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Development Of Hot/Cold Plate Apparatus For Determining Heat Transport Mechanisms In Mulch Materials

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DEVELOPMENT OF HOT/COLD PLATE APPARATUS FOR DETERMINING HEAT TRANSPORT MECHANISMS IN MULCH MATERIALS

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ABSTRACT. *To study the effects of mulches and crop residues on soil temperature, researchers have frequently used simulation models. In such models, quantification of heat transport within the mulch material is often weak and heat transport mechanisms are poorly understood. In this paper we describe an apparatus to quantify heat transport through dry mulch materials. In addition, heat transport mechanisms (conduction, thermal radiation, free and forced convection) can be identified and quantified using this apparatus. The apparatus consists of precisely controlled and monitored 0.9 m by 0.9 m hot and cold plates. The hot plate actually consists of three component plates: a test, a guard, and a bottom plate that are individually controlled (temperature) and monitored (temperature and power). The guard plate surrounds the test plate, minimizing undesired lateral heat flow. The bottom plate is positioned in parallel with the test and guard plates to insure that all wattage into the test plate moves off the top of the plate through the mulch. The correct functioning of the hot plate was verified using three reference materials with a known thermal resistance.*

The cold plate is based on techniques using thermoelectric devices (Peltier coolers). In addition, heat sinks and fans are used to transport heat away from the cold plate. A two–dimensional numerical simulation showed that errors caused by lateral heat flow in a sample contained between the hot and the cold plate can be neglected. The thermal conductivity of air was measured using the apparatus, yielding a value of 0.026 W m^{-1} $°C^{-1}$, exactly matching the theoretical value, thus confirming the correct functioning of the hot/cold plate combination.

Keywords. *Hot plate, Cold plate, Mulch, Heat transport.*

Soil temperature controls many biological, chemical, and physical processes, and a management practice such as mulching can have a large impact on soil temperature (Bussiere and Cellier, 1994; Bristow and Campbell, 1986). Soil temperature management offers the potential to grow crops that require a temperature regime different from the unmanaged environment. For example, in order to optimally grow Irish potatoes in the state of Georgia, USA, soil temperature should be cooler than in most cropped soils. Soil temperature management can aid in controlling diseases, such as aflatoxin development in peanuts (Hill et al., 1983). Soil temperature is also important in biological and chemical processes that control nutrient cycling.

For a variety of crops, mulches are used deliberately to change soil temperature (and moisture) regimes. Different mulch types modify soil temperatures in different ways. Mulches can be classified as natural or synthetic. Examples of synthetic mulches are plastic film, cloth, fiberglass matting, and chips from waste automobile tires. Some examples of natural mulch materials are cover crops, bark, compost, gravel, pine needles, wood chips, and layers of organic residue, typical for no–tillage systems.

Simulation models have been developed that predict the effect of mulches on soil temperature (Van Bavel and Hillel, 1975; Chung and Horton, 1987; Sui et al., 1992; Bussiere and Cellier, 1994; Bristow and Horton, 1996). Quantification of heat transport within the mulch material is often weak in such models. There is a lack of understanding of the heat transport mechanisms involved and there is a lack of good experimental data to be used in such models (Shen and Tanner, 1990; Bussiere and Cellier, 1994). Methods and instrumentation to measure heat transport and its mechanisms in mulch materials are virtually nonexistent.

The determination of soil thermal properties has received more attention. The line heat source method is typically used to measure thermal properties of soils. A single heat probe containing an electrical heater and thermocouple is commonly used to measure soil thermal conductivity, either for soil samples in the laboratory or for in situ measurement. Heat is generated in the probe for a short time by a constant current through a heating wire and thermal conductivity is determined by measuring the probe temperature change during the heating period and/or a subsequent cooling period. The temperature rise of the heated probe depends on the rate of heat transport away from the probe and therefore on the thermal conductivity of soil around the probe. No calibration

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is needed for this method (Shiozawa and Campbell, 1990). De Vries (1952) and Jackson and Taylor (1986) describe this method as it is applied to soil.

Campbell et al. (1991) developed a dual probe for measuring soil volumetric heat capacity using a heat–pulse method. This is based on the fact that temperature rise, measured a short distance from a line heat source, can be used to determine the volumetric heat capacity of soil and other materials. Bristow et al. (1994) showed that, with Campbell's dual probe, both volumetric heat capacity and thermal diffusivity can be determined from the measured temperature response with time at the sensor probe. Thermal conductivity is then calculated as the product of the diffusivity and heat capacity. Bristow (1998) confirmed the ability of the dual–probe technique to provide high quality thermal property data.

Thermal conductivity of grain in bulk has been determined typically by steady state heat flow across the grain. Bakke (1935) reported the thermal conductivity of oats. A steady state apparatus with oats placed between two concentric cylinders was used. Placing ice in the inner cylinder and then placing both cylinders in a constant temperature hot water bath created a temperature difference. The heat flow was determined by measuring the amount of ice melted during the test. The steady state cylinder method was also proposed by Carslaw and Jaeger (1947) and used by Skaggs and Smith (1968) for mineral soils, Tollner and Verma (1987) for potting soils, and others. Cylinders or spheres can only be used with materials that are tightly packed; otherwise the material will get distributed unevenly. Tollner and Verma (1987) encountered such challenges with potting soil. Cylinders and spheres will not be suitable for materials that are not packed tightly, which will be the case if one wants to measure the apparent thermal conductivity of unconsolidated mulch materials at different bulk densities. The materials will be packed loosely at the lower bulk densities.

Thermal radiation, conduction, and free and forced convection are all expected to be contributing mechanisms in heat transfer through unconsolidated mulch materials. Existing methods for soil and grain do not quantify heat transport by mechanism. Parallel hot and cold plates may be used to identify and quantify heat transport mechanisms in the following manner:

Heat transport upwards (hot plate on bottom, cold plate on top, see fig. 1) may be by different mechanisms than transport downwards (cold plate on bottom, hot plate on top). Heat transport upwards may include transport by free convection, because buoyancy is promoted. Transport downwards does not include free convection, since buoyancy is suppressed (Shen and Tanner, 1990). In the field, transport upwards can typically be expected during the night and transport downwards during the day. In both cases transport will also be by conduction and possibly by radiation and forced convection. Free convection will be more important when forced convection is negligible (low wind speed), and when pure conduction is small, as would be the case in unconsolidated mulches such as straws, with close to 100 volume percent being air (having a low thermal conductivity). To quantify free convection, two measure–ments are made: one in a configuration with the cold plate on the bottom and the hot plate on top and a second one in a configuration with the hot plate on the bottom and the cold plate on top, as in figure 1. Geometries other than parallel plate can not identify and quantify the contribution of free convection to overall heat transfer.

To quantify heat transfer within a mulch by forced convection, a fan may be used to simulate a wind above the mulch that is heated from below by the hot plate. The cold plate is not used here to allow free air flow over the top of the mulch. A wind tunnel may be used to make the air flow produced by the fan uniform. The hot plate is then placed at the end of the wind tunnel. Again, only a plate geometry will work to quantify heat transport by forced convection.

In order to experimentally determine the contribution to heat transfer by means of thermal radiation, hot and cold plates with different emissivities may be used, since the radiative heat flux between the plates depends strongly on

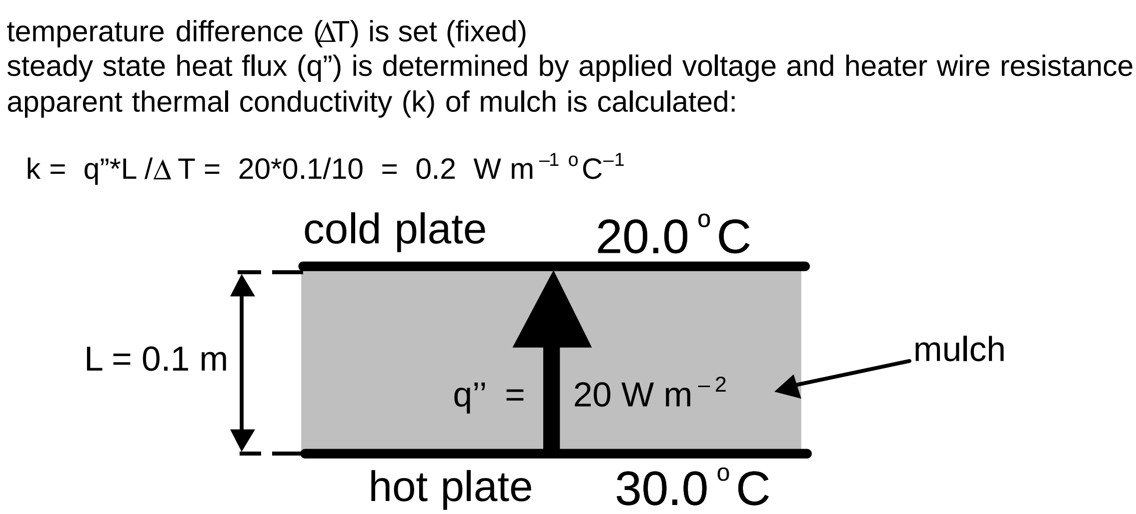

Figure 1. Example calculation of apparent thermal conductivity (k) of a mulch, using a hot and a cold plate.

plate emissivity. This approach has been used for research in low–density fiberglass thermal insulation (Pelanne, 1969). Measurements are made both for mulch material between a set of high emissivity plates and between a set of low emissivity plates. With all other things (temperatures of the hot and the cold plate, distance between the plates, material between the plates, etc.) kept equal, differences in measured heat flux would be due only to thermal radiation.

We concluded that a parallel hot/cold plate apparatus would be the only way to identify and quantify the heat transport mechanisms discussed above and thus set out to design and build such a device.

Methods and Materials

To determine its apparent thermal conductivity, a dry mulch material is put between two plates (fig. 1), which are set to and maintained at fixed temperatures. The temperature difference between the hot and the cold plate is maintained by supplying the appropriate amount of power to the hot plate. Readings of power input are taken after steady state (power input and temperature profile in the mulch are constant in time) has been reached. At steady state the power that is provided by the hot plate equals the energy rate that is absorbed by the cold plate. The thermal resistance of the mulch is then calculated from the temperature difference between hot and cold plates and the power input into the hot plate:

$$R = \frac{\Delta T}{q''} \tag{1}$$

where

R = thermal resistance of the mulch (m^2 °C W^{-1})
ΔT = temperature difference between hot and cold plate, °C)
q'' = power input into the hot plate (W m^{-2}).

The apparent thermal conductivity can also be obtained when the mulch thickness (distance between the hot and the cold plate, see fig. 1) is known:

$$k = \frac{q'' L}{\Delta T} = \frac{L}{R} \tag{2}$$

where

k = apparent thermal conductivity of the mulch (W m^{-1} °C^{-1})
L = distance between the hot and the cold plate (m).

Hot Plate

A hot plate was constructed as illustrated in figures 2 through 5. It consists of a top and a bottom plate separated by a framework of wooden spacers (fig. 4). The top plate consists of a square 460 by 460 mm test plate, centered in a 910 by 910 mm guard plate (figs. 2 and 3). A 3 mm strip of cork insulation separates test and guard plates. Each of the three component plates (test, guard, and bottom) consists of two aluminum plates with constantan heater wires embedded in silicone rubber sheets in between them (fig. 4). The hot plate is laterally insulated with a 6 mm cork sheet that is surrounded by a 2 mm aluminum band. The entire hot plate sits on a 6 mm sheet of cork insulation and a 13 mm sheet of wood.

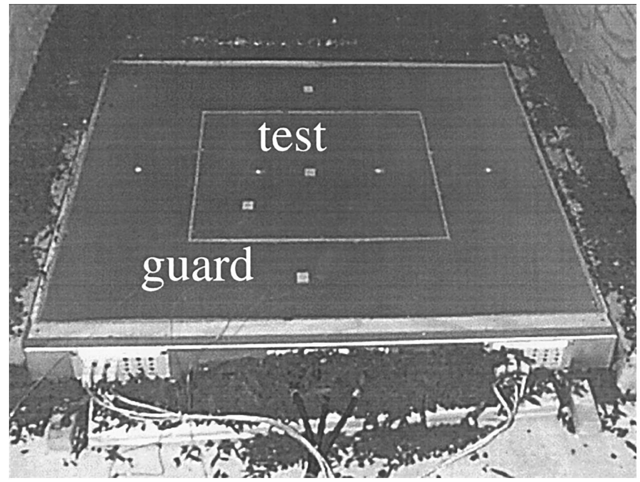

Figure 2. Hot plate consisting of test, guard, and (invisible) bottom plate. The latter is positioned in parallel with and under the test/guard plate combination.

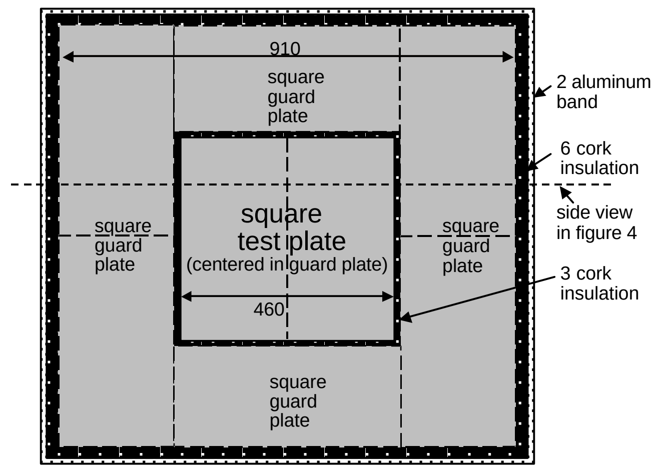

Figure 3. Schematic top view of hot plate and its components, including test plate with 2 heater pads and guard plate with 6 heater pads. All dimensions are in mm. Figure is not to scale.

Each of the three component plates (test, guard, and bottom) is heated independently. The sole function of the guard and bottom plates is to ensure that the heat provided to the test plate only flows in the desired direction, which is straight up through the mulch material contained between the hot and cold plates (fig. 1). One of the three heaters is used to heat the bottom plate, keeping it at the same temperature as the test plate at all times to ensure that all heat provided to the test plate flows up through the mulch and not in the opposite direction. Even if there were a small temperature difference between the top and bottom plates, heat flow between them would be minimized, because of the thermal insulation provided by the styrofoam and cork insulated wooden spacers (fig. 4). Another heater is used to keep the guard plate at the same temperature as the test plate to ensure that lateral heat flux is minimized. The cork insulation between the test and guard plates further reduces lateral heat flow. The third heater heats the test plate. Then, the apparent thermal conductivity of the test material (mulch) can be calculated from the power provided to the test plate and other parameters as described above. Because of the guard and the

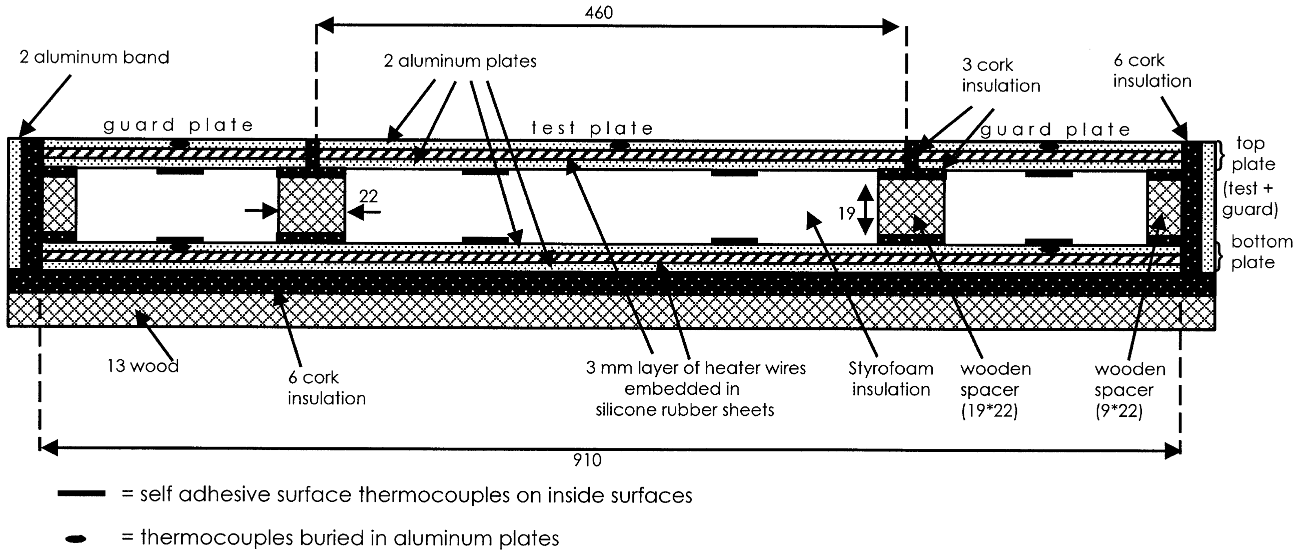

Figure 4. Side view (cross section) of hot plate and its components. All dimensions are in mm. Figure is not to scale.

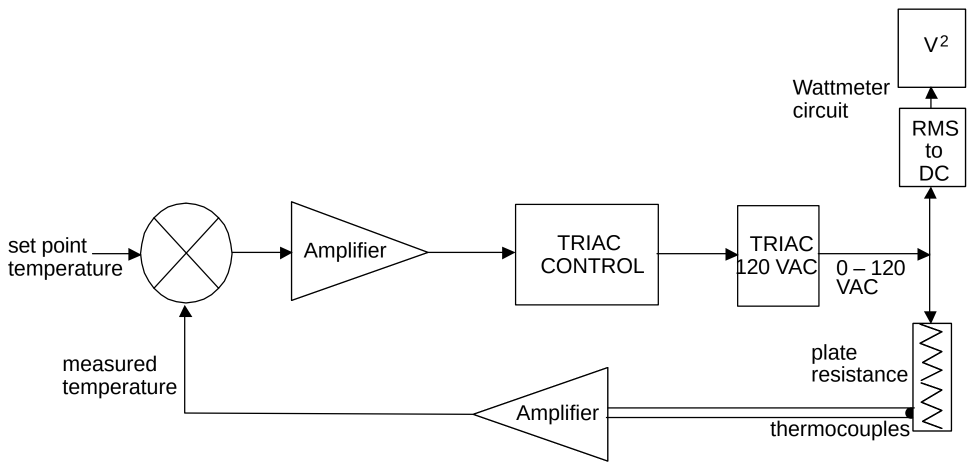

Figure 5. Temperature control loop for hot plate components. Each component (test, guard, bottom) has its own temperature control.

bottom plates, we can be confident that the heat provided to the test plate equals the heat flowing through the mulch.

The hot plate (test and guard together) was designed to deliver a maximum of 800 W. This number was based on the expected apparent thermal conductivity and temperature gradients of the materials (mulches) that this apparatus will be used for. In particular it was based on a calculation using dry soil with a thermal conductivity of 0.35 W m^{-1} $°C^{-1}$ and a temperature gradient of 20 °C over 10 mm of soil. This requires a power input of about 600 W to maintain steady state. The apparatus was designed for 800 W to build in an extra margin. All other combinations of mulches and temperature gradients are expected to require a power input much less than this extreme.

Constantan heater wires are used for heating the hot plate. The wires are sandwiched between two silicone rubber sheets of 230 by 460 mm, thus forming a pad. A voltage is applied over the wires in each individual pad. There are two pads for the test plate, six pads for the guard plate (fig. 3), and eight pads for the bottom plate. Versiwrap silicone rubber tape (Rowe Industries, Toledo, Ohio), 38 mm wide and 1.5 mm thick, was used to create the sheets. The heater wires are spaced at distances of 13 mm from each other. This spacing ensures that the maximum required wattage of 800 W is obtained at the maximum voltage of 120 V RMS. The function of the silicone rubber sheets is to electrically insulate the aluminum plates from the heater wires. Silicone rubber is a good thermal conductor, so heat flow to the aluminum plates is not hindered too much by introducing this material.

The voltage drop across the heater wires can be varied between 0 and 120 V RMS in order to obtain the desired temperature of the hot plate; the larger the voltage drop, the more heating takes place as shown in:

$$q = (V_{rms})^2 / R_{plate} \tag{3}$$

where

q = heat delivered to the plate (W)
V_{rms} = RMS voltage drop across the heater wires (V)
R_{plate} = total resistance of electrical heater wires in the plate (Ohm).

Thermocouples are 'buried' in holes that were drilled in the plates. There are 2 thermocouples in each of the three (test, guard, and bottom) plates (fig. 4). Each set of 2 thermo–couples is connected in series. The average temperature is compared to the desired temperature that is set by the user.

The voltage drop across the heater wires is adjusted accordingly in a proportional control loop (fig. 5). Each plate (test, guard, bottom) has its own temperature control. The power to each of the three plates is measured with a wattmeter circuit. The voltage drop across the wire in a plate is measured and sent to an RMS–to–DC converter circuit and then to a squaring circuit to produce an output signal that is proportional to the input power for each plate. The wattmeter circuit performs the function described in equation 3.

Cold Plate

The main purpose of the cold plate is to quantify the contributions of different heat transport mechanisms to the thermal conductivity of a certain material. The thermal conductivity itself could be measured using only the hot plate without the cold plate. However, to study the heat transfer mechanisms it is essential that the test material is contained between two plates that can be inverted (free convection) and that can have different emissivities (thermal radiation) as discussed in the introduction.

A 'cold plate' of 930 by 930 mm was constructed (figs. 6–8). Cooling is accomplished using 48 thermoelectric devices or Peltier coolers (Melcor Thermoelectrics, model CP1.4–127–045L) in combination with 48 heat sinks, in rows of 6 by 8 (fig. 6). Each Peltier cooler measures 40 by 40 by 3 mm. Figure 7 shows a top view of one single heat sink/Peltier cooler combination and its dimensions. A heat sink is positioned centrally on top of a Peltier cooler, connecting to its warm side. The cool sides of the Peltier coolers are connected (separated by 6 mm aluminum spacers) to a 930 by 930 by 6 mm aluminum plate (fig. 8). It is this plate that has to be cooled to a desired preset temperature. Aluminum was chosen because it is an excellent heat conductor. This causes temperature gradients on the plate to be as small as possible.

The function of the aluminum spacers (fig. 8) is to increase the distance between the heat sinks and the cold plate. This is necessary because the warm heat sinks tend to heat the cold plate through thermal radiation. Insulation material is placed between the heat sinks and the cold plate to minimize this undesired heating effect. At the warm side of the Peltier coolers, heat generated has to be taken away. This is accomplished using heat sinks and fans (fig. 6). There are 48 heat sinks (Farnell Components, model 523–185), one for every Peltier cooler. Twelve fans (Purdy Electronics Corporation, Interfan, model PM106–115–4B–7) are positioned in such a way that the air is blown in parallel with the fins of the heat sinks (see fig. 6).

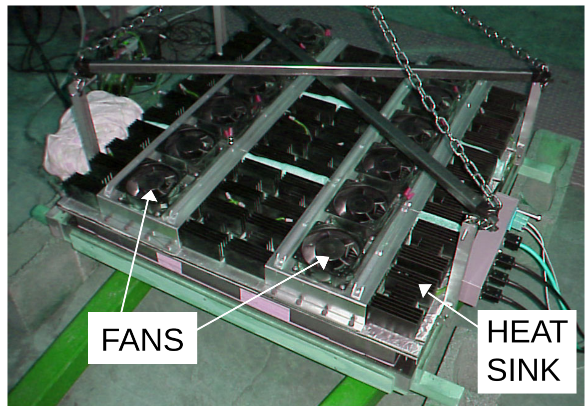

Figure 6. Back side of cold plate with 12 fans, 48 heat sinks, and 48 Peltier coolers. Half of the heat sinks are hidden under fans. Peltier coolers are hidden beneath heat sinks.

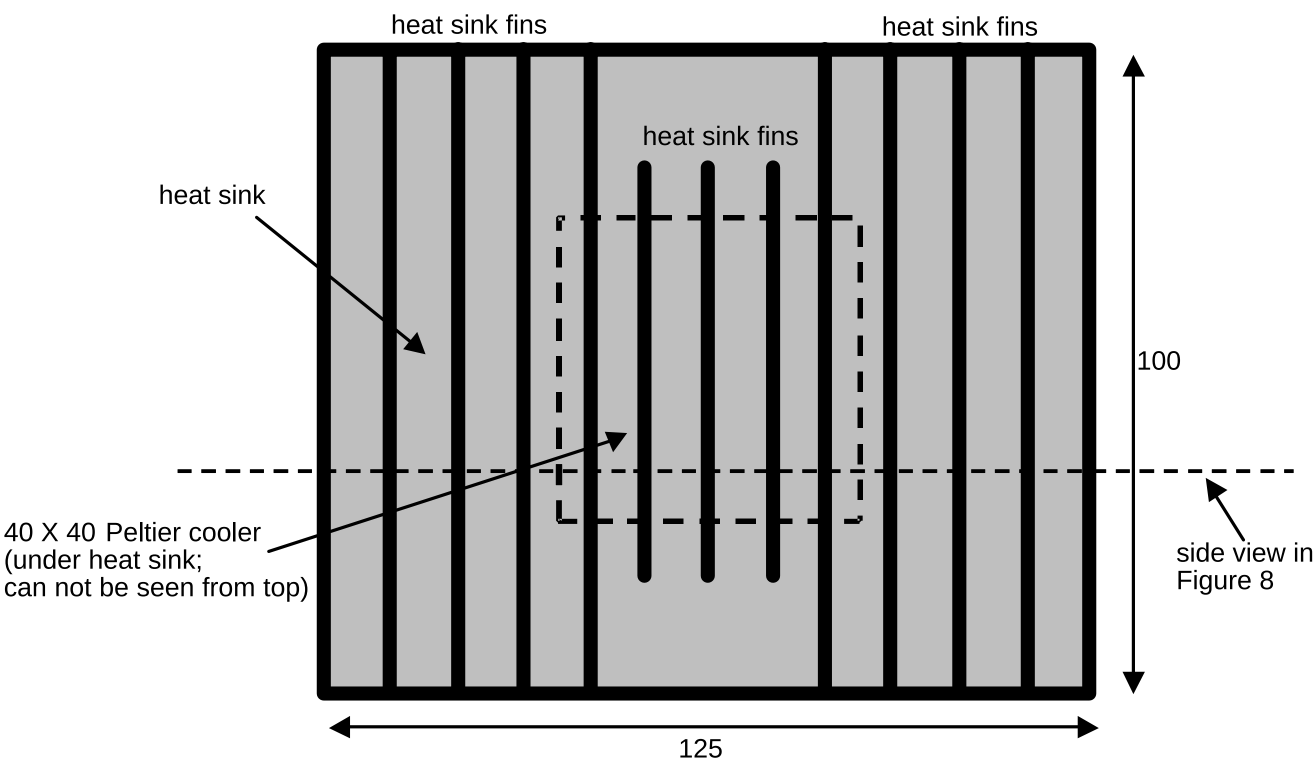

Figure 7. Top view of one heat sink and one Peltier cooler. All dimensions are in mm.

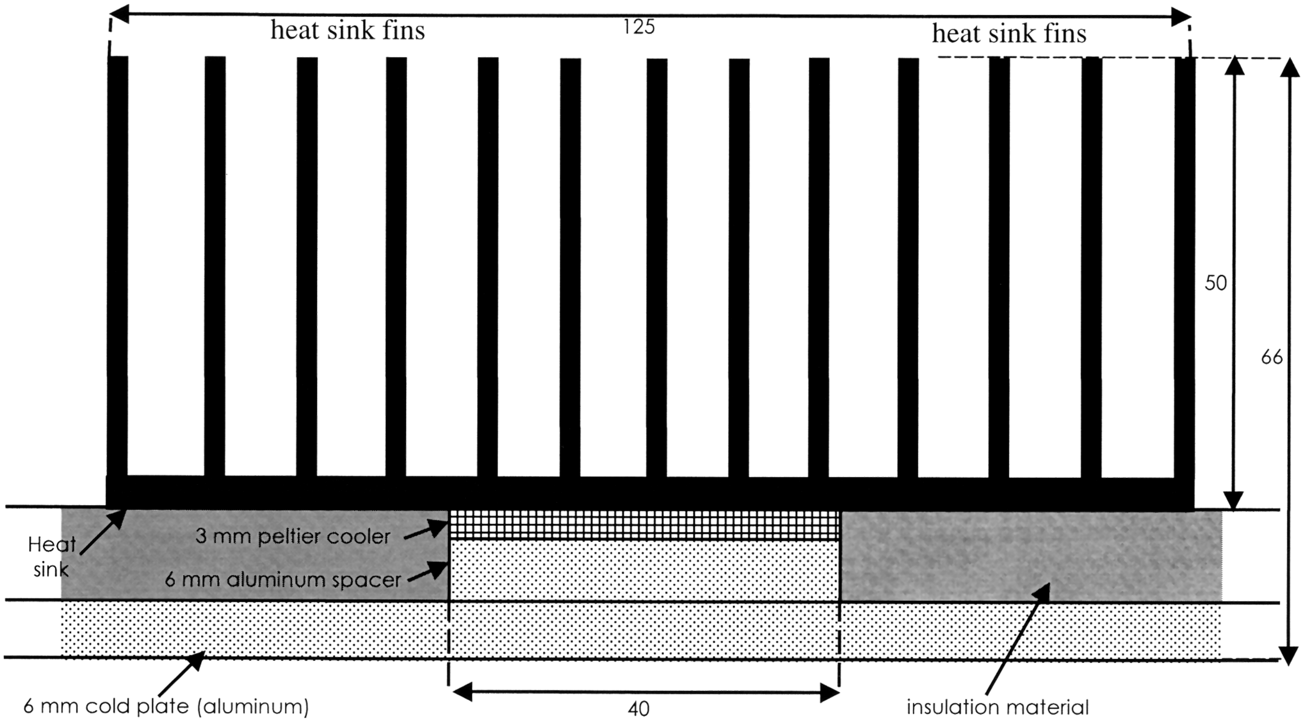

Figure 8. Side view (cross section) of cold plate assembly showing one heat sink and one Peltier cooler. All dimensions are in mm. Figure is not to scale.

The electric current through the Peltier coolers can be varied in order to obtain the desired temperature; the larger the current, the more cooling takes place. Two thermo–couples, connected in series, are buried in the cooled aluminum plate. The average temperature is compared to the desired temperature that is set by the user, in a manner that is very similar to that of the hot plate (fig. 5). The electric current into the Peltier coolers is adjusted accordingly; it is increased if cooling needs to speed up and decreased if cooling needs to slow down. The control is proportional and integral (PI). The plate was designed to absorb a maximum of 800 W, matching the capacity of the hot plate. If the cold plate can absorb the amount of heat from the mulch that the hot plate sends into the mulch, then a steady state can be maintained. Six 120 V transformers rated at 8 amps each are used to supply the amount of current that is needed to absorb 800 W.

When the set point temperature of the cold plate is lowered, a larger current is sent through the Peltier coolers to accomplish accelerated cooling. At this time, temperatures on the cold plate will be coolest at locations that are closest to the Peltier coolers; up to 1.5°C cooler than locations that are farthest away from the Peltier coolers. Once the setpoint has been reached, this temperature difference disappears quickly and temperatures across the cold plate become much more uniform.

A CR10X datalogger (Campbell Scientific, Inc., Logan, Utah) and an AM416 multiplexer (Campbell Scientific, Inc., Logan, Utah) were used to monitor and record the temperatures measured by 18 surface thermocouples. Five thermocouples were located on top of the cold plate and two on top of the test plate. The temperatures from these thermocouples were used to determine the temperature gradient across a test material. Eleven thermocouples were attached to the inside surfaces (fig. 4) of the hot plate components: two on the test plate, four on the guard plate and five on the bottom plate. These eleven thermocouples were used to correct for temperature differences among the three hot plate components (see Discussion section).

The wattage through a test material should be recorded after steady state has been reached. The time required to reach steady state depends on the test material, the initial temperature of the material, the hot and cold plate temperatures, and the distance between hot and cold plate. Time to steady state may be 10 hrs for a 0.1 m thick layer of dry soil with an initial temperature of 20°C, the hot plate at 30°C and the cold plate at 20°C. Less than one hour may be required for an unconsolidated fibrous mulch such as a straw material.

Only dry materials should be used with this apparatus, since redistribution of water will occur when a wet material is placed between the hot and the cold plate, causing changes and non–uniformity in the thermal conductivity of the material. This means that the apparatus cannot be used for investigating heat transport by moving water (vapor or liquid). The hot plate was designed to function properly for temperatures between ambient and 50°C. The cold plate is to be operated at sub–ambient temperatures, but should stay well above the dewpoint temperature to avoid condensation.

Discussion

After designing and constructing the apparatus, it was verified using various independent approaches. The hot plate by itself was verified using three reference materials with a known thermal resistance. The hot/cold plate ensemble was verified two different ways: (1) a theoretical analysis of the error caused by undesired lateral heat flow in a test material and (2) the measurement, using our apparatus, of the thermal conductivity of air.

VERIFICATION OF HOT PLATE

Three reference materials, with known thermal resistances, were used to verify the correct functioning of the hot plate. They are listed in table 1 along with some relevant properties. Known thermal resistances for both polystyrene insulation materials were provided by the companies that produced them. The thermal resistance for particle board was reported by the USDA (1989). Thermal resistance was measured using the hot plate only (no cold plate), with the reference material sitting on top of the hot plate. 'Measured' thermal resistance R (m^2 °C W^{-1}) was obtained from steady state power provided to the test plate and temperature difference across the material and calculated using equation 1. Temperature of the top (cool side) of the reference material was measured using a Telatemp infrared thermometer. The temperature of the bottom (warm side) of the reference material was measured using self–adhesive surface thermocouples. Measured resistances are given in figure 9. Resistance is shown as a function of average temperature difference between the test plate and the other plates (guard and bottom), since it was impossible to control all three plates at exactly the same temperature. Thermal resistance measurements appeared to be quite sensitive to these temperature differences, as figure 9 shows. When the test plate is warmer than the other plates, R became smaller due to the fact that some of the provided power translates into a heat flux going to the other plates instead of going through the reference material (eq. 1). When the test plate is cooler than the other plates, the opposite occurs: not all of the heat flux going through the reference material originates from the power provided to the test plate; some comes from the other plates, resulting a larger value for R.

The thermocouples buried in the aluminum plates (fig. 4) were not very useful in determining whether undesired heat flow through the bottom or sides would be a problem. These buried thermocouples can measure the exact same temperature in the test and bottom plate and still there may be heat flowing between these plates, due to large vertical temperature gradients within the plate assembly of Al – heater pad – Al. Only if the temperatures of the inside surfaces (where the surface thermocouples are located, fig. 4) are the same, there will be no undesired heat flow. Therefore, these temperatures were used to calculate the data presented in figures 9 and 10.

Figure 9 shows that measured and known thermal resistance matched almost perfectly for particle board (compare known thermal resistance with intercept of regression line). Measured thermal resistance of Dow Chemical insulation was about 10% lower than the known thermal resistance. For Owens Corning insulation, measured thermal resistance was about 5% higher than the known resistance. These differences are reasonable when considering possible sources of error: uncertainty about the 'known' thermal resistance and errors in temperature and power measurement. We conclude that the hot plate performs satisfactorily within this range of thermal resistances.

It is impossible to always control the three component plates at exactly the same temperature, which would be

Table 1. Reference materials used in verification of hot plate.

Reference material	Known thermal resistance (m^2 °C W^{-1})	Thickness (mm)	Density (kg m^{-3})
Extruded polystyrene insulation (Owens Corning Company)	0.88	25.4	24
Extruded polystyrene insulation (Dow Chemical Company)	0.71	19.1	27
Particle board	0.13	19.1	800

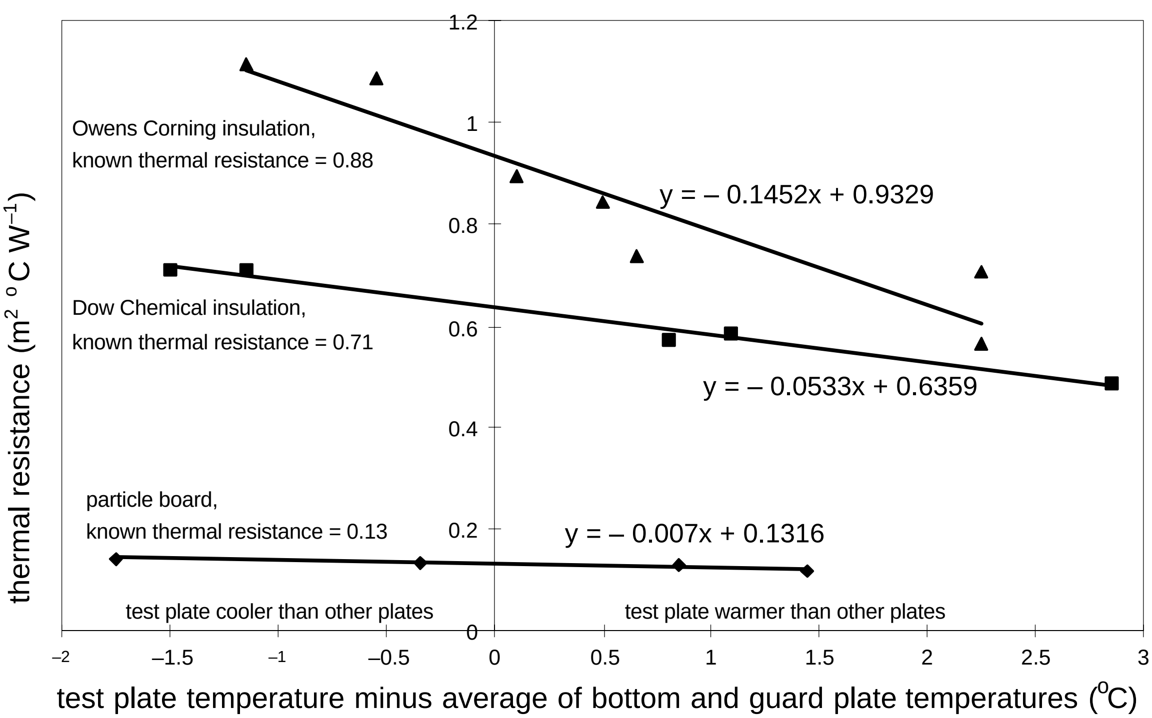

Figure 9. Measured thermal resistance of three reference materials with known thermal resistance.

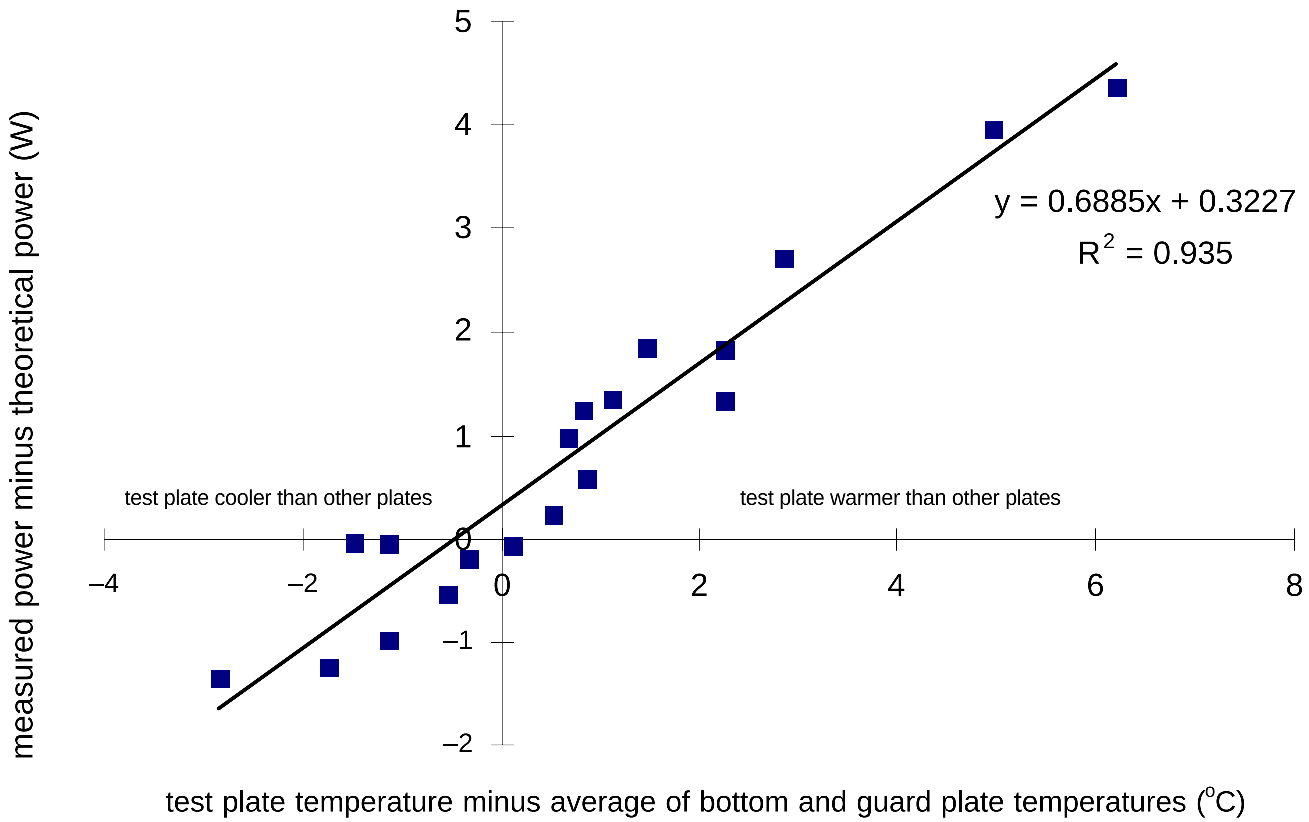

Figure 10. Development of an equation to correct the measured power provided to the test plate, which is subsequently used in the calculation of mulch thermal resistance and apparent thermal conductivity.

necessary to obtain correct measurements. When measuring materials of unknown thermal resistances, temperature differences among the plates should be corrected for. To develop a correction equation, measured power provided to the test plate was compared with theoretical power, i.e. the power calculated using the known (theoretical) thermal resistance and the measured temperature difference over the reference material. Results are shown in figure 10. These data come from the same measurements as the data in figure 9 plus some additional measurements at greater temperature differences. The advantage of the data representation in figure 10 is that the data of all three reference materials can be integrated and one correction equation can be obtained that is valid for all materials.

Figure 10 shows that power difference (measured minus theoretical power) strongly depends on temperature difference between the test plate and the other plates. This figure shows a linear relationship, which can be explained: for every degree of temperature difference between the test and the other two plates, there is a certain amount of (undesired) heat flow between the test and other plates. When the temperature difference is doubled, this heat flow is also doubled, since the thermal resistance between the test and other plates is always the same. The linear regression line of figure 10 can be used when measuring materials of unknown thermal resistance: the measured power is corrected and this corrected power is used in the calculation of thermal resistance (eq. 1) and apparent thermal conductivity (eq. 2). This regression equation has only one independent variable: test plate temperature minus the average of bottom and guard plate temperatures. Regression was also done with two independent variables: (1) test plate temperature minus guard plate temperature and (2) test plate temperature minus bottom plate temperature. The correlation $r^2 = 0.936$ was about the same as for the simple linear regression in figure 10 ($r^2 = 0.935$), so it was decided that the simple regression equation was adequate. This equation corrects for all undesired heat flow: vertical heat flow between test and bottom plate, lateral heat flow between test and guard plate, lateral heat flow in the test sample, and lateral heat flow in the insulation material between the test and the bottom plates. It should be redeveloped for each new hot plate apparatus that is built, unless constructed using the same materials in the same dimensions as presented here.

Verification of Hot/Cold Plate Combination

When a sample is sandwiched between the hot and cold plates, it can experience some undesired lateral heat flow, even when the temperatures of the test, guard and bottom plate are exactly equal. Errors because of lateral heat flow in the sample increase with (1) increasing difference between ambient temperature and average temperature of hot and cold plate, (2) increasing sample thickness, (3) decreasing sample thermal conductivity and (4) decreasing guard plate width. Steady state heat flow in a two–dimensional vertical cross section of the hot–cold plate setup (fig. 11) was numerically simulated using a finite difference model (Incropera and DeWitt, 1990, p. 194). Only half the cross section was modeled since the problem is symmetric. The top and bottom of the sample were set to fixed temperatures, determined by the hot and cold plate temperatures. The left side (fig. 11) of the sample was subjected to a convection boundary condition. Kreith and Bohn (1997) give a range of 6–30 W

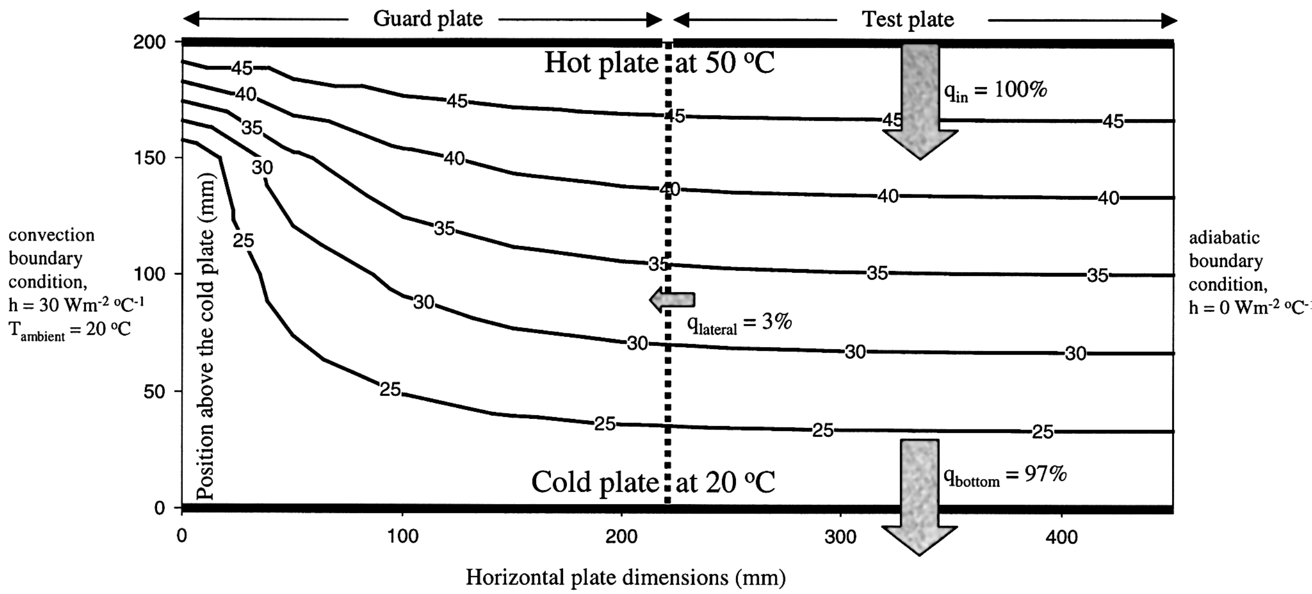

Figure 11. Simulation of steady state heat flow in a two–dimensional vertical cross section, with the hot plate at 50° C and the cold plate at 20° C. Figure is not to scale.

m^{-2} °C^{-1} for the convection coefficient (h) for air under free convection. In our simulations, h was taken as 30 W m^{-2} °C^{-1}. No heat flows across the right side (actually the center of the cross section) in figure 11, due to symmetry, thus an adiabatic boundary condition is appropriate here.

A worst–case scenario was simulated: sample thickness = 0.2 m, sample thermal conductivity = 0.02 W m^{-1} °C^{-1}, $T_{ambient}$ = 20°C, T_{cold} = 20°C, and T_{hot} = 50°C. The result was that 3% of the heat delivered to the test plate is lost to lateral flow, causing a 3% error in calculated thermal conductivity (k). More realistic scenarios (thinner sample thickness, larger k) produced errors in k of <1%. The use of styrofoam strips between the plates for supporting the media at the plate edge would further reduce lateral heat flow. Thus errors because of lateral heat flow in the sample can be neglected.

Measured data confirms the correct functioning of the hot/cold plate combination. Heat flux was measured with nothing but air between hot and cold plate, with the cold plate as the lower plate. In this thermally stable case, free convection is expected to be absent, so only conduction and thermal radiation contribute to the heat flux leading to:

$$q'' = k_{cd}\frac{\Delta T}{L} + \frac{\sigma\,(T_h^{\,4} - T_c^{\,4})}{2/\varepsilon - 1} \qquad (4)$$

where

k_{cd} = thermal conductivity of air (W m^{-1} °C^{-1})
σ = Stefan–Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}.
T_h = temperature of hot plate (K)
T_c = temperature of cold plate (K)
ε = emissivity of hot and cold plates.

Note that k_{cd} refers to pure conduction only, as opposed to the *apparent* thermal conductivity k (eq. 2), which takes all heat transport mechanisms into account. Measurements were taken for eight different combinations: two plate spacings (61 and 140 mm), two temperature settings (20–35 and 20–45°C), and two plate emissivities. Different emissivities were achieved using a set of unpainted Al plates and a set of black painted Al plates. Krylon ultra flat black spray paint was used to obtain black plate surfaces. The emissivity of the black plates was assumed to be 0.95 and the emissivity of the Al plates was taken as 0.05, based on values found in the literature (van Donk and Tollner, 2000a).

Air thermal conductivity (k_{cd}) was estimated from the measured data using non–linear regression techniques (eq. 4), yielding a value of 0.026 W m^{-1} °C^{-1} (standard error = 0.0031 W m^{-1} °C^{-1}), which matches exactly with the theoretical value of 0.026 W m^{-1} °C^{-1} for still air. This confirms the correct functioning of the hot/cold plate combination and the applied corrections. Application of the apparatus, using several mulch materials, has been reported elsewhere (van Donk and Tollner, 2000a, 2000b).

SUMMARY

A hot plate and a cold plate were designed and constructed for the measurement of heat transfer in dry mulch materials contained between the two plates. The hot plate consists of three components: a test, a guard, and a bottom plate. Each is individually controlled (temperature) and monitored (both wattage and temperature). The correct functioning of the hot plate was verified using three reference materials of known thermal conductivity. An empirical equation was developed to correct for temperature differences among the three hot plate components. The cold plate absorbs the heat given off by the hot plate. Its main contribution is that it enables the quantification of heat transfer mechanisms such as thermal radiation and free convection. The cold plate is cooled using thermoelectric devices in combination with heat sinks and fans. A theoretical analysis showed that errors due to undesired lateral heat flow in the sample between the plates can be neglected. The thermal conductivity of air was measured, yielding a value of 0.026 W m^{-1} °C^{-1}, which matches the theoretical value and confirms the correct functioning of the hot/cold plate combination.

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