



Evaluation of a new, perforated heat flux plate design [☆]

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ABSTRACT

Accurate measurement of heat flux is essential to optimize structural and process design and to improve understanding of energy transfer in natural systems. Laboratory and field experiments evaluated the performance of a new, perforated heat flux plate designed to reduce flow distortion for environmental applications. Laboratory tests involving dry and saturated sand showed that performance of the new CAPTEC plate is comparable to a solid, standard REBS plate. Very low thermal gradients may have however led to poor performance of the CAPTEC plate in saturated sand. Water infiltration and redistribution experiments using clayey and sandy soils showed an apparent reduced disruption of liquid water and vapour in the soil surrounding the CAPTEC plate as compared to solid Hukseflux and standard REBS plates. Surface area of REBS plate, though smaller than that of CAPTEC, did not lead to any significantly improved evaporation, due to perforations on CAPTEC plate. Field tests in a loam soil indicated that the CAPTEC plates were durable and produced daily total flux values within $\sim 0.15 \text{ MJ m}^{-2}$ of independent estimates.

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1. Introduction

Characterizing the ground thermal regime often involves continuous measurement of heat flux through the surface layers. There are many relevant applications for this information. In building science for instance, the investigation of the insulation capabilities of building materials, heat transfer coefficients, measurement of heat flux through walls and determination of the effectiveness of insulation materials are important topics. The temperature, heat flux and moisture content are usually the parameters of interest for determination of ground heat transfer and thermal comfort with low energy consumption in low rise earth-contact buildings, and to provide better prediction of building temperature and heating loads [1]. Simulations of geothermal pumps and underground power cables to predict energy efficiency also require accurate determination of heat diffusion through the surrounding layers. Heat flux is studied in field experiments to gain characteristic information for natural and managed surface boundaries under different climatic conditions.

Soil heat flux density (G) is often measured using heat flux plates, which are small, rigid, disc-shaped sensors of known and constant thermal properties placed horizontally in the soil near the surface [2]. Most heat flux plates consist of a thin disc with a differential

temperature sensor between the top and bottom. Assuming that the thermal conductivity of the plate is constant and the flow is static, the heat flux is proportional to the measured temperature difference. Heat flux plates were developed to measure heat flow through walls of buildings and bulkheads of ships. Falckenberg [3] was the first to use flux plates for measuring heat transfer in soils.

Recent investigations have demonstrated that the standard soil heat flux plate technique leads to systematic errors in G measurement. The heat flux through a calibrated plate is used to estimate G in the surrounding field at the plate depth [4]. Some of the errors associated with the use of heat flux plates include heat flow distortion near the plate, liquid water and vapour flow divergence and thermal contact problems between the plate and the soil matrix [5–8]. Mogensen [9] tested Philip's analysis and presented a more generalized form of Philip's equation that describes the ratio between heat flow through the meter of known dimensions and thermal conductivity to that in the surrounding medium:

$$\frac{G}{G_m} = 1 - \alpha_s r (1 - \lambda / \lambda_m) \quad (1)$$

Where G = medium heat flux, r = plate thickness/(area)^{0.5}, G_m = plate heat flux, λ = soil thermal conductivity, α_s = plate shape factor and λ_m = plate thermal conductivity. When $G_m/G < 1$, plates underestimate G and when $G_m/G > 1$ plates overestimate G .

The objective of this study therefore was to evaluate a new, perforated soil heat flux plate (CAPTEC Entrepise, Lille, France) that

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Nomenclature

G	heat flux through media
G_m	heat flux through plate
R	plate thickness/area ^{0.5}
T	temperature
Z	depth

Greek symbols

α_s	plate shape factor
λ	thermal conductivity of media
λ_m	thermal conductivity of plate

was designed to reduce heat flow distortion and disturbance of liquid water and water vapor flow in the adjacent soil. Comparisons are made with two widely-used, commercially-available plates (HFT3.1, Radiation and Energy Balance Systems, Seattle, WA, USA and HFP01SC, Hukseflux Thermal Sensors, Delft, The Netherlands).

2. Materials and methods

The new CAPTEC flux plate is very thin (0.3 mm-thick) with a large face area (103×105 mm $L \times W$) and 100 5 mm-square openings representing 23.1% of the plate face area (Fig. 1). The standard REBS plate (HFT-3.1) is round (38.6 mm-diameter), 3.9 mm-thick, and has a thermal conductivity of $1.22 \text{ W m}^{-1} \text{ K}^{-1}$. The Hukseflux plate is larger and thicker (80 mm-diameter and 5 mm-thick), and has a lower thermal conductivity of $0.8 \text{ W m}^{-1} \text{ K}^{-1}$ than the REBS plate. A comparison of the predicted performance using Eq. (1) of these two plates in soil of varying thermal conductivity is shown in Fig. 2. Herin and Thery [10] introduced the basic design of the CAPTEC sensor and Robin et al. [11] evaluated a non-perforated version of this type.

Laboratory experiment 1 was aimed at comparing the new CAPTEC and the standard REBS plates. Measurements were completed with 3 CAPTEC and 2 REBS plates embedded in dry and saturated sand inside an insulated cavity under steady-state, one-dimensional heat flux densities of 21, 43, 85, and 172 W m^{-2} . Each flux density was maintained for 2–4 days with sensor signals logged every 1 min. Comparisons were made using 24 24 h of hourly-average data for each plate type.

Laboratory experiment 2 was performed on the Hukseflux, REBS and CAPTEC plates in an enclosed chamber to ensure minimal impacts of atmospheric variables. Two dissimilar porous media (coarse sand and fine-textured clay) were subjected to the same dry and wet

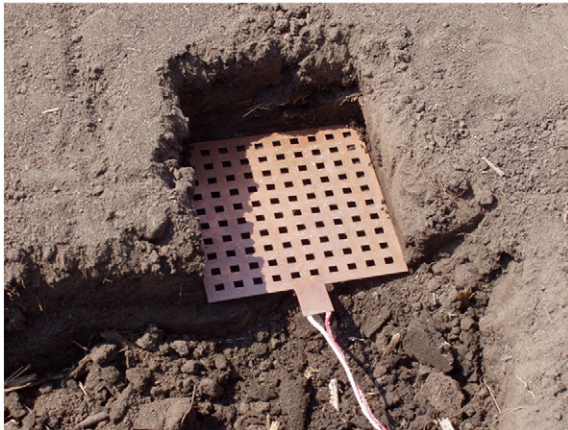


Fig. 1. CAPTEC heat flux plate.

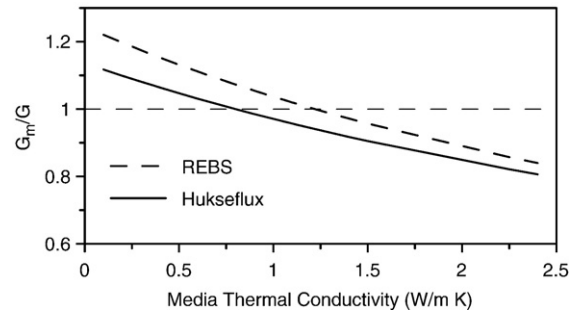


Fig. 2. Comparison of the predicted REBS and Hukseflux plate performance using Eq. (1).

conditions under a focus-type 60 W heat lamp suspended 40 cm above the soil to produce heat flux. The air-dry and saturated thermal conductivity values ($\text{Wm}^{-1} \text{ K}^{-1}$) for sand and clay were 0.18 ± 0.03 , 2.12 ± 0.16 and 0.12 ± 0.01 , 0.97 ± 0.06 . The samples were carefully packed in an acrylic box (30 cm square and 20 cm deep) at natural bulk density. For the first test, the CAPTEC plate was placed on top of a 15 cm thick layer of sun-dried sand, and then covered with 5 cm more of the same soil. The system was left for some days after which it was assumed to have come to equilibrium, and then carefully placed under the heat lamp. About 542 g of water, assumed to be equivalent to $\sim 1/4$ of the pore space above the plate was then sprinkled on the box to simulate a rain event with the heat lamp on. The thermal conductivity of the soil above, below and laterally around the plates was monitored after wetting to assess the soil water content distribution near the plates. Thermal conductivity was measured using a single-needle probe digital thermal analyzer (KD2, Decagon Devices Inc., Pullman, WA, USA) inserted horizontally into the soil approximately 1 cm from the plates. The weight of the chamber was monitored throughout the experiments to estimate evaporation and to determine when the soil near the plates was dry. The experiment was repeated with Hukseflux and REBS heat flux plates to compare the flow divergence around the plates before and after water redistribution with a view to capture the water diverging around the plate before and after it has had a chance to redistribute under the plate and to make observations after infiltration. The same procedure was repeated again for the clayey soil, using the three plates in turn.

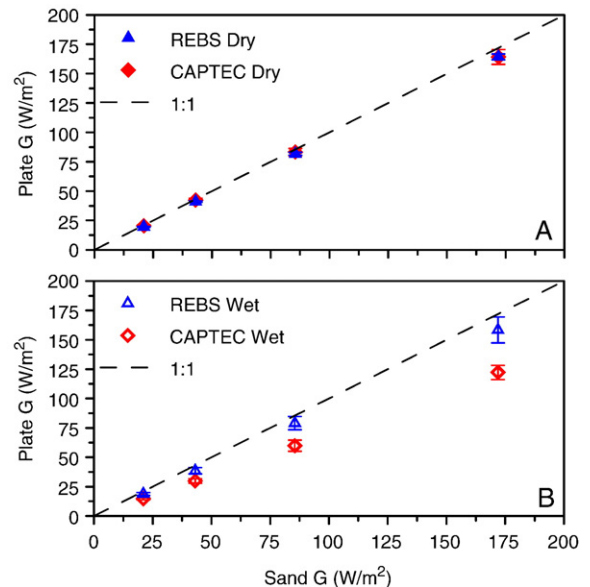


Fig. 3. CAPTEC and REBS soil heat flux plate results under steady-state, 1-D heat flow in dry and saturated sand. Error bars represent one standard deviation from the mean value.

Table 1
Evolution of evaporation using CAPTEC, Hukseflux and REBS plates in sands and clay

Media-plate	Evaporation after 12 h (g)	Evaporation after 24 h (g)	Evaporation after 50 h (g)	Time to equivalent evaporation (h)
Sand-CAPTEC	127	302	373	50
Sand-Hukseflux	102	272	345	70
Sand-Rebs	128	324	380	48
Clay-CAPTEC	117	239	312	88
Clay-Hukseflux	97	215	300	92
Clay-REBS	108	241	321	80

Field measurements were made with CAPTEC and REBS plates over 10 weeks in 2005 in a loam soil near Ames, Iowa USA. The gradient method [12,13] was used to obtain an independent measurement of G at the flux plate depth (60 mm) during the field experiment. Precipitation and net radiation were measured at the field site with a tipping bucket rain gauge (TE525, Texas Electronics, Inc., Dallas, TX)

and a net pyrradiometer (CN1, Carter-Scott Design, Box Hill, Victoria, Australia), respectively. Three-needle heat-pulse probes [14] were used to measure the soil thermal conductivity and temperature gradient necessary to calculate G using Fourier's Law:

$$G = -\lambda(\partial T/\partial z) \quad (2)$$

where $\partial T/\partial z$ is the measured temperature gradient.

3. Results and discussion

3.1. Laboratory experiment 1

In the dry sand, G values from the CAPTEC plates were significantly greater ($P > 0.05$, one-way Fisher's Protected Least Significant Difference test) than from the REBS plates at 3 of the 4 flux densities (Fig. 3). G values for both plates were less than the known flux density although by an average of only 3 to 5%. In the wet sand, G values from the CAPTEC plates were significantly lower than the REBS plate and

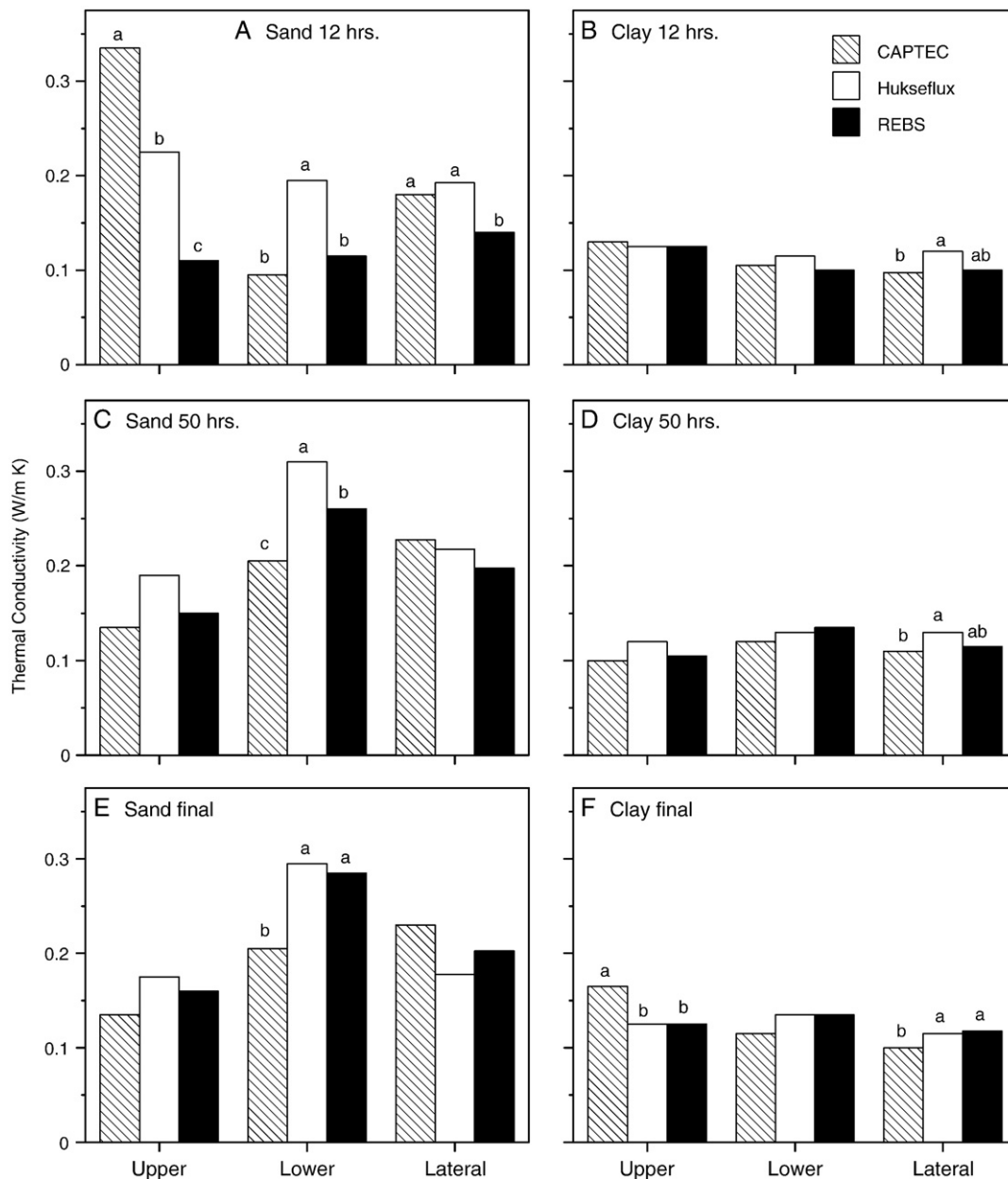


Fig. 4. Thermal conductivity of sands and clay in CAPTEC, Hukseflux and REBS plates after wetting until final termination of infiltration/evaporation experiments.

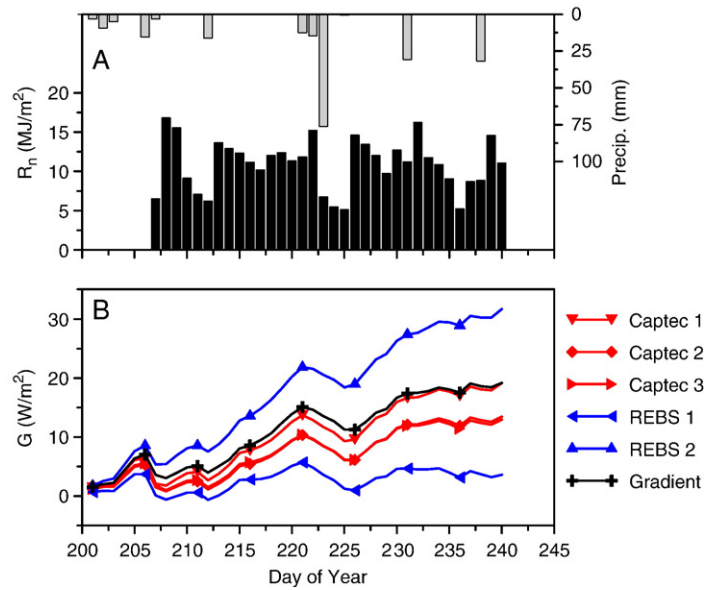


Fig. 5. Cumulative values of daily total G from CAPTEC and REBS soil heat flux plates and gradient method in Clarion loam soil including net radiation and precipitation.

both plates were significantly lower than the known G (30 and 9% for the CAPTEC and REBS, respectively). It is not certain why the CAPTEC plates produced such low G values in the saturated sand. One possible explanation is that the G underestimate is due to the very small temperature gradients ($0.15\text{--}0.6\text{ }^\circ\text{C cm}^{-1}$) and high thermal conductivity ($2.2\text{ W m}^{-1}\text{ K}^{-1}$) in the saturated sand compared to the dry sand ($0.65\text{--}4.7\text{ }^\circ\text{C cm}^{-1}$ and $0.35\text{ W m}^{-1}\text{ K}^{-1}$). Also, since the CAPTEC plate sensitivity only depends on the thermal conductivity of the surrounding material, its response depends on the gradient of thermal conductivity between its external sides and the surrounding material. Any unbalance in the gradient of thermal conductivity on both sensor sides will lead to a change in the device sensitivity.

3.2. Laboratory experiment 2

Table 1 shows the evolution of evaporation after wetting, for the CAPTEC, Hukseflux and REBS plates in sand and clay. After 24 h, there was 10% less evaporation with the Hukseflux plate than for the CAPTEC plate for both sand and clay. This suggests that the thinness of CAPTEC plate and its perforations allow greater movement of liquid water and water vapour. The same trend was observed after 50 h with greater evaporation with the CAPTEC plate as compared with Hukseflux though the relative difference was reduced. The evaporation in the samples (estimated by weight) as monitored on a scale revealed that equivalent evaporation of 373 g was reached at 50, 70, 48, 88, 92 and 80 h for the CAPTEC-sand, Hukseflux-sand, REBS-sand, CAPTEC-clay, Hukseflux-clay and REBS-clay experiments, respectively. This shows that the same moisture content was achieved with the Hukseflux plate compared to the CAPTEC with a 20 h lag in sand and a 4 h lag in clay, thus suggesting that the solid Hukseflux plate limits water vapor flow. A very slight difference was however observed between REBS and CAPTEC plates. Even though the CAPTEC is perforated, the plate area is 83.2 cm^2 compared to 11.7 cm^2 for the REBS. This suggests that the perforations were effective in reducing the disturbance of water flow. The textural characteristic of a clay soil, having fewer large pores than the sand, likely contributed to the relatively slower observed evaporation.

Thermal conductivity monitored after wetting until the final termination of each experiment is shown in Fig. 4 for the sand and clay experiments, respectively. The letters show statistically significant differences of thermal conductivity at $P > 0.05$ using Fisher's Protected Least Significant Difference (FPLSD). For the sand, the most

interesting result is for below the plates as the Hukseflux plate consistently has a higher thermal conductivity suggesting that it is preventing water from moving upward to the soil surface. The REBS plate is nearly the same but the CAPTEC shows significantly less disturbance of water flow. These findings are consistent with the evaporation data and suggest that the large, impervious Hukseflux plate was restricting water flow in its vicinity thereby reducing evaporation and resulting in greater water content and higher thermal conductivity. Differences were much less-pronounced for the clay soil and generally low (near air-dry) thermal conductivity. In this instance, the finer pore structure likely resulted in more uniform redistribution of water around both plates. Greater differences may occur at earlier times before redistribution occurs, which were not observed by these measurements made at 50 h or greater after water addition.

3.3. Field experiment

Diurnal variation of precipitation and solar radiation during the field measurements are presented in Fig. 5(A) to illustrate the dependence of G on environmental variables. Among the methods compared in the field, the gradient approach would be expected to provide the least interference to water movement. The two REBS plates produced daily total G values that were consistently lower (-0.31 MJ m^{-2}) and greater ($+0.39\text{ MJ m}^{-2}$) than the gradient values (Fig. 5B). The differences in plate performance resulted in progressively large departures from the cumulative daily G as determined by the gradient method. By contrast, there was less variation among CAPTEC plates and much closer agreement (-0.001 to -0.16 MJ m^{-2}) with the daily total G values from the gradient method. This experiment demonstrated the ability of the CAPTEC plates to perform under field conditions with a favorable comparison to a common soil heat flux plate.

4. Conclusions

Results of laboratory and field experiments to evaluate the performance of the new CAPTEC plate with both REBS and Hukseflux plates are presented. Initial evaluation of the unique CAPTEC plate is very positive. Theory predicts that such a thin, perforated plate should be optimal for soil heat flux measurement. Laboratory tests show that performance of the CAPTEC plate is comparable to the standard REBS plate in dry sand although both slightly underestimated the known

flux. However, very low thermal gradients may have led to poor performance of the CAPTEC plate in saturated sand. Further infiltration and redistribution experiments in the laboratory involving sand and clay indicated a reduced disruption in the flow of liquid water and vapour flow in the surrounding soil when using CAPTEC plate as opposed to Hukseflux plate. Surface area of REBS plate, though smaller than that of CAPTEC, did not lead to any significantly improved evaporation, due to perforations on CAPTEC plate. Field tests in a loam soil also demonstrated that the CAPTEC plates are reliable and produced daily total G values consistently within $\sim 0.15 \text{ MJ m}^{-2}$ of independent heat flux estimates from the gradient method. The potential advantages of the CAPTEC design in avoiding heat flow distortion errors warrant further investigation, especially in media with high thermal conductivity such as saturated sand.

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