sand was obtained by varying the applied voltage to the heater. The applied voltages, controlled with a Hewlett-Packard (Model 6289 A) power supply, were 12, 20, and 27 V (d.c.) which resulted in nominal heat flux of 40, 100, and 200 $\mathrm{W/m^2}$, respectively. Power applied to the heater was computed by the ratio of the square of the applied voltage to the resistance of the heater. Voltage and resistance of the heater were measured with a Hewlett-Packard (Model 3466 a) digital voltmeter. Heat flux through each side of the sand was assumed to be one-half of the heater energy flux. Thermal conductivity of the dry sand was estimated to be

0.32 W m^{-1} °C^{-1} (at 20 °C) according to the values from de Vries (1963). Calibration experiments were conducted both with dry sand and saturated sand. Thermal conductivity of the saturated sand (porosity 38%) was estimated to be 2.8 W m^{-1} °C^{-1} (at 20 °C).

The values K and α were computed for each transducer from the linear regression line for G_c/V_t versus λ_c. The heat flux through the calibration medium, G_c, was determined by two methods of 1) the heater method used the computed heat flux from the power applied to the heater and 2) the thermal conductivity (TC) method used the product of the mean measured thermal gradient and mean thermal conductivity. The calibration medium thermal conductivity (λ_c) was determined by the ratio of the heater heat flux and the mean thermal gradient and by the measured thermal conductivity, respectively. The value of the calibration factor was computed by

$$K = a + (\lambda_t b) \tag{6}$$

and the geometric factor, α, was computed by

$$\alpha = (\lambda_t b)/(r K) \tag{7}$$

where a and b are the linear regression intercept in W mV^{-2} mV^{-1} and slope in °C m^{-1} mV^{-1}, respectively. Values for λ_t and r were taken from the manufacturer's data (Tables 1 and 2).

Results and Discussion

Calibration measurements for the Micromet transducers and for the Radiation Energy Balance Systems (REBS) transducers are summarized in Table 3. Variations in the measured heat flux from the heater through the sand medium were small (mean standard errors were less than 0.5 W/m^2). The mean measured thermal conductivity for the dry sand (0.40 W m^{-1} °C^{-1}) was larger than that estimated from theory (0.32 W m^{-1} °C^{-1}) but similar to the "apparent" thermal conductivity (ratio of heater heat flux to the thermal gradient of 0.42 W m^{-1} °C^{-1}). This discrepancy may be due to the small amount of water in the sand or variation in the bulk density. Although, the sand was air-dry, subsequent measurements found that the gravimetric water content was about 0.3%. The mean thermal conductivity at saturation (2.84 W m^{-1} °C^{-1}) was approximately the same as the theoretical value (2.8 W m^{-1} °C^{-1}) and the "apparent" thermal conductivity (2.93 W m^{-1} °C^{-1}). The heat flux in the sand determined by the heater heat flux was linearly related to the heat flux computed by the product of the measured thermal conductivity and thermal gradient ($G_h = -3.89 + 1.10\, G_{tc}$) indicating that both methods produced similar results ($G_h/G_{tc} = 1.06$) increasing the reliability of the calibrations (Fig. 3). Apparently at the larger heater heat fluxes, 5 to 10% of the applied heat was lost to heat transfer through the walls of the box.

Table 4 gives the mean and standard errors of the transducer output signals for each transducer during the calibration experiments. In almost every case, the standard error of the mean transducer signal was less than 10% of the mean transducer signal.

The resulting calibration parameters for the transducers are given in Table 5. Essentially, only two values of λ_c actually existed (one for dry sand and one for saturated sand although minor effects on thermal conductivity were measured due to temperature differences), so the linear regression calibration equations had high coefficients of determination. The mean coefficient of determination was 0.93 for the Micromet transducers and 0.78 for the REBS transducers (Table 5). The low value of the coefficient of determination for the REBS transducer was mainly due to the flat slope rather than deviations in the data. The mean standard error of the estimate, $S_{y/x}$ for the regressions was 13.6 W m^{-2} mV^{-1} and 2.5 W m^{-2} mV^{-1} for the Micromet and REBS transducers, respectively. Figure 4 shows the mean calibration line for the 6 Micromet and 8 REBS transducers. The calibration factor, K, was consistent for the individual transducers within each manufacturer's group, and the coefficient of variation of K was less than 0.07 for both types of transducers. The variation in the α value was much greater for the REBS transducers than for the Micromet transducers. The CV for α was 0.06 and 0.26 for the Micromet and REBS transducers, respectively. The mean calibration factor for the 6 Micromet transducers was only about 12% lower than the mean manufacturer's calibration factor when it should have been 36% lower according to theory (using an α value of 1.70, r of 0.053, and ε of 0.137 where F will be 0.638). The mean calibration factor for the 8 REBS transducers was about 7% larger than the mean manufacturer's calibration factor while the theoretical value would be 1% larger (using an α value of 1.70, r

Table 3. *Mean Heat Flux Transducer Measurements for the Calibrations*

Parameter	Dry			Saturated		
	Heater voltage, V d.c.					
	12	20	27	12	20	27
(Part a, Micromet transducer calibrations)						
Heater Heat Flux, G_h, W/m^2	39.35 (0.16)	109.10 (0.40)	198.45 (0.66)	39.36 (0.15)	109.21 (0.39)	198.55 (0.45)
Thermal Conductivity, λ_c, W m^{-1} °C^{-1}	0.49 (0.09)	0.34 (0.02)	0.36 (0.02)	2.84 (0.19)	2.71 (0.31)	2.99 (0.47)
Thermal Gradient, $\Delta T/\Delta Z$, °C/m	101.58 (2.42)	271.26 (9.60)	485.11 (14.33)	14.06 (0.59)	37.82 (2.62)	67.28 (4.40)
Conductivity Heat Flux, $\lambda_c \Delta T/\Delta Z$, W/m^2	49.69 (8.82)	91.02 (7.29)	172.00 (2.19)	39.81 (1.01)	101.67 (4.61)	199.09 (18.48)
Apparent Thermal Conductivity, $G_c/(\Delta T/\Delta Z)$, W m^{-1} °C^{-1}	0.39 (0.01)	0.40 (0.01)	0.41 (0.01)	2.81 (0.11)	2.90 (0.19)	2.96 (0.19)
(Part b, REBS transducer calibrations)						
Heater Heat Flux, G_h, W/m^2	39.12 (0.03)	108.05 (0.55)	197.05 (0.35)	39.15 (0.03)	108.11 (0.25)	195.97 (0.61)
Thermal Conductivity, λ_c, W m^{-1} °C	0.39 (0.04)	0.42 (0.04)	(0.39) (0.04)	2.70 (0.14)	2.95 (0.57)	2.82 (0.48)
Thermal Gradient, $\Delta T/\Delta Z$, °C/m	91.90 (5.00)	246.97 (15.07)	459.57 (12.94)	13.02 (0.57)	36.80 (0.14)	66.83 (0.15)
Conductivity Heat Flux, $\lambda_c \Delta T/\Delta Z$, W/m^2	35.64 (1.72)	104.17 (2.50)	177.39 (21.07)	35.03 (0.23)	108.48 (20.56)	188.04 (31.33)
Apparent Thermal Conductivity, $G_c/(\Delta T/\Delta Z)$, W m^{-1} °C^{-1}	0.43 (0.02)	0.44 (0.03)	0.43 (0.01)	3.01 (0.13)	2.94 (0.02)	2.93 (0.02)

Numbers in parenthesis are standard errors.

of 0.109, and ε of 1.117 where F will be 1.012). If the α values are changed to the α values of 1.07 and 0.89 in Table 5, the theoretical F values will increase to 0.737 for the Micromet transducers and to 1.010 for the REBS transducers. The exact precision of the assumed values of λ_t is uncertain and directly affects both K and α. Values of K for the Micromet transducers would be tenfold as sensitive to variations in λ_t according the calibration slopes compared to the REBS transducers. However, α for both types of transducers would be directly proportional to variations in λ_t as shown by equation [7], but again the Micromet transducers would be much more sensitive to λ_t than the REBS transducers.

The value of α appears to be lower than the value of 1.70 predicted by Philip (1961). The mean α value was 1.07 for the circular Micromet transducers and 0.89 for the square REBS transducers.

The exact reason for the differences in α for the two transducers is uncertain. Philip (1961) computed a mean α value of 1.31 for the electric analog

Table 4. *Mean Soil Heat Flux Transducer Output Signals, V_t*

Transducer	Dry			Saturated		
Serial	Heater voltage, V (d.c.)					
Number	12	20	27	12	20	27
			mV			
(Part a, Micromet transducers)						
406	0.359	1.075	1.952	0.187	0.566	1.079
	(0.009)	(0.039)	(0.099)	(0.021)	(0.046)	(0.063)
412	0.378	1.077	1.940	0.196	0.561	1.038
	(0.009)	(0.028)	(0.043)	(0.019)	(0.044)	(0.053)
431	0.338	0.981	1.793	0.175	0.505	0.932
	(0.016)	(0.053)	(0.087)	(0.033)	(0.077)	(0.107)
432	0.359	0.991	1.783	0.198	0.530	0.967
	(0.010)	(0.032)	(0.062)	(0.012)	(0.010)	(0.011)
434	0.427	1.168	2.119	0.232	0.608	1.121
	(0.004)	(0.024)	(0.038)	(0.014)	(0.022)	(0.006)
435	0.370	1.028	1.866	0.218	0.564	1.027
	(0.013)	(0.034)	(0.066)	(0.007)	(0.038)	(0.037)
Mean	0.372	1.053	1.909	0.201	0.556	1.027
CV	0.092	0.088	0.090	0.138	0.106	0.088
(Part b, REBS transducers)						
88078	1.039	2.878	5.344	0.811	2.334	4.544
	(0.049)	(0.075)	(0.113)	(0.053)	(0.173)	(0.275)
88079	1.149	3.184	5.957	0.874	2.299	4.601
	(0.017)	(0.056)	(0.144)	(0.041)	(0.372)	(0.456)
88080	1.016	2.812	5.230	0.883	2.547	4.840
	(0.025)	(0.061)	(0.144)	(0.055)	(0.157)	(0.221)
88081	0.970	2.721	5.062	0.813	2.250	4.365
	(0.054)	(0.110)	(0.229)	(0.040)	(0.210)	(0.328)
88082	1.045	3.038	5.770	0.867	2.326	4.286
	(0.051)	(0.192)	(0.312)	(0.079)	(0.094)	(0.212)
88083	1.115	3.223	6.089	0.964	2.415	4.788
	(0.057)	(0.172)	(0.251)	(0.041)	(0.188)	(0.021)
88084	0.942	2.720)	5.112	0.780	2.359	3.946
	(0.044)	(0.140)	(0.201)	(0.061)	(0.243)	(0.175)
88085	1.001	2.796*	5.216	0.751	2.221*	3.896
	(0.034)			(0.087)		(0.332)
Mean	1.035	2.924	5.743	0.843	2.344	4.408
CV	0.067	0.070	0.074	0.080	0.044	0.080

Numbers in parenthesis are standard errors.
* Missing data from one test.

data of Portman (1958). Mogensen (1970) computed an α value of 1.82 for the data of Portman (1958) and reported an α value of 1.02 for the transducer that he calibrated. Mogensen's calibration value for α is about in the middle of the range of our values. It is possible for discrepancies in the assumed transducers thermal conductivity, transducer dimensions, or thermal contact effects between the transducer and the calibration medium to affect the α value as shown by equation (7).

The calibration of soil heat flux transducers must be conducted over a range of calibration medium thermal conductivities to adequately characterize α and *K* according to equation (5). This greatly complicates the normal calibration procedures and increases the time required for calibrations as well. The Fuchs and Tanner (1968)

Table 5. *Calibration Summary of the Linear Regression Between G_c/V_t and λ_c (Eq. [5]) with K and a Computed with Eq. [6] and [7], Respectively*

Serial Number	Calibration regression					
	Intercept a W m^{-2} mV^{-1}	Slope b °C m^{-1} mV^{-1}	Coefficient of determination r^2	Standard error of estimate $S_{y/x}$ W m^{-2} mV^{-1}	Philip α	Calibration factor, K W m^{-2} mV^{-1}
(Part a, Micromet transducers)						
406	90.5	36.1	0.88	17.8	1.06	95.9
412	88.2	36.8	0.93	13.4	1.11	93.7
431	96.7	41.7	0.93	15.8	1.15	102.9
432	95.6	37.0	0.95	12.2	1.04	101.2
434	80.1	32.7	0.95	10.3	1.09	85.0
435	93.1	32.9	0.93	12.2	0.95	98.0
Mean	90.7	36.2	0.93	13.6	1.07	96.1
CV	0.07	0.09		0.20	0.065	0.07
(Part b, REBS transducers)						
88078	34.8	3.4	0.77	2.5	0.85	38.4
88079	31.4	4.3	0.80	2.9	1.10	35.9
88080	36.1	1.8	0.59	2.1	0.44	38.0
88081	36.9	3.1	0.76	2.4	0.74	40.2
88082	32.7	4.1	0.84	2.4	1.07	37.0
88083	31.0	3.5	0.75	2.8	0.97	34.7
88084	37.1	3.5	0.80	2.4	0.83	40.8
88085	35.1	4.8	0.90	2.2	1.15	40.1
Mean	34.4	3.6	0.78	2.5	0.89	38.1
CV	0.07	0.25		0.11	0.261	0.06

heater method produced values of heat flux and "apparent" thermal conductivities that were more stable than direct measurements of thermal conductivity using heated probes. If soil heat flux transducer thermal conductivity is large (>1 W m^{-1} °C^{-1}) and if the transducer value of r is small (<0.1), then the simpler calibration procedure of Fuchs and Tanner (1968) should be satisfactory; however, the value of α should be carefully estimated as it will probably be less than the theoretical value of 1.70.

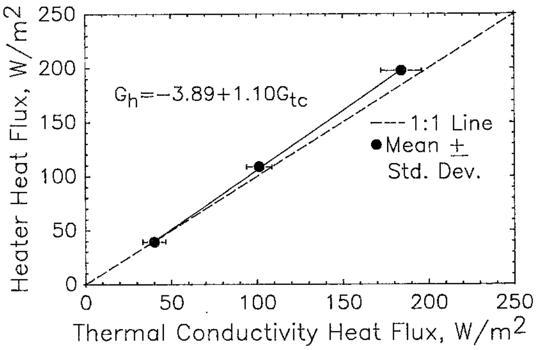

Fig. 3. Comparison of mean heat fluxes computed from heater power measurement (heater heat flux) and that computed from the product of the measured thermal conductivity and the thermal gradient (thermal conductivity heat flux). Error bars represent ± one standard deviation

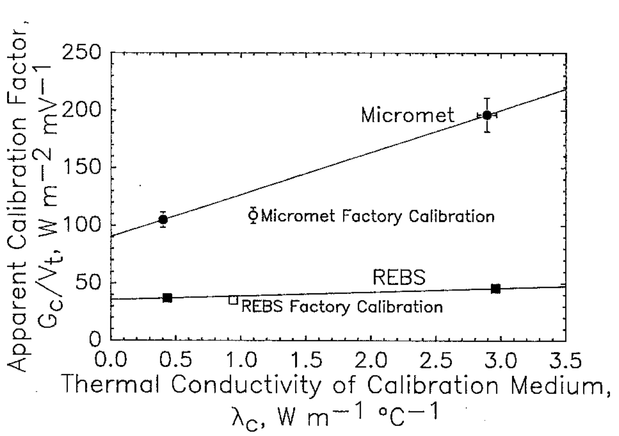

Fig. 4. Mean calibration lines for the 6 Micromet and 8 REBS transducers. Error bars represent ± one standard deviation

Acknowledgements

The authors gratefully acknowledge the contributions of ideas and discussions from Dr. R. J. Reginato, USDA-ARS, Phoenix, AZ, Dr. J. L. Steiner, USDA-ARS, Bushland, TX, and Dr. L. J. Fritschen, University of Washington, Seattle, WA.

References

Deacon, E. L., 1950: The measurement and recording of the heat flux into the soil. *Q. J. Roy. Met. Soc.*, **76**, 479–483.

De Vries, D. A., 1963: Thermal properties of soils, pp. 210–235. In: van Wijk, W. R. (ed.), *Physics of Plant Environment*. North-Holland, Amsterdam, The Netherlands.

De Vries, D. A., Peck, A. J., 1958: On the cylindrical probe method of measuring thermal conductivity with special references to soils. I. extension of theory and discussion of probe characteristics. *Austral. J. Phys. Sci.*, **11**, 255–271.

Fritschen, L. J., Gay L. W., 1979: Environmental instrumentation. Springer, New York, 216 pp.

Fuchs, M., Hadas, A., 1973: Analysis of the performance of an improved soil heat flux transducer. *Soil Sci. Soc. Am. Proc.*, **37**: 173–175.

Fuchs, M., Tanner, C. B., 1968: Calibration and yield test of soil heat flux plates. *Soil Sci. Soc. Am. Proc.*, **32**, 326–328.

Hatfield, H. S., Wilkins, F. J., 1950: A new heat-flow meter. *J. Sci. Instr.*, **27**, 1–3.

Mogensen, V. O., 1970: The calibration factor of heat flux meters in relation to the thermal conductivity of the surrounding medium. *Agric. Met.*, **7**, 401–410.

Philip, J. R., 1961: The theory of heat flux meters. *J. Geophys. Res.*, **66**, 571–579.

Portman, D. J., 1958: Conductivity and length relationships in heat-flow transducers performance. *Trans. Am. Geophys. Union*, **39**, 1089–1094.

Tanner, C. B., 1960: Energy balance approach to evapotranspiration. *Soil Sci. Soc. Am. Proc.*, **24**, 1–9.

Authors' address: Dr. T. A. Howell and J. A. Tolk, USDA-ARS, Conservation & Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012, U.S.A.

Verleger: Springer-Verlag KG, Mölkerbastei 5, A-1010 Wien. — Herausgeber: Prof. Dr. I. Dirmhirn, Universität für Bodenkultur, Institut für Meteorologie und Physik, Türkenschanzstraße 18, A-1180 Wien. — Redaktion: Türkenschanzstraße 18, A-1180 Wien. — Hersteller: Filmsatz und Offsetdruck: Adolf Holzhausens Nachfolger, Kandlgasse 19-21, A-1070 Wien. — Verlagsort: Wien. — Herstellungsort: Wien. — Printed in Austria.