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The effects of probe misalignment on sap flux density measurements and *in situ* probe spacing correction methods

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ABSTRACT

The accurate measurement of sap flow is important for estimating transpiration. This paper is focused on the errors in sap flux density (J) caused by probe misalignment and on how to reduce these errors. We found that probe misalignment caused errors in the heat pulse velocity (V_h). Furthermore, probe misalignment had a large influence on thermal diffusivity (κ) and the determination of zero flow points. Assuming uniform axial thermal diffusivity and zero sap flow conditions, we developed a new *in situ* probe spacing correction method based on three temperature sensor measurements inside the same temperature probe, which can be used for correcting both linear and nonlinear misalignments. Laboratory experimental results verified that our method could significantly reduce the errors in determinations of J by using the Compensation Heat Pulse velocity (CHP) method, the Heat Ratio (HR) method and the T-max method.

1. Introduction

Sap flux density plays a key role in evaluating plant transpiration and understanding the soil-plant-atmosphere system. Its accurate measurement is important in hydrology, climatology, ecophysiology and forestry. Thermal methods have been widely used by many researchers to estimate sap flux density. The sap flux density measurement methods include continuous heat sap flux density methods and heat pulse sap flux density methods. The thermal dissipation (TD) method (Granier, 1985) and the heat field deformation (HFD) method (Nadezhdina, 1999; Nadezhdina et al., 2012) are some of the continuous heat sap flux density methods. The compensation heat pulse velocity (CHP) method (Swanson and Whitfield, 1981), the T-max method (Cohen et al., 1981; Kluitenberg and Ham, 2004), the HR method (Burgess et al., 2001), the calibrated average gradient (CAG) method (Testi and Villalobos, 2009) and the Sapflow+ method (Vandegehuchte and Steppe, 2012a,b) are all heat pulse sap flux density methods.

Heat pulse sap flux density methods are based on a heat conduction-convection equation and have low power requirements and simple instrumentation (Poblete-Echeverria and Ortega-Farias, 2012). In contrast, continuous heat sap flux density methods are empirically based methods. The HFD method requires empirical calibration and can cause large deviations between experimental observations and theoretical predictions (Vandegehuchte and Steppe, 2012c). Furthermore, the TD method seriously underestimates the sap flux densities (Steppe et al., 2010). In this study, we focus on the heat pulse methods instead of the continuous heat sap flux density methods.

Huber (1932) was the first researcher to use heat as a tracer to determine sap flux density. Then, Marshall (1958) developed a theoretical model of the heat pulse method by approximating a heater as an instantaneous line source. For the T-max method, Kluitenberg and Ham (2004) improved Marshall's (1958) theory by considering the finite heating duration.

In the field, the use of heat pulse sap flux density methods must contend with a major challenge: probe misalignment (Burgess et al., 2001; Liu et al., 2013). For example, Burgess et al. (2001) found that in the CHP method, a 1-mm error in probe spacing would introduce a 20% error in V_h for a −5, 0, 10 mm configuration (the heater is 5 mm and 10 mm away from the upstream and downstream probes, respectively). Therefore, precise probe spacing is important, as was emphasized by Cohen et al. (1981), Steppe et al. (2010), Swanson and Whitfield (1981) and Vandegehuchte and Steppe (2012a).

Thin and long probes are often used in heat pulse sap flux density measurements because of the following factors. First, to reduce the width of the wound (Swanson and Whitfield, 1981) and the distortion of the flow field around the probes (Warrick and Knight,

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2002), thin probes work better than sturdy probes. Second, the radius of the probes should be small enough to reduce the fraction of heat absorbed by the probe body (Kluitenberg et al., 1995). Thus, to increase the accuracy in sap flow measurements, thin probes are recommended.

When the sapwood depth is larger than 30 mm, accurately inserting the probe becomes difficult (Swanson, 1994). The growth of plant tissue around the probe may cause misalignment of probes. In addition, the heterogeneous characteristic of wood and drill torque related (Barrett et al., 1995) centering accuracy of the drilling process also contributes to the error in alignment between drilling hole and probe. Therefore, the misalignment of thin and long probes is common and unavoidable.

The following four methods have emerged to cope with probe misalignment. (1) Some researchers used a template to guide the insertion of probes into sapwood, but the accuracy of this treatment has not been tested yet, and the placement of the probes would change as the trees grow. (2) Hatton et al. (1995) used blank probes outside the cambium at a distance equal to the depth of the sensor implant to determine the precise spacing of the probes, they rejected the implanted sensors when the spacing deviated greater than 0.1 mm. (3) Burgess et al. (2001) provided a simplified mathematical correction to the HR method by assuming that only one probe was misaligned or displaced, but the correction effect was not significant. (4) Vandegehuchte and Steppe (2012a) cut the wood segment along the direction of the inserted probe to determine the exact probe spacing, however, their method was suitable for laboratory experimentation rather than field measurements. Therefore, there is no popularly accepted method for correcting probe spacing *in situ*.

Recently, based on the heat conduction equation, Liu et al. (2013) proposed a new method for *in situ* probe spacing correction in a linear misaligned dual probe heat pulse system (Campbell et al., 1991), i.e., after deploying, probe spacing can be corrected in their original positions without excavating the probes and returning them to the laboratory for calibrating. Their results indicated that this method was promising for reducing errors in the measured heat capacity (c) of soil caused by probe misalignment. However, their research was limited to the measurements of thermal properties, and they assumed that the probes were linearly misaligned (Liu et al., 2013; Wen et al., 2015), i.e., linear displacement. Based on this earlier work, a new method is introduced for *in situ* probe spacing correction in the heat pulse method, which can solve both linear misalignment and nonlinear misalignment (i.e., nonlinear displacement) problems. Numerical simulations and laboratory experiments were performed to test the new method.

2. Theoretical background and method

2.1. Heat conduction equation

In this study, we assume that all probes are misaligned in the flow direction. For an infinite and uniform medium, suppose that the heating probe can be approximated by an infinite line source (ILS), and the heat from the line source is instantaneously released, Marshall (1958) gave the following expression for temperature evolution:

$$T(x,y,t) = \frac{q}{4\pi\rho c\kappa t}\exp\left[-\frac{(x-V_h t)^2+y^2}{4\pi t}\right] \quad (1)$$

where T is temperature (K); t is the time (s); κ is the thermal diffusivity ($m^2\ s^{-1}$) of the plant tissue and sap; V_h ($m\ s^{-1}$) denotes the heat pulse velocity; q is the quantity of heat released per unit length of heater per second ($W\ m^{-1}$); x (m) and y (m) are axial and tangential distance from the heater, respectively; ρc is the volumetric heat capacity of sapwood ($J\ m^{-3}\ K^{-1}$). A full listing of symbols used in this article can be found in Table 1.

Table 1
List of symbols.

Symbol	Unit	Explanations
J	$m^3\ m^{-2}\ s^{-1}$	Sap flux density
l_i	m	Distance from the i*th* temperature sensor to the plug
q	$W\ m^{-1}$	Quantity of heat released per unit length of heater per second
r	m	Distances between the heater and the temperature probe
r_{down}	m	Distances between the heater and the downstream temperature probes
r_i	m	Corrected probe spacing
r_{i0}	m	Initial probe spacing of the i*th* temperature sensor
r_{up}	m	Distances between the heater and the upstream temperature probes
T	K	Temperature rise measured at distance (x, y) from the heater
t_c	s	Time when the thermal equilibration of the downstream and upstreamnewline probes is reached
t_m	s	Time when the temperature rise reaches a maximum
t'_m	s	Time from the onset of heating to the occurrence of t_m under zero flow conditions
t_0	s	Heating duration
V_h	$m\ s^{-1}$	Heat pulse velocity
x	m	Axial distance from the heater
y	m	Tangential distance from the heater
Δr_i	m	Displacement of the i*th* temperature sensor
ΔT_{down}	K	Temperature rise at equidistant points of downstream temperature probes
ΔT_m	K	Maximum temperature rise
ΔT_{up}	K	Temperature rise at equidistant points of upstream temperature probes
ρc	$J\ m^{-3}\ K^{-1}$	Volumetric heat capacity of sapwood
$(\rho c)_s$	$J\ m^{-3}\ K^{-1}$	Volumetric heat capacity of sap
κ	$m^2\ s^{-1}$	Thermal diffusivity
λ	$W\ m^{-1}\ K^{-1}$	Thermal conductivity
λ_{ax}	$W\ m^{-1}\ K^{-1}$	Thermal conductivity along the grain
λ_{tg}	$W\ m^{-1}\ K^{-1}$	Thermal conductivity across the grain
θ	°	Misalignment angle

If the heating duration (t_0) cannot be ignored, and the wood is not isotropic, Eq. (1) should be replaced by the following expressions (Vandegehuchte and Steppe, 2012d):

$$T(x,y,t) = \begin{cases} T_1; & 0 < t \le t_0 \\ T_2; & t > t_0 \end{cases}$$

$$T_1 = \frac{q}{4\pi\sqrt{\lambda_{ax}\lambda_{tg}}}\int_0^t s^{-1}\exp\left[\frac{\rho c}{4t}\left(\frac{(x-V_h s)^2}{\lambda_{ax}}+\frac{y^2}{\lambda_{tg}}\right)\right]ds \quad (2)$$

$$T_2 = \frac{q}{4\pi\sqrt{\lambda_{ax}\lambda_{tg}}}\int_{t-t_0}^t s^{-1}\exp\left[\frac{\rho c}{4t}\left(\frac{(x-V_h s)}{\lambda_{ax}}+\frac{y^2}{\lambda_{tg}}\right)\right]ds$$

where s is the variable of integration; λ_{ax} is the thermal conductivity along the grain ($W\ m^{-1}\ K^{-1}$); λ_{tg} is the thermal conductivity across the grain ($W\ m^{-1}\ K^{-1}$).

When V_h was zero, Bristow et al. (1994) derived the following expressions for calculating thermal conductivity λ ($W\ m^{-1}\ K^{-1}$) and ρc:

$$\rho c = \frac{q}{4\pi\kappa\Delta T_m}\left\{Ei\left[\frac{-r^2}{4\kappa(t_m-t_0)}\right]-Ei\left(\frac{-r^2}{4\kappa t_m}\right)\right\} \quad (3)$$

$$\lambda = \kappa\rho c \quad (4)$$

where ΔT_m is the maximum temperature rise (K); r is the spacing (m) between the heater and the temperature probe; t_m is the