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ON THE MEASUREMENT OF THE HEAT FLUX INTO THE SOIL

by

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Abstract

A simple instrument for measuring the heat flux into or out of the soil is described, together with a calibration apparatus. The instrument is similar to the heat flux plates used by Falckenberg and Deacon. The calibration apparatus is composed of a heat-insulating case having an electric oven on its bottom. An upward heat flux can be produced by the oven and its intensity can be computed with great accuracy.

Several experiments were carried out both in the laboratory and in the field with a view to studying the accuracy of the method. The laboratory experiments revealed that errors of up to 50% may be caused by evaporation if a plate is placed close to the soil surface. The field experiments, however, were so encouraging that this method, together with the classical method, will be adopted at the aerological stations in Finland during the International Geophysical Year.

1. *Introduction.*

A very important problem in investigations concerning the heat balance of the earth's surface is how to estimate the heat flux into or out of the soil. About twenty years ago this quantity was generally estimated by measuring the temperature and the specific heat at various depths. This method is rather laborious and inaccurate, however, and therefore a number of simpler methods have been developed during recent years.

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The simplest of these methods is probably that of FALCKENBERG [1] and DEACON [2]. The instruments constructed by them are relatively thin plates made of a material with a thermal conductivity greater than that of the soil. The temperature difference through the plate can be measured by means of a thermocouple or a thermopile. During measurements the flux plates are placed horizontally on the soil surface or just beneath it. The vertical heat flux can now be determined by multiplying the thermocouple voltage, which is proportional to the temperature difference through the plate, by an experimental constant.

Very considerable local variations are observed in the heat flux into the soil. These variations are so great that the accuracy attained in measuring the flux depends at least as much on the sampling technique as on the accuracy of the measurements themselves. The great advantage of the plates mentioned above lies in the fact that we can eliminate local variations in the heat flux by placing several plates at the same depth at suitable distances. However, some errors of unknown magnitude are involved in this method. When studying the accuracy of the method we must pay particular attention to the following sources of error:

1. Because the thermal conductivity of a heat flux plate is in general different from that of the soil, the heat flux through the plate is not identical with the flux through the surrounding soil.

2. The amount of heat flowing through a plate may be diminished by poor thermal contact between the plate and the soil.

3. Since the plates are impervious to moisture, the distribution of the moisture as well as the thermal characteristics of the surrounding soil may be changed. If a plate is placed on the earth's surface the evaporation will be checked and the heat economy of the surface will be changed at the place in question.

The purpose of this investigation was to test the accuracy of this method. A number of heat flux plates and an apparatus for their calibration were built for this purpose.

The calibration apparatus is a case made of insulating material filled with suitable soil. On the bottom of the case lies an electric oven designed so as to produce an upward heat flux regulable with great accuracy.

The investigations concerning the error sources of the heat flux plates were carried out both in a laboratory with the above-mentioned calibration apparatus and in a field by comparing the results obtained with the plates and the computed values obtained by measurements of the temperature and specific heat profiles of the soil.

2. *Instruments.*

The heat flux plates are of Jena glass and they are of rectangular shape with rounded edges and dimensions of 60 × 25 × 2 mm. The temperature difference through the plate is measured by a thermopile of copper and constantan. The thermopile was built by winding around the plate 50 turns of flattened clear constantan lead and by covering the constantan lead with copper according to the method of WILSON and EPPS [3]. The plates were placed in the plating solution in such a way that half of every constantan turn was covered with a 0.02 mm thick copper film. The resistance of a thermopile is 35 Ω and a heat flux of 1 cal cm^{-2} min^{-1} will generate a voltage of about 1 mV. The plates are coated with Silicone Varnish MS 997, made by Mitland Silicones Ltd.

The case of the calibration apparatus is of wood, the inside being lined with a heat-insulating cover of 2.5 cm Styropor plastic ($\lambda = 0.00006$ cal cm^{-1} sec^{-1} $°C^{-1}$). The inner dimensions of the case are 42 × 42 × 10 cm. The electric oven on the bottom of the case is composed of two parallel square plates of 7 mm copper with a heat insulator of 8 mm Perflex sheet between them. Both the upper and the lower plate are divided in two by a 1.5 mm slit, the two parts thus forming a square inside plate of 30 × 30 cm and a frame round this. These four plates are called in the following text: upper inside plate (P_{ui}), upper outside plate (P_{uo}), lower inside plate (P_{li}) and lower outside plate (P_{lo}). Each of these plates is furnished with a heating resistance of 5.5 Ω.

In the course of the heating process the heating current of each plate in the oven can be regulated in such a way that the plates will gain equal temperatures. For temperature measurements the electric oven is furnished with two thermopiles. One of them serves as an indicator of the temperature difference between the upper and lower inside plates, while the other indicates the temperature difference between the upper inside and outside plates.

Once the current has been regulated, all the heat led to the upper inside plate will flow upwards. In this way, an upwardly directed heat flux can be produced and its intensity measured with great accuracy. The circuit diagram of the electric oven is presented in Fig. 1.

While the electric oven is being heated, the temperature difference between the upper and lower inside plates can easily be regulated to be less than 0.1 °C. There would be no point in endeavouring to attain a

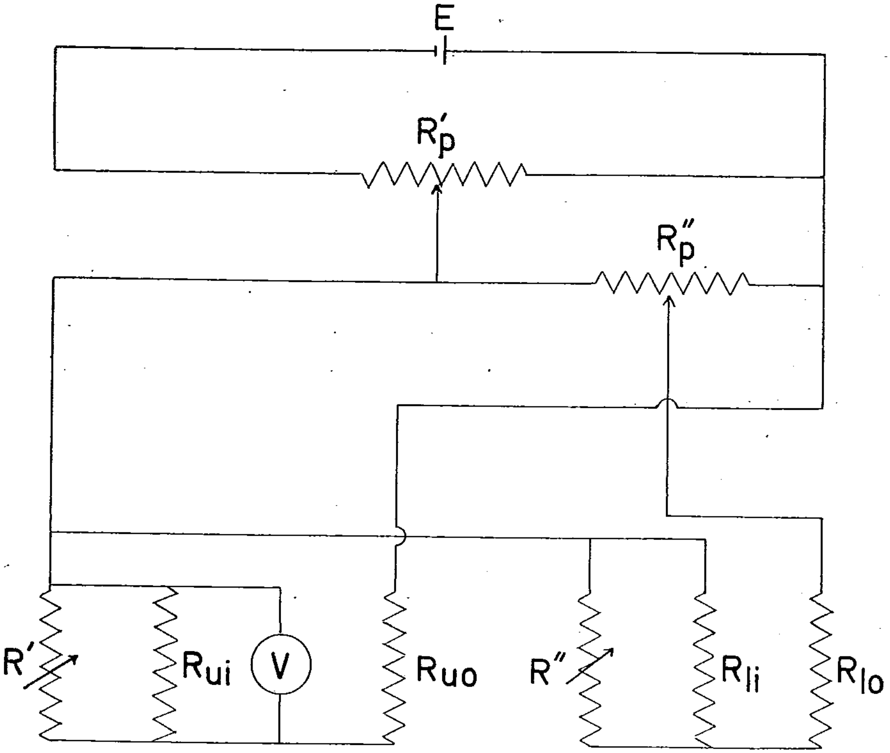

Fig. 1. Circuit diagram of the electric oven.
R_{ui}, R_{uo}, R_{li} and R_{lo}= heating resistances of the copper plates. R' and R''= rheostats in parallel with the inside plates for eliminating the temperature difference between the inside and outside plates. R_p' and R_p''= potentiometers for voltage regulation. E= voltage source. V=voltmeter.

higher accuracy, for the heat flux between the plates can quickly be computed from the correction formula:

$$\triangle\dot{Q} = -0.033\ (t_{ui} - t_{li}).$$

If $t_{ui} - t_{li}$ is below 0.1 °C, the correction term is:

$$\triangle Q < 0.003 \text{ cal cm}^{-2} \text{ min}^{-1}.$$

The temperature difference between the upper inside and outside plates can be regulated to keep within 0.2 °C. Hence, the error from this source is of no account.

The thermal resistance of the calibration apparatus will depend on the relation of the thermal conductivity (λ) of the case contents to their thickness (h). To reach a stationary condition will take about 12 hours if the layer in question is 6 cm of air-dried sand $\left(\frac{\lambda}{h} = 0.0007 \text{ cal cm}^{-2} \text{sec}^{-1} \,{}^{\circ}\text{C}^{-1}\right)$.

The above calibration apparatus can also be used when calibrating the thermal conductivity of various materials. A sheet of the material is placed on the case bottom, the electric oven is started and the temperature gradient caused by the vertical-heat flux is measured on the sheet. With a view to making an accuracy test, the thermal conductivity of a plastic sheet with well known thermal characteristics was calibrated. The observed value and the given value were in good agreement (within 1 per cent).

3. *Laboratory experiments.*

Calibration of the heat flux plates. For the calibration process the calibration case was filled with a 6 cm thick sand layer, the consistency of the sand being as follows:

Grain size (mm)	<0.2	0.2—0.5	0.5—1.0	>1.0
Percentage of the sample	22	58	13	7

The instruments were placed horizontally above the upper inside plate at a distance of 1.5 cm from the bottom. The electric oven was started and the voltage given by the heat flux plates was measured with a potentiometer as soon as the vertical heat flux through the sand layer seemed to be stationary.

The calibration constant k was computed from the equation:

$$Q = \frac{1}{k} E$$

where:

Q = vertical heat flux (cal $\text{cm}^{-2}\ \text{min}^{-1}$)
E = voltage produced by the plates (mV)

It was verified that k was independent of Q, and the value $Q \sim 0.2$ cal $\text{cm}^{-2}\ \text{min}^{-1}$ was applied thereafter.

With a view to calibrating the thermal conductivity of the sand sample, the vertical temperature distribution in the sand layer was measured with copper-constantan thermocouples.

Laboratory tests. When studying the thermal contact between the heat flux plates and the soil, the case was filled with moistened sand and covered with a plastic film to prevent evaporation. Then the plates were calibrated once a day for seven days. The values of k obtained by this means at distances of 1.5 and 4.5 cm from the bottom are presented in the following table:

Table 1.

Height from case bottom (cm)	Days from start of experiment 1	2	3	5	7
	Calibration constant				
1.5	1.85	1.94	1.96	1.99	2.00
4.5	1.70	1.82	1.88	1.98	2.02

The calibration constant k increases quite rapidly at first, then gradually retarding and reaching a nearly stationary value after approximately a week. This is obviously due to the fact that the thermal contact between the instruments and the sand improves in the course of time. It seems as if k reaches a stationary value sooner at the height of 1.5 cm, where the pressure is higher than at 4.5 cm.

The following tests were carried out with the object of estimating the thermal contact between the heat flux plates and a dry sand sample.

1. The plates were calibrated in dry sand on four successive days.

2. The calibration case was filled with moist sand and covered with a plastic film. After a week, when the plates had made good thermal contact with the sand, the film was removed and the sand allowed to get dry. A week after the removal of the film, the instruments were calibrated, the sand now being air-dry.

Experiment 1 revealed that the calibration constant will become stationary sooner in dry sand than in wet sand. The calibration constants obtained in experiment 2 are some 4 per cent higher than the values of k given by experiment 1. This is an indication that the favourable effect of moistening upon the thermal contact between the plates and the soil will persist even after the soil has become dry.

Values of the calibration constant k and the thermal conductivity λ observed in a moist and an air-dry sand sample are presented in Table 2.

Table 2.

	Calibration constant (mV/cal cm^{-2}min^{-1})	Thermal conductivity (cal cm^{-1} sec^{-1} °C^{-1})
Moist sand	2.01	0.0038
Dry sand	2.14	0.0007

Because the thermal contact was good during both experiments, the values of k give at least an approximative idea of the dependence of k on the thermal conductivity of the soil. If it is supposed that the thermal conductivity of the soil remains between the limits of 0.0007 and 0.0038 cal cm^{-1} sec^{-1} °C^{-1} and the value of k corresponding to the mean of these values is employed, the maximal error amounts to 3 per cent. In general, however, the error will be much smaller.

The plates, being impervious to moisture, will alter the moisture conditions of the surrounding soil. The error caused by this factor was investigated in such a way that the calibration case was filled with moist sand and the plates were placed at a depth of 1.5 cm from the surface of the sand. After the plates had made good thermal contact with the soil, the plastic film was removed and the calibration constants of the instruments were determined once a day until the sand had got dry. The results of this experiment are presented in Table 3.

Table 3.

Depth (cm)	Days from start of experiment 0	1	2	3	4	5	6	7
	Calibration constant (mV/cal $cm^{-2}min^{-1}$)							
1.5	2.02	1.93	1.28	1.52	1.88	1.98	2.12	2.09
	Thermal conductivity (10^{-4} cal cm^{-1} sec^{-1} °C^{-1})							
0—1.5	37	32	28	12	08	07	07	07
1.5—3.0	37	28	32	22	10	09	08	08

The moisture conditions of the sand can be deduced from the thermal conductivity. The surface layers of the sand will begin to dry soon after removal of the film. In the 0—1.5 cm layer, the value 0.0007 for the thermal conductivity, which is characteristic of air-dry sand, will be reached in five days, in the 1.5—3.0 cm layer some days later.

The effect of evaporation on the calibration constant is evident. Since the sand layer over the plate cannot draw up moisture from the lower layers, it will dry out sooner than the surrounding sand. An area with poor thermal conductivity will be formed over the plate and the heat flux will avoid this area. Hence it follows that the calibration constant will diminish. The lowest value (65 per cent of the initial) was observed after two days. As the sand continues to dry out, the moisture difference between the sand on the plate surface and in its surroundings will diminish and the constant k will increase. After a week the value characteristic of dry sand will be reached.

The above experiment reveals that evaporation may cause a very notable error in the results obtained with the heat flux plates if one of these is placed very near the surface. The deeper the instrument is placed the smaller this error will probably remain. With the calibration apparatus available, however, it was not possible to study the process more thoroughly.

4. *Field comparisons.*

A short series of comparisons with the classical method mentioned in the introduction to this paper was carried out in July 1956 at the Viiki Research Station of the Institute of Meteorology, University of Helsinki. The station is situated in the middle of a large cultivated area about 8 kilometres north-east of Helsinki.

The experimental area was a fairly even and homogeneous plot bearing short cut grass about 5 centimetres in length. The soil was composed of humus to a depth of 20—25 cm.

Four calibrated heat flux plates were placed in the soil, two of them at a depth of 5 cm and the other two 10 cm and 15 cm below the surface. A well calibrated bead type thermistor was also placed as a thermometer at each of the depths 5, 10, 15 and 25 cm. The thermistors were of the type Stantel F 2200, made by Standard Telephones and Cables Ltd. The electric circuit allowed a relative accuracy of 0.05 °C in temperature measurements. The soil samples were taken by means of an ordinary soil bore at depths of 5 and 15 cm. A Dewar flask with a mixer and a calibrated thermometer served as a calorimeter.

The heat flux values at 5 cm, 10 cm and 15 cm below the surface were computed both from the voltage indications given by the heat flux plates and from the temperature and specific heat measurements made at the given depths. In order to diminish the errors in readings the duration was extented over 8—12 hours per comparison and the mean of the heat flux during this time was computed from hourly observations. The daily results obtained in this way, as well as the ratio of the results of the two different methods are given in Table 4. The differences between the heat flux values at the 5 cm level and the 15 cm level are given as the most representative values.

Table 4.
Mean difference of the heat flux values at 5 cm and 15 cm below the soil surface (cal cm^{-2} min^{-1}).

Date 1956	Hours	Heat flux plates	Classical method	Ratio of results
9.7	6—18	0.0287	0.0277	1.04
11.7	6—18	0.0295	0.0291	1.01
14.7	8—18	0.0345	0.0299	1.15
16.7	8—18	0.0296	0.0274	1.08
17.7	8—18	0.0274	0.0294	0.93
18.7	8—16	0.0438	0.0405	1.08
				Mean: 1.05 ± 0.06

Considering the errors to which these two methods are liable, we can regard the results as being in fairly good agreement. In view of the conditions during such comparisons, it follows that we cannot draw absolute conclusions regarding the magnitude of the various errors. To place an instrument at a depth of, say, exactly 5 cm is not so easy in a natural soil, as every expert is aware. Further, we cannot with certainty take the soil samples very near the underground instruments and thus occasional or systematic errors depending on the homogeneity of the soil may be caused. In addition, all the errors mentioned in the previous text may be included in the result. From this point of view the conformity of the two methods as given in Table 4 is very evident.

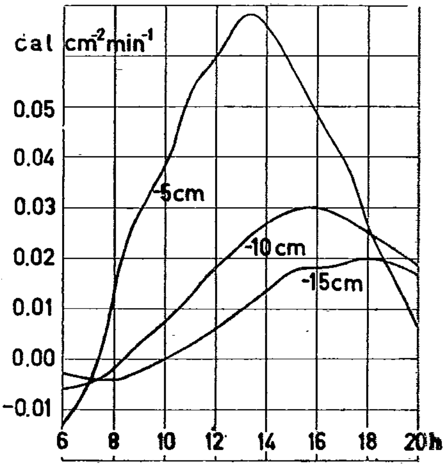

Fig. 2. Course of the heat flux on a clear day as shown by the heat flux plates at depths of 5, 10 and 15 cm below the soil surface.

In Fig. 2 we see an illustration of the results given by the heat flux plates on a clear day at depths of 5, 10 and 15 centimetres below the surface. When cloudiness is very variable a continuous recording is needed, whereas observations every two hours are sufficient on perfectly clear or completely overcast days.

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