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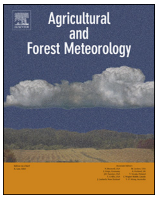

Correction of anisotropy effects on penta-needle heat-pulse probe sap-flux density and thermal property measurements

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ABSTRACT

Growing interest in methods for estimating plant stem/trunk sap-flux density and thermal properties include the use of heated needles inserted into the plant. A penta-needle heat-pulse probe (PHPP) coupled with an on-chip integrated INV-WATFLX algorithm was newly developed for inverse estimation of isotropic porous media thermal-diffusivity, κ, -conductivity, λ, and heat velocity, V_h (converted to water-flux density, J), thus heat capacity, C (=λ/κ), and water content could also be derived. This integrated sensor, however, has yet to be applied in anisotropic sapwood sensing. Here, we conducted a numerical simulation of the PHPP heat pulse and a deviation analysis when using an INV-WATFLX code developed by Yang and Jones [Comput. Geosci.—UK. 35 (2009) 2250] in anisotropic porous media. Deviations in J were up to +40% and as low as -30%, and within 12% in κ, λ and C at static conditions for varied PHPP installation angles, α, in sapwood. We developed a correction of anisotropy effects, and followed up with a field test of the sensors installed on standing poplar (*Populus simonii* Carr.) trees using $\alpha = 0°$, 15° and 30°. Field tests showed the corrected J estimated using PHPPs at $\alpha = 15°$ and 30° both agreed well with J from thermal dissipation probes (TDPs) in 1:1 line ($R^2 = 0.87$ and 0.83, $P < 0.01$). The corrected J at $\alpha = 0°$ showed an apparent 30% underestimate ($R^2 = 0.87$, $P < 0.01$), which was assumed to be due to wound effects. All PHPP estimates exhibited similar and stable κ, λ and C at night, but showed a diurnal fluctuation in J to varying extents likely due to the flow turbulence by inserted needles.

1. Introduction

Sap flow measurement facilitates a unique and practical tool for investigating whole-plant transpiration and plant-water relations (David et al., 2013). It is of growing interest in advancing techniques for accurately estimating sap flow and stem thermal properties by using the heated needles inserted into plant xylem. These techniques derive sap flow via tracing the heat transported through the mobile sap, by injecting an exogenous heat source and measuring the resulting changes in temperature field around the heater. The family of current sap flow techniques mainly comprises the continuous heating based heat balance, thermal dissipation probe (TDP) and heat field deformation methods, and a wide range of heat pulse (HP) methods. Within them, most of current HP techniques – including compensation heat pulse velocity (CHP), Tmax and heat ratio (HR) methods – quantify sap-flux density (J) by measuring the velocity of heat (V_h) introduced into sapwood; Tmax method can also resolve thermal diffusivity (κ) from the recorded travel time for the temperatures to peak, t_m, in the upright temperature needle. They originate from a widespread analytical solution of the fundamental heat convection-conduction equation on an assumption of instantaneous infinite line source of heat (IILS) in isotropic media given by Marshall (1958). In practice, however, they apply a pulsed infinite line source of heat (PILS) with heating durations up to 10 s, rather than the relatively small heating duration (0.25–1.5 s) used by Cohen et al. (1981), to relieve the possible excessive heating damage to plant at heater position. Kluitenberg and Ham (2004) had focused on such severe violations against the IILS assumption, and improved theory for calculating sap flow with PILS theory, inspired by the work of Ren et al. (2000). The improved theory can avoid underestimates in calculated κ and V_h, up to 10 and 20%, respectively, in the case of a typical probe configuration (i.e., 8-s heating duration and 0.6-cm needle spacing) by Schaeffer et al. (2000). For methods, for instance HR method, the requisite κ and sapwood water content (θ) are mostly determined from destructive wood core measurement. Wood cores are

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usually taken from tree only once and the estimated κ and θ are taken as constants in J estimation during the entire sap flow observation period. There would be a loss of accuracy from neglecting temporal variations in κ and θ, probably resulted from plant water-status and seasonal changes. Moreover, deriving κ from wood core measurement, linked to the measured wood density and θ, often misinterprets the correct κ context and neglects the anisotropic nature of sapwood properties (Vandegehuchte and Steppe, 2012a, b; Vandegehuchte and Steppe, 2012d).

Wood is clearly an anisotropic material with vascular structure, an adaption to axial water and nutrient transport in xylem (Backman and Lindberg, 2001). As early as six decades ago, Marshall (1958) had stated that wood is not isotropic, there is a distinct difference between thermal conductivity in axial direction (λ_{ax}) and in tangential direction (λ_{tg}). As stated by Vandegehuchte and Steppe (2012d), λ_{tg} are smaller, on average, 54 ± 7.5% of λ_{ax} cross all dry wood densities and water contents, by applying the equations as mentioned in Swanson (1983). As in literatures where HR methods are applied, the equations of Swanson (1983) have also been widely used to derive thermal diffusivity ($\kappa = \lambda/C$), however, only in axial direction is taken into account. Similarly, Tmax method can estimate κ as aforesaid directly in axial direction, and it is also adopted in the external heat ratio method (Clearwater et al., 2009) for thin stems, pedicels and petioles. Nevertheless, these HP techniques are still based on the key equations of heat conduction-convection in isotropic media.

Only recently were concerns with respect to the application of the isotropic equation for heat transport in anisotropic media raised (Vandegehuchte and Steppe, 2012c, d). Vandegehuchte and Steppe (2012d) proposed an analytical solution of heat conduction-convection equation with IILS considering anisotropy. They numerically simulated the heat transport in the anisotropic sapwood, and confirmed the temperature field around the heater are clearly different due to the difference in axial- and tangential thermal diffusivity (i.e., κ_{ax} and κ_{tg}, respectively), with the isotropic κ taken as the geometric mean of κ_{ax} and κ_{tg}. Such difference in temperature field leads to a difference in t_m for the Tmax method, and clearly influences the ratio of temperature changes for the HR method. Vandegehuchte and Steppe (2012d) further stated that, if the anisotropic κ_{ax} is coupled to temperatures simulated by the isotropic equation, or if the otherwise κ is considered isotropic and the anisotropic equation is applied, erroneous results will emerge in determining J for both Tmax and HR methods. Vandegehuchte and Steppe (2012d) deduced that, existing HP methods based on the inaccurate, isotropic equation – for instance, Tmax and HR methods – remain valid as if the correct anisotropic theory is applied. However, for numerical simulations or the use of inverse optimization techniques, etc., where anisotropic effect can't be canceled out, a solid basis of anisotropic equation must be required.

Vandegehuchte and Steppe (2012c) updated the analytical solution of heat transport equation considering both the finite heating duration and anisotropy, by combining the work of Kluitenberg and Ham (2004) and Vandegehuchte and Steppe (2012d). This theoretical updates directly led to the development of a novel "sapflow+" technique using a four-needle heat pulse sensor, enabling non-empirical J and θ determinations. Yang and Jones (2009) and Yang et al. (2013) developed an inverse method for simultaneous determination of porous media κ, λ and V_h using a penta-needle heat-pulse probe (PHPP) with an INV-WATFLX code based on two-dimensional heat conduction-convection equation in isotropic media by Ren et al. (2000). Sheng et al. (2016) provided a technical instruction to this PHPP and coupled it with an electromagnetic sensor for porous media multi-functional sensing. This smart probe communicates with an SDI-12 interface and performs on-board parameter optimization (Sheng et al., 2016), which is more user-friendly and suitable for general scientific use without expertise in HP measurement techniques. The extension of these smart sensors to include sensing in anisotropic porous media, for instance sapwood, should be of great interest, once the anisotropic effect is carefully considered.

The objectives of this study were to numerically and physically evaluate the impact of anisotropy and PHPP installation angle when determining sapwood sap-flux density and thermal properties. Numerical simulations of heat-pulse measurements using prescribed thermal properties and heat velocities under anisotropic conditions were employed. Numerically derived data were set as input conditions in INV-WATFLX code to retrieve the estimated parameters to match PHPP performance in an anisotropic medium. Field tests were also conducted using six PHPPs on poplar trees with α = 0°, 15° and 30° installation angles.

2. Materials and methods

2.1. Theoretical considerations

Two-dimensional heat conduction-convection (assuming conductive heat dominates over convective effects) for uniform transport of water in an incompressible isotropic porous medium can be expressed as

$$\frac{\partial T}{\partial t} = \kappa(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) - V_x\frac{\partial T}{\partial x} - V_y\frac{\partial T}{\partial y} \tag{1}$$

where T is temperature (°C), t is time (s), κ is thermal diffusivity ($m^2 s^{-1}$), x and y are spatial coordinates in a plane normal to the needles (m) as shown in Fig. 1, V_x and V_y are components of heat velocity V_h ($m\,s^{-1}$), in the respective coordinates. An analytical solution to a PILS injected into an infinite and isotropic medium is given by Ren et al. (2000) and Yang et al. (2013):

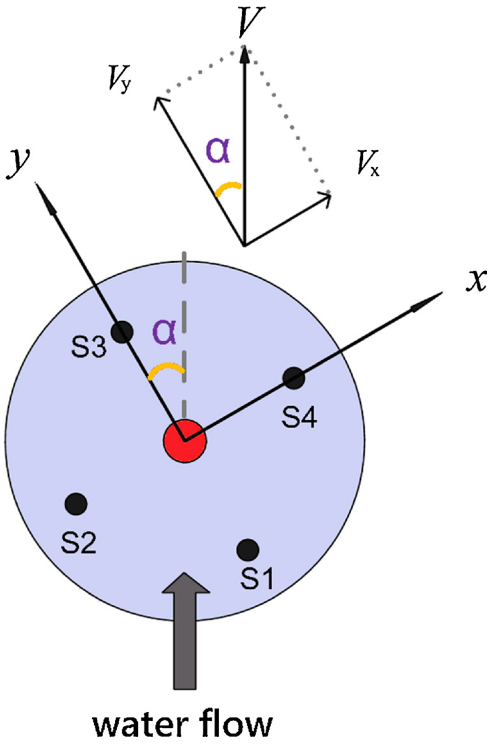

Fig. 1. Schematic illustration of the locations of the heater needle (red) and four thermistor needles (S1–S4) of the penta-needle heat-pulse probe (PHPP) in a coordinate system within a plane normal to the probe axis. Symbols V_x and V_y are the two components of the heat velocity (V_h, $m\,s^{-1}$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)