

Dual Thermal Probes

9.1 INTRODUCTION

The hydraulic properties of the surface layer of the soil require a careful study. This is the zone of compacting, cracking, erosion, seed beds, and is often the most dense portion of a root system. The tension infiltrometer is an instrument developed to allow the measurement of surface hydraulic properties (Clothier and White, 1981). We shall discuss it in detail in Chapter 13. With it, preferential flow of water through the macropores and soil cracks in contact with the soil surface is controlled by applying water to the soil at water potentials less than zero. We can obtain the unsaturated hydraulic conductivity, sorptivity, repellency, and mobility of solutes in soil with a tension infiltrometer, but not the soil water content.

To represent the hydraulic character of a soil, the water content needs to be known. It is the most sought-after soil-physical parameter of the four soil-physical factors that affect plant growth. As we saw in the first paragraph of Chapter 1, the other three are soil temperature, aeration, and mechanical impedance (Kirkham, 1973). After soil water, soil temperature is perhaps the most important physical property of soil to affect crop growth (Mohanty et al., 1997). The temperature of the soil surface is of interest to micrometeorologists, because it influences the atmospheric boundary layer (Ham and Senock, 1992). Dual measurements of water and temperature are important for the development of models (Nassar and Horton, 1997a,b; Hiraiwa and Kasubuchi, 2000).

Mohanty et al. (1997) point out the need for improved precision of measurements of water content. Measurement of soil water content can be done by several means, and each method has its advantages and disadvantages. These methods include the gravimetric method, time-domain reflectometry (TDR), which we discussed in Chapter 8, the

neutron-probe technique, and the dual-probe heat-pulse technique, also called the dual thermal probe technique.

The simplicity and accuracy of the gravimetric method are major advantages (Song et al., 1998). The method also is well suited for measuring the soil water content in the zone of active root water uptake. Unfortunately, the method is time consuming and destructive and cannot be automated. The TDR technique also can provide accurate measurements of soil water content. A significant advantage of TDR over the gravimetric method is that it permits automated, nondestructive measurements. A disadvantage of TDR is that the method requires calibration for soils high in organic matter and other soils in which the standard equation used to determine soil water content (called the "Topp equation") does not work (Topp et al., 1980) (Gerard J. Kluitenberg, Kansas State University, personal communication, July 17, 2013). Other barriers in using the TDR technique are the instrument's cost and its complexity. The neutron-probe technique is well suited for measurements deep in the soil profile, but it is ineffective within about the top 15 cm of the soil surface, the zone of active root water uptake for many plants. However, the neutron probe is still needed for measurements of water uptake at great depths. When monitoring water extraction by roots in semiarid Kansas, we measure to a 3.2 m depth to make sure that we are measuring below the depth of water uptake by roots. Rachidi et al. (1993) found that sunflower (*Helianthus annuus* L.) grown under dry-land conditions depleted water to the 2.7-m depth. No technique other than the neutron-probe method could have measured to such great depths. Although the neutron-probe technique is relatively easy to employ, the method is time consuming, requires calibration, and cannot be automated. The use of a neutron probe also requires special licensing for the handling of radioactive materials. The paper work required for the safe use of the neutron probes deters one from using them (G.J. Kluitenberg, personal communication, July 17, 2013). Improper storage and handling of the radioactive isotopes have caused laboratories to switch from neutron probes to TDR for soil water content measurements.

No traditional method can monitor soil water content near the surface of the soil (<20 mm). Mallants et al. (1996) found that measurements with TDR were valid at an observation depth of 50 mm. The shallowest probe that Clothier and Kirkham (1991) and Clothier et al. (1992) used was 20 mm long. Probes 10 mm long gave aberrant results. In a discussion of wave guide length, Dalton (1992) talks of the maximum probe length, not minimum. He includes an analysis of probes as short as 10 mm, but the analysis is theoretical, not experimental. To quantify the error in propagation time measurement using short transmission lines, Amato and Ritchie (1995) made measurements in air using rod lengths

from 10 to 150 mm. The coefficient of variation was greater for times <100 ps for air-dry soil, and it varied from 2.8% to 7.3%. For longer times, corresponding to higher water contents, the coefficient of variation was $<3\%$. Nadler et al. (2002) say that the width of the soil layer affecting the moisture measurement with TDR is close to 30 mm. As far as I know, no one has put TDR wave guides as short as 10 mm in the soil and obtained meaningful soil water contents with them. Thus, I would say that TDR measurements cannot make measurements to the soil surface closer than 20 mm.

The dual-probe heat-pulse technique has been developed to monitor soil thermal properties, that is, heat capacity, thermal conductivity, and thermal diffusivity, which are determined from temperature measurements (Campbell et al., 1991; Bristow et al., 1994b; Bilskie et al., 1998; Bristow, 2002; Kluitenberg, 2002). Campbell et al. (1991) showed that the method can also measure volumetric soil water content (θ), because the soil water content is dependent upon soil thermal properties. Since Campbell et al. (1991) introduced the method, the dual-probe heat-pulse technique has been developed and tested for measuring volumetric water content, θ , and changes in volumetric water content, $\Delta\theta$, in the laboratory and in the field (Bristow et al., 1993, 1994a; Tarara and Ham, 1997; Bristow, 1998; Ham and Knapp, 1998). Dual-probe heat-pulse sensors have been used for routine θ and $\Delta\theta$ measurement in field experiments (Bremer et al., 1998, 2001; Ham and Knapp, 1998; Bremer and Ham, 1999; Campbell et al., 2002).

Figure 9.1 shows a dual-probe heat-pulse sensor as made by Yan Song and used in the experiment by Song et al. (1998). It consists of two parallel probes each made out of a 1.27-mm-diameter hypodermic needle, which are held apart at a fixed distance (~ 6 mm) by inserting them through predrilled holes in a polyvinyl chloride (PVC) block ($26 \times 16 \times 6$ mm). One needle houses the heater wire, and a voltage is applied to the wire to create a heat pulse. The other needle, which holds a thermocouple

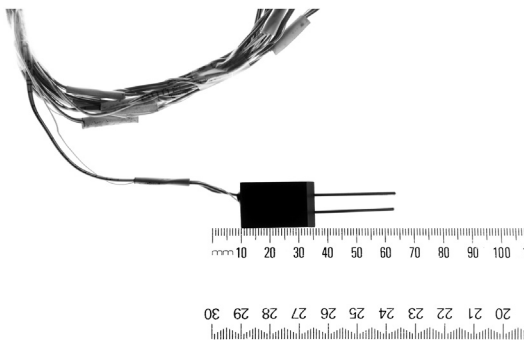


FIGURE 9.1 A dual-probe heat-pulse sensor. The scale is in millimeters. Photograph courtesy of Marsha K. Landis, Graphic Designer, Kansas State University, Manhattan, Kansas.

junction made out of constantan and copper, senses the heat pulse. The length of each sensor, or of the length of the needles protruding from the PVC housing, is 27–29 mm.

A significant advantage of the dual-probe heat-pulse technique is the ability to measure water content close to the surface of the soil (theoretically as close as 6 mm, a value to be discussed later in this chapter) in a nondestructive, automated manner. This should be of great benefit in soil with roots, where often the greatest density of roots is near the surface of the soil. Later in the chapter, we shall turn to the use of the dual-probe heat-pulse technique to monitor the water uptake by roots.

9.2 THERMAL PROPERTIES OF SOILS

Because the dual-probe heat-pulse technique measures the thermal properties of the soil, we need to understand them. The amount of heat that will move a given distance through a porous body such as soil depends on how fast the body will conduct the heat (Kirkham and Powers, 1972, p. 463). The rate at which a body conducts heat is called the “thermal conductivity” K and is defined as the number of calories of heat a material will conduct each second across a distance of 1 cm if the temperature difference across this distance is 1 °C. Thermal conductivity has dimensions in metric units of calories per centimeter per second per degrees centigrade. The amount of heat that a volume of soil stores before its temperature rises a certain amount also governs how fast a soil will increase in temperature as heat is applied to it. This quantity is called the “heat capacity”. The heat capacity can be based on the mass, when it is called the “gravimetric heat capacity” c , or on the volume, when it is called the “volumetric heat capacity” ρc , of the material. The volumetric heat capacity is equal to the gravimetric heat capacity multiplied by the density ρ of the material. The gravimetric heat capacity is defined as the amount of heat required to raise 1 g of material by 1 °C and has units of calories per gram per degrees centigrade. The volumetric heat capacity is defined as the amount of heat required to raise 1 cc of material by 1 °C and has units of calories per cubic centimeter per degrees centigrade. The “specific heat” of a material is the ratio of the heat capacity of the material to that of water and is dimensionless. The “heat content” q in calories of a material can be given as

$$q = \rho c V T, \quad (9.1)$$

where V is the volume of the material and T is the temperature of the material in degrees centigrade.

The time required for a soil to increase in temperature depends on how fast the applied heat is conducted through the soil and its heat capacity.

When heat flow in the soil is studied, a constant D called the “thermal diffusivity” is used and given by

$$D = K/\rho c, \quad (9.2)$$

where K is the thermal conductivity and ρc is the volumetric heat capacity. The diffusivity has metric units of centimeters squared per second. The water content and the porosity of the soil both have an effect on K and ρc so that D also changes with changes in water content and porosity (Kirkham and Powers, 1972, p. 463).

There is considerable variety in terminology (Carslaw and Jaeger, 1959, p. 9, first footnote). Some writers regard the definition for gravimetric heat capacity as being the specific heat, as does de Vries (1966). Other writers define the specific heat of a material as the ratio of the heat capacity of the material to that of water, and it is dimensionless. Kirkham and Powers (1972) use the latter definition.

9.3 THEORY OF THE DUAL-PROBE HEAT-PULSE METHOD

The theory for obtaining θ from measurements with dual-probe heat-pulse sensors has been described (Campbell et al., 1991; Bristow et al., 1993, 1994a,b, 1995; Kluitenberg et al., 1993, 1995; Tarara and Ham, 1997; Song et al., 1998). As noted, a dual-probe heat-pulse instrument has a temperature sensor positioned at a fixed distance from a line heat source, which are used to measure the volumetric heat capacity of soil, ρc . We shall follow the analyses of three different references to understand the theory: de Vries (1966); Carslaw and Jaeger (1959); and Campbell et al. (1991).

We first consider the analysis of de Vries (1966). As noted above, two independent thermal properties enter into a quantitative description of the heat transfer by conduction. They are the thermal conductivity, abbreviated as K above and as λ by de Vries, who uses units of mill-calories per centimeter per second per degrees centigrade, and the heat capacity per unit volume, abbreviated as C by de Vries with units of calories per cubic centimeter per degrees centigrade. Also, as noted above, the volumetric heat capacity, C , is equal to ρc , or $C = \rho c$, where ρ is the density of the medium (grams per cubic centimeter) and c is the specific heat (calories per gram per degrees centigrade). In many equations, the quotient of these two quantities appears. It is called the “thermal diffusivity” and is denoted by the symbol D above and as a by de Vries. Thus, using de Vries’s symbols, $a = \lambda/C$.

The heat capacity per unit volume of soil can be found by adding the heat capacities of the different soil constituents in 1 cm^3 . Thus, if x_s , x_w ,

and x_a denote the volume fractions of solid material, water (or ice), and air, respectively, one has

$$C = x_s C_s + x_w C_w + x_a C_a. \quad (9.3)$$

The third term on the right-hand side usually can be neglected, because the heat capacity of air is small. The volumetric heat capacity of air at 10 °C is 0.00030 cal/cm³/°C (de Vries, 1966, p. 210) or, at 20 °C, 0.0012 MJ/m³/K (= 0.0012 MJ/m³/°C) (Kluitenberg, 2002, p. 1203). This is small compared to the volumetric heat capacity of water, C_w , which at 10 °C is 1.00 cal/cm³/°C (de Vries, 1966, p. 210) (or 4.18 MJ/m³/°C). de Vries (1966, p. 211) reports that the specific heat of most soil minerals varies linearly from 0.16 ± 0.01 cal/cm³/°C at -18 °C to 0.19 ± 0.01 cal/cm³/°C at 60 °C. One can take a middle value of about 0.17 cal/cm³/°C for the specific heat of mineral soils. Because the specific mass of these minerals is about 2.7 g/cm³, an average value of C_s of about 0.46 cal/cm³/°C or 1.92 MJ/m³/°C holds for a mineral soil at 10 °C.

The specific heat of soil organic matter is about 0.46 cal/g/°C or 1.92 MJ/m³/°C (de Vries, 1966, p. 211). An average value of the specific mass of the organic materials in soil is 1.3 g/cm³, and, therefore, $C_s = 0.60$ cal/cm³/°C or 2.51 MJ/m³/°C is a good average value in the case of organic soils.

If we denote the volume fractions of soil minerals and of organic matter by x_m and x_o , respectively, the heat capacity per unit volume equals

$$C = 0.46 x_m + 0.60 x_o + x_w \text{ cal/cm}^3/\text{°C} \quad (9.4)$$

or

$$C = 1.92 x_m + 2.51 x_o + 4.18 x_w \text{ MJ/m}^3/\text{°C}, \quad (9.5)$$

where we remind ourselves that

C = volumetric heat capacity of the soil (MJ/m³/°C),
 x_m = volume fraction of soil minerals,
 x_o = volume fraction of organic matter,
 x_w = volume fraction of water.

We also remember

$$C = \rho c, \quad (9.6)$$

where

C = volumetric heat capacity (cal/cm³/°C),
 ρ = density (g/cm³),
 c = gravimetric heat capacity (cal/g/°C).

So

$$C = \rho c = 1.92 x_m + 2.51 x_o + 4.18 \theta, \quad (9.7)$$

where

x_m = (bulk density)/(particle density),
 x_o = organic matter content,
 θ = volumetric water content.

The bulk density of a soil needs to be known. The particle density can be assumed to be 2.65 Mg/m^3 . x_o can be neglected in soils with low organic matter. We can determine heat capacity and solve for θ .

We next turn to the analysis of [Carslaw and Jaeger \(1959, p. 258; their Eqn \(3\)\)](#), who present the following equation for a temperature change when heat is applied to a line source:

$$\Delta T = [Q/(4\pi kt)] [\exp(-r^2/4kt)], \quad (9.8)$$

where

ΔT = temperature change (degrees centigrade) (Carslaw and Jaeger use the symbol v for ΔT),
 Q = source strength (meter square degrees centigrade) (see later for more discussion of Q),
 r = distance from the line (meters),
 t = time after the instantaneous heat pulse (seconds),
 k = thermal diffusivity (meter square per second).

The assumptions in the analysis by Carslaw and Jaeger are as follows: (1) an infinite line; (2) an instantaneous heating; and (3) an infinite, homogeneous medium.

Finally, we turn to the analysis of [Campbell et al. \(1991\)](#). They differentiate the equation of Carslaw and Jaeger with respect to time to find the time of maximum temperature change, t_m , at a fixed distance, r_m , from the line source. This gives

$$t_m = -r^2 m / (4k). \quad (9.9)$$

We substitute this result for t_m into the equation of Carslaw and Jaeger. We get a maximum temperature rise, ΔT_m ([Campbell et al., 1991](#); see their Eqn A2),

$$\Delta T_m = Q / (e\pi r_m^2). \quad (9.10)$$

The source strength, Q (meter square degree centigrade), is defined as

$$Q = q/\rho c, \quad (9.11)$$

where

ρc = volumetric heat capacity (Joules per cubic meter per degrees centigrade),

q = quantity of heat liberated per unit length of heater (Joules per meter).

So we have (Campbell et al., 1991; see their Eqn A3)

$$\rho c = q/(e\pi r_m^2 \Delta T_m). \quad (9.12)$$

We see that the volumetric heat capacity is linearly related to the inverse of ΔT_m .

We now combine the above equation from Campbell et al. (1991) with de Vries's equation (Eqn (9.7)), and we get

$$\theta = \{ [q/(e\pi r_m^2 \Delta T_m)] - (1.92 x_m + 2.51 x_o) \} / 4.18. \quad (9.13)$$

9.4 EXAMPLE CALCULATION

Data collected by Song et al. (1998) on November 13, 1996, from a dual-probe heat-pulse sensor in a column containing a very fine sandy loam were as follows:

$$\text{Initial temperature } (^{\circ}\text{C}) = 20.660$$

$$q \text{ (J/m)} = 693.42$$

$$\Delta T_m (^{\circ}\text{C}) = 1.1702$$

$$r_m \text{ (mm)} = 5.83$$

$$\text{Bulk density (Mg/m}^3\text{)} = 1.45$$

$$\text{Particle density (Mg/m}^3\text{)} = 2.65$$

$$x_m \text{ (b.d./p.d.)} = 0.547$$

$$x_o = 0.000$$

$$\rho c = q/(e\pi r_m^2 \Delta T_m),$$

$$\rho c = 0.0020415 \text{ J/mm}^3/^{\circ}\text{C} \text{ or } 2.0415 \text{ J/cm}^3/^{\circ}\text{C},$$

$$\theta = (\rho c - 1.92 x_m \text{ J/cm}^3/^{\circ}\text{C}) / (4.18 \text{ J/cm}^3/^{\circ}\text{C}),$$

$$(1.92 \text{ J/cm}^3/^{\circ}\text{C})(0.547) = 1.05024 \text{ J/cm}^3/^{\circ}\text{C},$$

$$\theta = (2.0415 \text{ J/cm}^3/^{\circ}\text{C} - 1.05024 \text{ J/cm}^3/^{\circ}\text{C}) \text{ divided by } 4.18 \text{ J/cm}^3/^{\circ}\text{C},$$

$$\theta = 0.237.$$

This is volumetric water content. So, adding the units, we have $0.237 \text{ m}^3/\text{m}^3$.

9.5 MEANING OF Q

At this point, we need to understand Q . A memorandum that I received from Dr Gerald Kluitenberg, Department of Agronomy, Kansas State University, dated December 27, 1997, explains Q . I quote directly from the memorandum:

"In your memorandum dated August 28, 1997, you indicated that you were trying to reconcile the units for Q in the Appendix of the [Campbell et al. \(1991\)](#) with the units of Q given in the attached pages of Carslaw and Jaeger ([Carslaw and Jaeger, 1959](#), pp. 1–3). The Q discussed on pages 2–3 of Carslaw and Jaeger is not at all related to the Q in the Appendix of Campbell et al. Note that Campbell et al. refer the reader to page 258 of [Carslaw and Jaeger \(1959\)](#). [Bristow et al. 1994a](#) refer the reader to the same place. The units for Q discussed by Campbell et al. and Bristow et al. agree with the units given on page 258 of Carslaw and Jaeger.

"On page 258, Carslaw and Jaeger state that $Q\rho c$ is the heat liberated per unit length of line. Thus, $Q\rho c$, which is the same as q , has units of Joules per meter. Dividing $Q\rho c$ (J/m) by ρc (Joules per cubic meter per degrees centigrade) yields units of m^2C (meter squared degree centigrade) for Q . These are the same units that [Campbell et al. \(1991\)](#) and [Bristow et al. \(1994a\)](#) use for Q .

"In your memorandum dated August 29, 1997, you indicated that you are trying to understand the physical meaning of the quantity Q . I have struggled with this issue myself. Carslaw and Jaeger consistently call Q the source strength in their chapter on heat sinks and sources (Ch. X) [Chap. X contains p. 258]. Q appears to be simply a mathematical construct that has no physical meaning beyond the physical meaning of q and ρc , whose ratio define Q . I have always accepted Q as a mathematical construct that has no particular physical significance of its own, but I've always wondered whether I might be missing something. I delayed my response to you on this issue so that I would have the opportunity to ask this question to Dr. Philip during his KSU visit. This was the first question I asked him during our visit. His response was no different than that of Carslaw and Jaeger. Q is simply a mathematical construct that has no physical significance of its own."

9.6 MEASUREMENTS OF DIFFERENCES OF WATER CONTENT, $\Delta\theta$

Tarara and Ham (1997) noted that the real strength of the dual-probe heat-pulse technique is in measuring changes in θ or $\Delta\theta$, because they are not affected by errors in measurements of soil bulk density and soil organic matter, if these properties do not change between sampling times. From Eqn (9.13), we can obtain Eqn (9.14), which shows that measurements of $\Delta\theta$ between two sampling periods eliminates x_m and x_o (Song et al., 1998; see their Eqn (9.4)):

$$\Delta\theta = \theta_{t2} - \theta_{t1} = (1/4.18\pi r^2) (q_{t2}/\Delta T_{m,t2} - q_{t1}/\Delta T_{m,t1}), \quad (9.14)$$

where the subscripts $t1$ and $t2$ represent two sampling times. Tarara and Ham (1997) found that the dual-probe heat-pulse technique could measure $\Delta\theta$ on a daily basis to within $0.01 \text{ m}^3/\text{m}^3$ in nonvegetated soil columns. Campbell et al. (1991) reported that the resolution of $\Delta\theta$ with the dual-probe heat-pulse sensor was about $0.005 \text{ m}^3/\text{m}^3$. These results suggest that the dual-probe heat-pulse sensors may have sufficient resolution to monitor water uptake in a root zone, which we shall discuss at the end of the lecture.

9.7 ERRORS

Without roots, Tarara and Ham (1997) found in a laboratory study that the dual-probe heat-pulse method and the gravimetric method agreed to within 0.03 and $0.04 \text{ m}^3/\text{m}^3$ for a Haynie sandy loam and a Kahola silt loam, respectively, over a range of water contents of 0.10 – $0.45 \text{ m}^3/\text{m}^3$. As noted above, they found that the estimates of $\Delta\theta$ for the methods agreed to within $0.01 \text{ m}^3/\text{m}^3$ for both soils. Campbell et al. (2002) and Noborio et al. (1996) also evaluated the dual-probe heat-pulse method for measuring θ and $\Delta\theta$. Campbell et al. (2002) inserted dual-probe heat-pulse sensors in undisturbed peat cores obtained from two peat bogs in New Zealand. Dual-probe heat pulse-based θ estimates were compared with values obtained by the gravimetric method over a water content range of approximately 0.15 – $0.90 \text{ m}^3/\text{m}^3$. Regression analysis with θ estimates obtained by the two methods showed the dual-probe heat-pulse method to be unbiased. The analysis also revealed that excellent precision was achieved with the dual-probe heat-pulse method.

Basinger et al. (2003) evaluated the level of precision that can be achieved with the dual-probe heat-pulse method. Tempe pressure cells fitted with DPHP (dual-probe heat-pulse) sensors were used to conduct desorption experiments in which dual-probe heat pulse-based estimates of θ and $\Delta\theta$ were compared with values estimated by the gravimetric method.

For water contents corresponding to soil water pressure potentials below -100 kPa, comparisons were made by packing the pressure cells with soil wetted to known water contents. The investigation was conducted with seven soil materials representing a wide range of physical properties for mineral soils. Dual-probe heat-pulse sensors slightly overestimated θ at low water contents, but it was shown that the bias could be removed by using an empirical calibration equation, $\theta = 1.09\theta_{\text{DPHP}} - 0.045$. This relationship appears to be general in as much as it was shown to be applicable for all seven soil materials and for water contents ranging from 0.02 to $0.59 \text{ m}^3/\text{m}^3$. The general calibration equation was also shown to be effective in removing bias in $\Delta\theta$ estimates. Pooled regression analysis (all soil materials) showed that θ can be measured with a root mean square error (RMSE) of $0.022 \text{ m}^3/\text{m}^3$. Greater precision can be achieved with $\Delta\theta$ measurements (RMSE = $0.012 \text{ m}^3/\text{m}^3$). However, the results indicated a decrease in precision with increasing magnitude of $\Delta\theta$.

9.8 ADVANTAGES

One advantage of the dual-probe heat-pulse method is that it requires no calibration (even though a calibration is still needed to determine the apparent probe spacing, which we shall discuss later). Another advantage is that it can be automated to measure θ , volumetric heat capacity, and soil temperature simultaneously and frequently. The technique monitors the thermal properties of rocks and soils and, consequently, can be used to analyze soil water content over a wide range of values, including residual water content. Roots utilize water from bedrock ([Zwieniecki and Newton, 1995](#)), so it is important to be able to monitor the water content of rock. Peat soils represent the other end of the scale. They can hold large amounts of water. As noted above, [Campbell et al. \(2002\)](#) in New Zealand showed that dual-probe heat-pulse sensors can be used to measure the wet peat soils endemic to the North Island of that country. They found that the method had a greater sensitivity in peat soils compared with mineral soils and excellent resolution is possible, even at moisture contents as high as 90% by volume.

Because the dual-probe heat-pulse technique samples a small soil volume compared to other methods, the method is well suited for the measurement of water content where fine spatial resolution is required. Some examples are (1) near-surface measurements where other methods fail; (2) measurements near soil heterogeneities such as textural interfaces, rocks, cracks, or holes created by soil organisms or decayed roots; and (3) measurements in the vicinity of live roots. Much research is needed to describe root water uptake as a function of water in the root zone

(van Genuchten, 1994), and the dual-probe heat-pulse method now offers an experimental method to obtain data for root models.

9.9 CALIBRATION

As noted, an advantage of the dual-probe heat-pulse method is that no calibration is required, because the method is based on a physical model of heat flow in soil. However, calibration is still required to get the distance, r , the distance between the two needles. The measured distance cannot be used. Tarara and Ham (1997) tell how this distance can be determined. They suspended probes in three media of known heat capacities. The media were water stabilized with agar, dry glass beads, and glass beads saturated with water. They measured ρc in each medium. Values of q and ΔT_m , along with measured r , were used in Eqn (9.12) to get ρc . Data collected from the water–agar medium were subsequently reanalyzed by inserting the known heat capacity for water into Eqn (9.12) and solving for r . This calculated value of probe spacing was denoted by r' . This method of calibrating dual probes to a known heat capacity (Campbell et al., 1991) uses calculated probe spacing to account for nonideal heat flow between the heater and the thermocouple junction and extraneous factors in sensor materials or geometry that may affect the accuracy of a dual-probe measurement. All new probes are tested in the water–agar medium and calibrated to the heat capacity of water. The calculated probe spacing (r') for each instrument was then used by Tarara and Ham (1997) for determining ρc in soil columns and the field.

Tarara and Ham (1997) list mean values of measured r and calculated r' probe spacings for 24 dual probes. Calculated values of r' were in good agreement, regardless of test medium, but were all slightly larger (0.1 mm) than measured values. Correlation coefficients for the relationship between r' and r were 0.84, 0.81, and 0.74 for water, dry glass beads, and water-saturated glass beads, respectively, which suggests that the variation in probe spacing causes the variability in ρc measurements among probes immersed in the same medium. These results support the use of the calibration technique described above, in which the input value of probe spacing for each instrument is calculated so that the probe is calibrated to the known heat capacity of water. Calibration to a known heat capacity eliminates the need for precise, accurate, physical measurements of the distance between the heater and the thermocouple junction, and it corrects for the probe's estimate of ρc for nonideal heat flow. Despite the slight bias between r' and r , the results indicate that r' is stable and repeatable, and that the r' measured in one medium can be applied to measurements collected in other media.

The key to successful use of the dual probe is not the magnitude of r or r' per se, but that r' is known and remains fixed. Once the instruments are calibrated in water, the distance between the needle probes must remain constant. Therefore, the probes must be installed in the soil with care (Tarara and Ham, 1997). Because the probe spacing appears as a squared term in Eqn (9.12), any error in measurement of r or r' is squared. Thus, it is important that r remains stable and fixed.

9.10 MEASUREMENTS NEAR THE SOIL SURFACE

As stated, a key advantage of the dual-probe heat-pulse technique is its ability to measure soil water content closer to the soil surface than any other instrument now available. But the question arises: How close to the soil surface can one take measurements with the dual-probe heat-pulse method? The soil surface was one form of heterogeneity examined by Philip and Kluitenberg (1999) and Kluitenberg and Philip (1999). They found theoretically that heterogeneity errors are small provided the heterogeneity is no closer to the probes than needle separation. They concluded that the estimates of C may provide a good resolution of soil water content in critical regions such as near soil surfaces, at interfaces between different soils, or behind a wetting front. So, if the needles are 6 mm apart, a typical separation in a dual-probe heat-pulse sensor, one can obtain soil water content as close as 6 mm to the surface, but not closer. The theory has not been checked by measurements. The closest surface measurement that Song et al. (1998, 1999a) took was 15 mm from the soil surface, more than twice as deep the theoretical limit of a near-surface measurement.

Knight et al. (2007) also investigated the measurement volume that a dual-probe heat-pulse sensor is measuring. They found that for a sensor with a probe spacing of 6 mm, the boundary containing 99% of the total spatial sensitivity is closely approximated by an ellipse with an area of 168 mm^2 and a major axis of 15.6 mm in length.

9.11 CONVECTION AND ITS EFFECT ON MEASUREMENTS

Kluitenberg and Heitman (2002) studied the effect of convection (movement of water) on soil water content measurements made with the dual-probe heat-pulse method. They noted that the dual-probe heat-pulse method is useful for measuring soil volumetric water near heterogeneities such as the soil surface, but it does not consider convective heat transfer that may result from soil water movement (forced convection). They

examined the effect of forced convection on estimates of soil water content using three different dual-probe heat-pulse sensor orientations. Heat transfer theory that explicitly accounts for forced convection was used to test this effect. The three orientations were (1) the heater and temperature probes were parallel in a plane normal to the direction of steady water flow (e.g., the two needles were an equal distance from the soil surface and parallel to the soil surface); (2) the temperature probe was directly downstream from the heater probe (e.g., the temperature probe was deeper in the soil than the heater needle); (3) the temperature probe was upstream from the heater probe (e.g., the temperature probe was closer to the soil surface than the heater probe). They concluded that the effect of forced convection may be large enough to render the dual-probe heat-pulse method useless for orientations where the temperature probe is upstream or downstream from the heater probe (i.e., if the heater and temperature probes are inserted into a soil profile face, so water infiltrating into the soil first hits a heater probe or a temperature probe). However, it does not appear to limit the practical utility of dual-probe heat-pulse sensors when the parallel heater and temperature probes are in a plane normal to the direction of steady water flow (i.e., the heater and temperature probe are side by side and placed horizontally so that each needle is an equal distance from the soil surface). (Note that the two needles cannot be pressed vertically into the soil from the soil surface, as one inserts wave guides on a TDR instrument, because, as noted above, at least 6 mm of soil needs to be above the needles for accurate measurements.)

Dr Kluitenberg (personal communication, March 17, 2003) said that even if the sensors are placed so that water meets the two needles at the same time, errors may still occur during rains or irrigations. For example, he said that if there were a heavy rainfall and the sensors were in a sandy soil, the measurements of soil water content could be off by several per cent.

9.12 MEASUREMENT OF ELECTRICAL CONDUCTIVITY

Further development of the dual-probe heat-pulse technique has led to the simultaneous measurement of soil thermal properties, water content, and electrical conductivity using TDR in combination with the dual-probe heat-pulse method (Noborio et al., 1996; Ren et al., 1999). Ren et al. (1999) combined the TDR and dual-probe heat-pulse methods to measure simultaneously soil water content, bulk electrical conductivity, thermal conductivity, heat capacity, and thermal diffusivity. TDR was used to measure soil water content and electrical conductivity, and the dual-probe

heat-pulse method was used to determine thermal conductivity, heat capacity, and thermal diffusivity. They called their probe the thermo-TDR probe. Laboratory tests on a silica sand and a clay loam soil showed that the probe determined soil water content accurately, and the measured electrical conductivity values of saturated soil correlated well with values determined by a four-electrode probe. Measurements in agar-immobilized water produced values of thermal conductivity and heat capacity that closely corresponded with standard values of these properties for water, an indication of the sensor's functionality in other media. [Bristow et al. \(2001\)](#) showed that a simple modification of the dual probe with an additional two needles for bulk soil electrical conductivity measurements provides an alternative measure of the soil's electrical conductivity.

9.13 DETERMINATION OF SOIL WATER MOVEMENT

[Ren et al. \(2000\)](#) followed up on the work of [Ren et al. \(1999\)](#) and used the same thermo-TDR probe to measure soil water flux density (also called flux density), J , in which a heat tracer was used to quantify the magnitude of convective heat transfer resulting from soil water movement. (See Chapter 7, Section 7.1, for the definition of flux density; it is the time rate of transport of a quantity per unit area perpendicular to the direction of flow.) In the method, constant heat input during a small time interval (15 s) is used to emit a heat pulse from a line heat source. Asymmetry in the thermal field near the heat source is quantified by computing the maximum dimensionless temperature difference (MDTD) between upstream and downstream locations. Heat transfer theory was used to relate MDTD to J . A thermo-TDR probe was used to obtain measurements of MDTD in water-saturated soil materials of different textures (sand, sandy loam, and clay loam) with imposed water flux densities ranging from 1.16×10^{-5} to $6.31 \times 10^{-5} \text{ m}^3/\text{m}^2/\text{s}$. A nearly linear relationship between measured MDTD's and fluxes was observed for all soil materials. The experimental results indicated that the proposed method may provide a useful means of measuring J . Because the thermo-TDR probe can be used to make TDR-based measurements of volumetric water content, the proposed method also may permit measurement of pore water velocity (J/θ).

The method of [Ren et al. \(2000\)](#) utilized analytical solutions of the heat equation to describe temperature changes that occur upstream and downstream of a line heat source following the emission of a heat pulse. Their solutions contain integrals that must be evaluated using numerical integration techniques. [Kluitenberg and Warrick \(2001\)](#) developed an improved procedure for evaluating the integrals of the analytical

solutions by recognizing that they can be reduced to a single function, W , known as the well function for leaky aquifers. Thus, numerical integration is not required to implement the heat-pulse method for measuring soil water flux density.

Wang et al. (2002a,b) followed up on the work of Kluitenberg and Warrick (2001). They noted that although their improved method eliminates the need for numerical integration, it still is inconvenient to analyze the relations among variables and to estimate J , because the infinite series is complicated. Wang et al. (2002a) analyzed the heat-pulse signal in a new way with the goals of clarifying the relationships between the variables in the heat transfer problem and simplifying the procedure for calculating J from heat-pulse measurements. Their new mathematical analysis showed that a simple linear relationship exists between soil water flux and the natural log of the ratio of the temperature increase downstream from the line heat source to the temperature increase upstream from the line heat source. The simplicity of this relationship makes heat-pulse sensors an attractive option for measuring soil water fluxes. In theory, the method is valid for fluxes with magnitudes between 10^{-4} and 10^{-7} m/s. The range of measurable fluxes is defined by temperature-measurement resolution at the lower end and by the assumptions used in the analysis at the higher end.

The results of Ren et al. (2000) suggested that the method is limited at higher fluxes (larger than about 2.4 m/day), because of a systematic overestimation of MDTD by $\geq 10\%$ at these higher water velocities (Hopmans et al., 2002). The discrepancy may be the result of ignoring the finite heater geometry in the heat analysis, which assumes infinitely small point sources and sensors with negligible diameter. Although not important for zero-water flow conditions (Kluitenberg et al., 1995), it could be an important consideration when using the dual-probe heat-pulse method for the estimation of water flux. Moreover, the finite physical size of the needles may distort the water flow field between the needles, thereby affecting flow of water and heat between the heat source and sensor. Although the proposed flux density measurement of Ren et al. (2000) requires a priori knowledge of the thermal properties, these can be obtained separately from zero-water flux heat probe measurements, using the method of Bristow et al. (1994a). It is expected that even lower water velocities can be measured for unsaturated soils because of the reduction in the bulk soil heat capacity with decreasing water content.

Hopmans et al. (2002) hypothesized that the difficulties in using the dual-probe heat-pulse method for water flux density measurements are partly caused by the omission of dispersive heat transport in the heat flow equation. Therefore, Hopmans et al. (2002) did a sensitivity analysis to show the influence of thermal dispersion on heat transport and on the estimation of thermal properties and water flow density using parameter

estimation by inverse modeling. They showed that inverse modeling provides an accurate estimation of soil water flux density in both unsaturated and saturated soil conditions for a wider range of water velocities than originally thought possible. They suggested that inverse modeling of dual-probe heat-pulse temperature data may allow the simultaneous estimation of soil water retention, when combined with matric potential measurements, and unsaturated hydraulic conductivity through water flux estimation from simple laboratory experiments.

Kluitenberg et al. (2007) described an improved method to determine soil water flux using a three-probe sensor. The center probe heats the soil, and the outer probes measure temperature increases downstream and upstream from the heater. Kamai et al. (2008, 2010) employed large heater needle diameters (4 mm) to increase the capability of the heat-pulse probe technique to estimate low values of water movement in the soil. They were able to measure values near 1 cm/day, which was about 10 times lower than previous values. Knight et al. (2012) present a semianalytical solution that accounts for the finite radius, as well as the finite thermal properties of the probes. For accurate work when using the dual-probe heat-pulse technique, the finite radius and finite heat capacity of the probes should be taken into account.

To eliminate errors associated with needle deflection (note the two needles must be perfectly parallel for the theory to work), Kamai et al. (2009) designed a button heat-pulse probe that does not use needles. Instead, it consists of a ring-shaped 6-mm-radius heating element and a central thermistor, both embedded in the face of a plastic disk (6 mm thick and 16 mm in diameter). The button heat-pulse probe was more robust compared to the conventional heat-pulse probe.

9.14 MEASUREMENTS WITH ROOTS IN SOIL

Because no work had been done to determine if the dual-probe heat-pulse technique could be used in soil with roots, Song et al. (1998, 1999a,b) carried out experiments with a fibrous root system (turf grass) and a tap-rooted root system (sunflower) to determine if dual-probe heat-pulse sensors could be used to monitor water content, temperature, and root water uptake in a root zone. In the turf grass experiment, tall fescue (*Festuca arundinacea* Schreb., 'Kentucky 31') was chosen because of its dense, uniform root system near the surface of soil. The grass grew in 20-cm diameter containers packed with a Haynie very fine sandy loam (coarse-silty, mixed, calcareous, mesic Mollic Udifluvents). Water content was measured with the dual-probe heat-pulse sensors that were placed horizontally at different depths between 1.5 and 14.4 cm from the surface of the soil columns and at different distances from the axis of the columns. Water content also was

monitored gravimetrically from changes in container mass. Measurements started when the soil surface was covered completely by tall fescue. Hence, changes in θ could be attributed entirely to water being taken up by roots of tall fescue. Daily measurements were taken over multiple six- or seven-day drying cycles. Each drying cycle was preceded by an irrigation, and free drainage had ceased before measurements were initiated. Soil water content dropped from about 0.35 to $0.10 \text{ m}^3/\text{m}^3$ during each drying cycle. Correlation was excellent between θ and changes in water content ($\Delta\theta$) determined by the DPHP and gravimetric methods. Comparisons with the gravimetric method showed that the DPHP sensors could measure average container θ within $0.03 \text{ m}^3/\text{m}^3$ and $\Delta\theta$ within $0.01 \text{ m}^3/\text{m}^3$.

In the follow-up of the work with the fibrous root system of turf grass that completely penetrated soil columns, Song et al. (1999b) carried out an experiment to see if the dual-probe heat-pulse sensors could be used with a taprooted plant. A sunflower plant (*Helianthus annuus* L. 'Hysun 354') was grown in a column (0.20 m in diameter and height) with a Haynie very fine sandy loam, the same soil used in the experiments with the turf grass. Eleven dual-probe heat-pulse sensors were in the container. Results from the sensors were compared with those from the gravimetric method. Discrepancies between measurements of soil volumetric water content, θ , and changes in soil volumetric water, $\Delta\theta$, by the DPHP and gravimetric methods were small (within 0.018 and $0.01 \text{ m}^3/\text{m}^3$, respectively). The sunflower had a small amount of nocturnal transpiration, and roots took up water at a higher rate near the surface of the soil than at greater depths.

At the harvest of the two experiments, roots were extracted and the dual-probe heat-pulse sensors were removed. Both turf grass roots and sunflower roots had grown between the two needles of the dual-probe heat-pulse sensors. Having roots between the needles (rather than soil only) apparently did not affect the readings made with the dual-probe heat-pulse sensors.

Data from the turf grass study (Song et al., 1998) were further analyzed by Song et al. (1999a) to determine the resolution of measurements, including both soil water content and temperature, and to determine root water uptake by monitoring depletion during drying cycles. Moisture depletion at different depths in the soil columns was determined by plotting the soil water content, measured with the dual-probe heat-pulse sensors, at the beginning and end of each of the drying cycles. Water uptake by roots was estimated by averaging depletion during drying cycles and dividing these mean values by root weight.

The columns were usually drier near the surface than at greater depths (Figure 9.2). The dual-probe heat-pulse sensors monitored soil water content as close as 1.5 cm to the surface and to values as low as $0.09 \text{ m}^3/\text{m}^3$ and as high as $0.44 \text{ m}^3/\text{m}^3$. Temperatures were usually coolest near the surface of the columns (Figure 9.3), where most roots occurred.

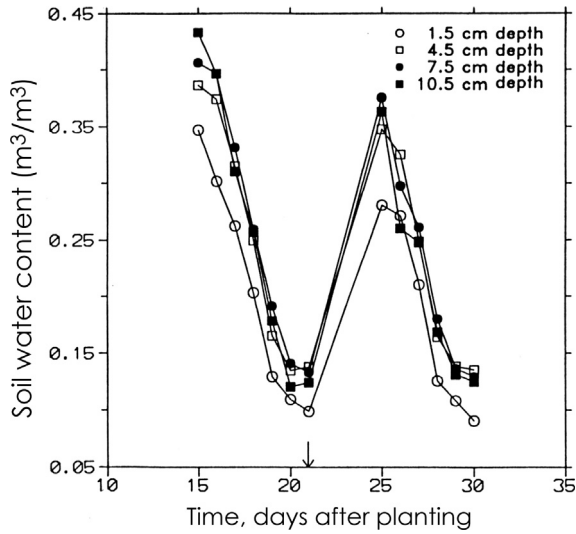


FIGURE 9.2 Volumetric water content at different depths in a soil column with turf grass determined using dual-probe heat-pulse sensors. The arrow indicates when the column was irrigated. The average coefficient of variation was 10.1%. From [Song et al. \(1999a\)](#). Reprinted by permission of M. Th. van Genuchten and L. Wu.

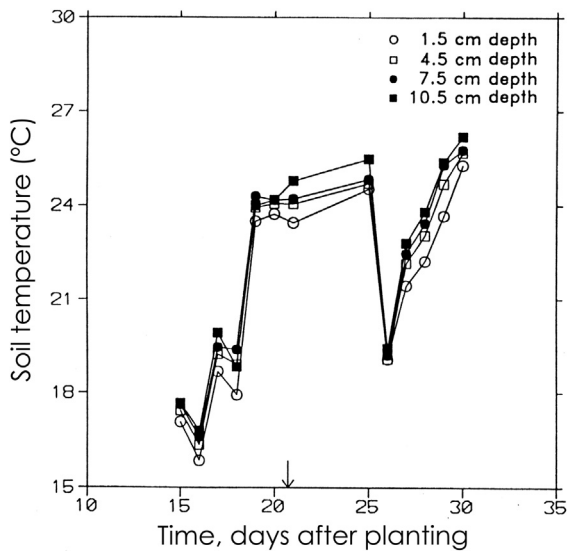


FIGURE 9.3 Temperature in a soil column with turf grass determined using dual-probe heat-pulse sensors. The arrow indicates when the column was irrigated. The average coefficient of variation was 1.5%. From [Song et al. \(1999a\)](#). Reprinted by permission of M. Th. van Genuchten and L. Wu.

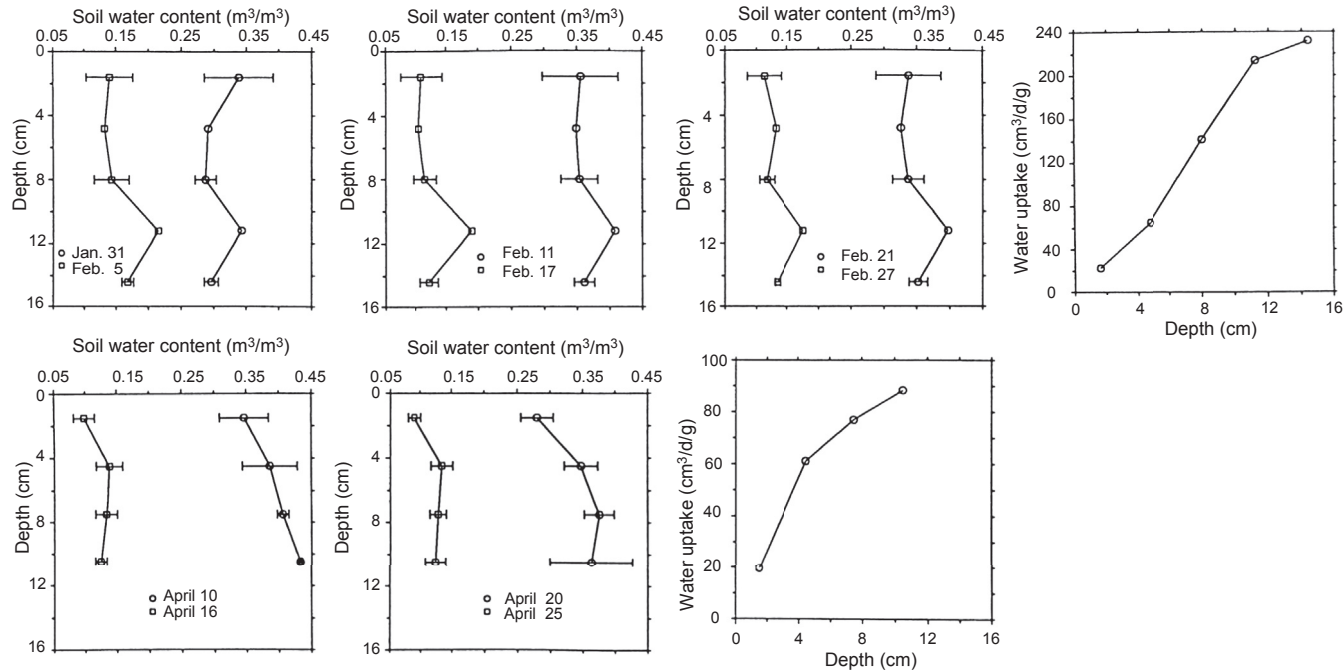


FIGURE 9.4 Top: three drying cycles during an experiment in which the water content in soil with turf grass was measured using dual-probe heat-pulse sensors. Estimate of root water uptake based on average depletion during the three drying cycles is shown at the right. Bottom: two drying cycles during an experiment in which water content in soil with turf grass was measured using dual-probe heat-pulse sensors. Estimate of root water uptake based on average depletion during the two drying cycles is shown at the right. From [Song et al. \(1999a\)](#). Reprinted by permission of M. Th. van Genuchten and L. Wu.

Temperatures were as much as 1 °C cooler near the surface than at greater depths. The smaller range in coefficients of variation for the temperature measurements (1.5%) compared to that for water measurements (10.1%) showed that measurements of soil temperature vary less than those of soil water. Moisture depletion was fairly uniform with depth (Figure 9.4). However, the root distribution was not uniform. Roots were denser near the surface of the soil than close to the bottom of the columns. To maintain a uniform depletion, the roots at the bottom of soil columns apparently were taking up more water than roots near the surface of the columns (Figure 9.4, right-hand side).

From a plant physiological point of view, a main strength of the dual-probe heat-pulse technique, as shown by Song et al. (1999a), is the ability to monitor depletion of water in a root zone on a fine scale (every 2 cm). With the neutron probe, depletion cannot be measured at intervals closer than about 15 cm apart due to the limitations of the method.

9.15 HYDRAULIC LIFT

The dual-probe heat-pulse technique was used to see if it could monitor hydraulic lift (Song et al., 2000). Roots are movers of water in the soil. One method of movement is through hydraulic lift, which occurs when plants extract water from a moist subsoil and release it into a dry topsoil. Detection of hydraulic lift has been hampered by the lack of instruments sensitive enough to measure the small amount of water moved. The dual-probe heat-pulse sensors were used to determine if water is released by hydraulic lift. Sunflower was grown in a column (38-cm height; 25-cm diameter; bulk density = 1.45 Mg/m³) packed with a Haynie very fine sandy loam with its roots divided between a top dry layer and a lower wet layer. Eight DPHP sensors installed in the soil column were used to monitor soil water content. During 24 measurement days, hydraulic lift was evident only when the plant was wilted. This occurred when the lower “wet” layer had been allowed to dry and then it was rewatered. At this time, the roots in the upper dry layer released water, increasing the soil water content in the center of the root mass by 0.019 m³/m³ (increase from 0.121 to 0.140 m³/m³). The soil water increase was similar to other values reported in the literature and shows that it is small.

9.16 COMMERCIALY AVAILABLE EQUIPMENT

To use the dual-probe heat-pulse technique, as described above in the experiments by Song et al. (1998, 1999a,b, 2000) or Campbell et al. (2002),

one needs to know how to build the dual-probe heat-pulse sensors and write the software necessary to take the measures. For people who do not have the time or skill to make the equipment, Decagon Devices (Pullman, Washington) has made an instrument, called the KD2 PRO, which comes with three different sensors. It is marketed to measure the thermal properties of liquids, solids such as rock or concrete, and soils. Thermal properties measured include the specific heat, thermal conductivity, and thermal diffusivity. One sensor, the SH-1, measures specific heat and thermal diffusivity. However, there is no reason that this sensor cannot be used to measure the soil water content using the dual-probe heat-pulse technique (G.J. Kluitenberg, personal communication, July 17, 2013). The SH-1 is 30 mm long, 1.28 mm in diameter, and has a 6-mm spacing between the two probes. It is the only sensor on the market that measures thermal diffusivity and specific heat, and which, hence, can be used to measure soil water content.

The soil water content obtained with the dual-probe heat-pulse technique (i.e., using the SH-1 sensor attached to the KD2 PRO of Decagon Devices) is much more accurate than the water content gotten with soil moisture sensors that are now on the market. Even though the soil moisture sensors are easy to use, require no special training so anyone can deploy them, need only AA batteries (batteries readily available in stores), and are cheap, they are not reliable. One does not know the exact principle of measurement. Some dielectric property of the soil is being measured. They are not capacitance probes, and they are not frequency domain probes, but something in between (G.J. Kluitenberg, personal communication, July 17, 2013). Neutron probes and true TDR (as described in Chapter 8, true TDR is TDR that is calibrated and detects the trace of the electromagnetic signal; some equipment commercially available is not true TDR) are accurate ways to measure soil water content. They are tried pieces of equipment that have stood the test of time and will be around for a long time, unlike soil moisture sensors that may be made by a company that goes out of business. When that happens, the effort that one has put into calibrating soil moisture sensors is useless. One cannot go back and repeat an experiment with equipment that is no longer available (G.J. Kluitenberg, personal communication, July 17, 2013).

The limitations in using neutron probes and TDR were cited in the first section of this chapter. The dual-probe heat-pulse technique allows one to use another method, whose principles are known, to measure soil water content. The equipment can be made in the laboratory, so researchers in the future can use it, even if commercially available equipment is no longer available. However, the dual-probe heat-pulse technique always will remain useful just for researchers, and it will never catch on as a general way to measure soil water content or thermal properties of soils. It is just too hard to use, and it takes a lot of battery power. It is difficult to

keep batteries working in the field. But it is the best piece of equipment for accuracy in measuring soil water content (G.J. Kluitenberg, personal communication, July 17, 2013).

9.17 SUMMARY

The dual-probe heat-pulse sensors, also called dual thermal probes, offer a method to monitor thermal and hydrological properties of soil near the surface and in the soil and at a fine spatial resolution. It is becoming increasingly clear that multifunctioning sensors are critical for accurate in situ soil-physical measurements because of inherent soil spatial variability (Hopmans et al., 2002). From a plant physiological point of view, the method provides unique opportunities to measure water uptake by plant roots on a small scale. However, the method will not replace other more traditional means of measuring soil water content, such as TDR, which can measure over larger soil volumes, and neutron probes which can monitor soil water at great depths (e.g., 3 m), which is necessary for deep-rooted plants, like sunflower, under dry-land conditions.

9.18 APPENDIX: BIOGRAPHY OF JOHN JAEGER

The following biographical material comes from Paterson (1982).

John Conrad Jaeger (1907–1979), coauthor of the classic book *Conduction of Heat in Solids* (Carslaw and Jaeger, 1959), was born in Sydney, Australia on July 30, 1907. Little is known about his father, Carl Jaeger. He was born in Frankfurt-am-Main, Germany, in 1869 or 1870. Carl lived in South Africa and fought in the Boer war on the British side. He married Christine Louisa Sladden, born in England, but who went to Johannesburg, South Africa, for health reasons and where her brother, who managed a gold mine, lived. Carl and Christine Louisa married in Johannesburg on November 7, 1905. They then moved to Sydney where Carl was a cigar manufacturer.

John was an only child. His mother called him Conrad, but everyone else called him John or sometimes Jack. The German pronunciation of his surname was used in his youth, but when he returned from studies at Cambridge in England, he insisted on the English pronunciation. He was a precocious child. He entered Sydney Church of England Grammar School at the young age of 13 and was dux (top pupil) of the school in 1923. In 1924, at the age of 16, he entered Sydney University, where he had a brilliant record. The degree of Bachelor of Science was conferred on him in April 1928. He received a scholarship that allowed him to travel to England at age 21 in 1928 for further mathematical studies at Cambridge

University, where he studied for two years for the mathematical tripos. (At Cambridge University, the tripos is the honors examination for the BA degree.) He completed Part II of the mathematical tripos in 1930, being listed as wrangler (Class I). (At Cambridge University, a wrangler is a person placed in the first class of the mathematical tripos.) After his tripos success, Jaeger stayed on in Cambridge to do research in theoretical physics. In 1931, he was elected to a Research Scholarship at Trinity College. He got an MA in 1934, but he never got a PhD. However, later, in December 1941, he received the DSc degree from the University of Sydney for a thesis entitled "A study of the mathematical theory of heat conduction."

In August 1935, he applied for a post as a lecturer in mathematics at the University of Tasmania. He was attracted to Tasmania, because he had had a three-day sojourn in Hobart while en route to England in 1928 and said, it was "one of the most delightful places in Australia." He started the appointment on February 15, 1936, and taught mathematics. After returning to Australia, Jaeger's links with Carslaw, although never broken during his time at Cambridge, became closer and the famous collaboration began on the mathematical theory of the conduction of heat.

Horatio Scott Carslaw (1870–1954) was a Scot by birth and was educated in Glasgow and Cambridge. He worked in Germany, at Glasgow University, and at Cambridge before being appointed to the Chair of Pure and Applied Mathematics at the University of Sydney in 1903. He held this post until his retirement in 1935. He had married in 1907, but his wife died within a year of his marriage, and he never remarried. His students became his family, and the one to benefit the most from this was John Jaeger. Jaeger visited Carslaw at Carslaw's retirement home, a country property in New South Wales, and they carried on a voluminous correspondence, most of which has been lost. From 1938 to 1941, Carslaw and Jaeger wrote a number of joint papers on the application of the Laplace transformation method, a particular operational method to problems on the conduction of heat. This work represents the beginning of Jaeger's long-continued involvement with the conduction of heat, which he inherited from Carslaw whose publications on the topic date back to 1902. Collaborative efforts tapered off with World War II and with Carslaw's failing health. The task of preparing a new book based on Carslaw's *Introduction to the Mathematical Theory of the Conduction of Heat in Solids* (published by Macmillan in London in 1921) was taken up in 1945, and Jaeger carried the main responsibility. The new *Conduction of Heat in Solids* was published by Oxford University Press in 1946.

At the beginning of World War II, Jaeger was called to the University of Sydney to work on practical projects that involved the production of charcoal and the fracture of sandstone rollers used in newsprint production. The scarcity of liquid fuels during the war years had led to the

use of gas producers on motor vehicles, which required supplies of suitable charcoal. When the Australian Newsprint Mills began operations in Tasmania in 1941, trouble was soon experienced with cracking of the grindstones used, which at that time were made of natural sandstone. Jaeger applied the theory of conduction of heat to calculate the temperature profile developed in the grindstone in operation and from this calculated the thermal stresses. Later in the war he worked at the Radiophysics Laboratory in Sydney to engage in researches connected with the generation and propagation of radio waves. Another war-time problem in which Jaeger became involved soon after his transfer to the Radiophysics Laboratory was that of determining the temperature reached in the retina of the eye when looking into the sun. This problem had arisen because eye damage was being suffered by antiaircraft gunners attempting to intercept dive bombers attacking from the direction of the sun.

After the war, Jaeger returned to the University of Tasmania and he published four books between 1946 and 1951, including the first edition of *Conduction of Heat in Solids*. Also in the postwar years, Jaeger worked on several problems, including the nature of the moon's surface. He studied the rate of cooling at the moon's surface during an eclipse and, using values for thermal conductivity of dust without air between the particles, he concluded that over most of the surface of the moon there was a layer of dust of only about 2 mm in thickness. It overlay a granular layer similar to pumice or gravel. His conclusion that the layer of dust was thin became important years later for the landing of space craft on the moon. He also studied the design requirements for electronic computers. His devices for analog computation helped stimulate developments in computers.

In 1951, Jaeger was appointed to a chair at the new Australian National University in Canberra. He was the foundation chair of geophysics, a new area of research in physics at the time. In 1963, Jaeger was appointed Dean of the Research School of Physical Sciences. At the same time, he continued as chair of the Department of Geophysics. He was dean for two years, and then remained chair of the department until 1971. In 1972, he retired from the Australian National University at the age of 65 and returned to Tasmania with his second wife, Martha Elizabeth (Patty) Clarke (born in 1901), whom he had married in Hobart on October 24, 1950. His first marriage had been in England to Sylvia Percival Rees on December 23, 1935. On the same day, they left for Australia. The marriage was not successful, and Jaeger called it "a great mistake". The marriage ended in divorce in 1950. Jaeger's first marriage had no children, and he and Patty were too old to have children when they married. Patty had joined the staff of the University of Tasmania as a typist in 1927. She helped him with his computations and typed his

books. It was on her family's property where he carried out research on charcoal during the war.

From 1965, Jaeger began to be troubled by illnesses that were affecting his mobility by 1971. He had three operations between 1971 and 1973 and suffered a heart attack during one of them. In July 1978, Patty, aged 77, had to be taken to the hospital where she died within about two weeks on July 31, 1978. This was a great blow to Jaeger. He lived on in Tasmania and was helped by visits from Patty's nieces. In late 1978, he agreed to move back to Canberra and there died on May 15, 1979, at the age of 71.

He won many awards. In 1954, he became Fellow of the Australian Academy of Science. In 1970, he was elected as Fellow of the Royal Society. He was known as a reticent and shy man. Few people were on intimate terms with him. His interests outside science included a passion for cats. There were always a large number of cats in the Jaeger household. He also had an enthusiasm for old machinery and collected steam engines and agricultural machinery.

The following information comes from a speech that Dr John Philip sent to me on May 1, 1999 (copy of speech available from M.B. Kirkham). Each year the Australian Academy of Sciences gives a Jaeger Medal. Dr Philip received it on April 29, 1999. In his acceptance speech, Dr Philip said, "An occasion such as this is as much about remembering and honouring the dead as encouraging the living. That man up on the screen is John Jaeger. I refer you all to Merv Paterson's biographical memoir of Jaeger, published by both the Royal Society and this Academy in 1982. Merv gives an excellent account of Jaeger the kindly man and pioneering scientist; but I should like to add one thing. It concerns the book 'Conduction of Heat in Solids', nominally by Carslaw and Jaeger. In reality the volume is wholly an expression of John Jaeger's manner of presenting mathematics in the most understanding and useful way possible. I'm afraid the writings of many mathematicians (though, I'm sure, of none here today) seem dedicated rather to showing how smart they are, and the hell with the reader. After Jaeger's death Oxford University Press approached me about a new edition of the book. It was no surprise to learn from them that Carslaw and Jaeger is their mathematical best seller of all time."

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