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Water content measurement in tree wood using a continuous linear heating technique

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A B S T R A C T

This paper deals with the analytical and experimental analysis of heat transfer in the xylem of trees and the determination of stem water content (WC). The aim of this paper was to derive and verify a new approach to WC calculation from measured temperature differences around a continuously heated needle.

The configuration of heater and thermocouples of the heat field deformation (HFD) method for sap flow measurements was taken for this purpose. The suggested formula is derived from the heat conduction equation with a continuous linear source of heating. The ability of the HFD method to non-destructively determine the radial distribution of the local conditions of sap flow measurements under zero flow (referred to as K-value) was used to derive the radial distribution of WC.

Examples of the application of our method on several contrasting species with different plant hydraulic architecture are given where calculated WC along stem xylem radius was compared with its direct gravimetrical measurements or with relative determination of wetness of cross-sectional stem discs using a modified differential translucence method.

The proposed method enables water content measurements during continuous linear heating and is important for information about WC and sap flow together per day or season when there is possible to extrapolate the temperature difference for zero flow condition.

1. Introduction

Internally stored water in tree stems contributes to daily transpiration even in well-watered trees, indicating that stored water plays an important role not only during periods of drought, but whenever water transport occurs within the tree [28]. Water stored within the woody tissues of trees has been viewed as a reservoir from which water can be withdrawn to buffer the evaporative demands of a transpiring plant canopy [19,25,27,7].

Attempts to better visualize the spatial distribution of water in woody tissues have led to the promising use of gamma-ray attenuation [8], nuclear magnetic resonance [4], and computer tomography [18], and to the application of methods such as stem capacitance [9,10], electrical resistance [1,2], and time-domain reflectometry [5,10] for the study of relative changes in stem water content [27]. However, absolute values of water content are still a “hot topic” in tree water relations research after almost 20 years have passed since Holbrook [9] pointed out that attention must be directed toward improved methods for *in situ* monitoring of stem water content in order to better quantify the contribution of stem water storage to the whole-plant water balance.

WC is also an important parameter for sap flow methodology. All thermodynamics methods based on application of heat pulses require determination of WC in sapwood for sap flux density calculations from measured heat pulse velocity. Schenk et al. [20] strongly underlined the importance of seasonal changes of active conducting sapwood area and wood water content on sap flow estimation. When a tree is drying, its sapwood area may become narrower [6,21] and this may negatively influence the results of flow up-scaling according to the sapwood area unless its real changes are taken into account. Usually sapwood area and WC are determined destructively by an increment borer just before or after sap flow measurements. In most of the cases, the WC is determined only once and without taking into account the spatial and seasonal variability of sapwood parameters.

Active water-conducting area [21] and its changes over time [3] are well determined in real time by multi-point sap flow

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measurements using the HFD method. The effect of possible changes in WC on sap flow measurements using the HFD method is objectively corrected by changes of the K-value in each point of measurements along stem xylem radius. The K-value represents the temperature differences around a linear heater under zero flow. Hence, the K-value reflects a condition of zero flow without the need to provide destructive treatment as it is required for many sap flow methods. All the above mentioned including the consideration of real anisotropy of sapwood has been first considered in the HFD using a side probesLater this HFD configuration was used by Vandegehuchte and Steppe [26] for a method referred to as Sapflow+ which was reported to enable regular updates of water content values for more accurate calculation of sap flux densities without application of destructive gravimetrical measurements of WC. Until now thermodynamic approaches were used for *in-situ* water content measurement based on heat pulses [11,26]. However, there were no examples of practical use of WC monitoring by Sapflow+ presented in Ref. [26]. López-Bernal et al. [11] underlined that the ability of the volumetric specific heat–compensated heat pulse (VSH–CHP) methodology to provide actual values of WC is uncertain at the present stage of understanding. Thermodynamic approaches to water content measurement need more research.

This work introduces a new approach to measurement of water content in sapwood using continuous linear heating. Whenever sap flow radial profiles were measured by the HFD method, the K-value for each measuring point along the needle was also evaluated as it is the input parameter in formula for sap flow calculation. It was assumed that the K-value can be used for the calculation of water content under zero flow conditions based on continuous sap flow measurements using the HFD method. As the K-value is an important attribute for sap flow calculation in the HFD methodology and should be determined for each measuring point along the xylem radius, the possibility to determine the radial variability of WC is presented. By application of more multi-point sensors around the tree stem for long-term measurements, spatial and seasonal WC monitoring has become also possible. To demonstrate this, in addition to the main aim of WC calculation, we investigated spatial (radial and circumferential) and seasonal variability of WC in tree stems of several species with different wood anatomy.

2. Material and methods

2.1. Theoretical analysis

2.1.1. Analytical solution of thermal conductivity

According to the generally known partial differential equation (Eqn. (1)) describing the temperature field solely for heat conduction (not for convection because we can assume the sap flow is zero), the analytical analysis of continuous linear heating can be performed. The zero sap flow condition is recorded during HFD measurement and can be determined although the current sap flow is not zero (it is the advantage of the HFD method).

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot \boldsymbol{\lambda} \nabla T = q, \tag{1}$$

where T is temperature (K), $\boldsymbol{\lambda}$ is matrix of thermal conductivity coefficients of fresh sapwood (W m^{-1} K^{-1}), ρ is density of fresh sapwood (kg m^{-3}), c is specific heat of fresh sapwood (J kg^{-1} K^{-1}), q is heat power (W m^{-3}), t is time and ∇ denotes the vector differential operator $\nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z)$.

Because we assume the steady state condition (the derivative of a temperature with respect to time is equal to zero) and only 2D heat transfer in plane xy, thus the equation (Eqn. (1)) is simplified into equation (Eqn. (2)):

$$-\lambda_T \frac{\partial^2 T}{\partial x^2} - \lambda_L \frac{\partial^2 T}{\partial y^2} = q, \tag{2}$$

where λ_T and λ_L are the thermal conductivities of wood in the tangential and axial directions respectively.

The analytical solution of the equation (Eqn. (2)) for a continuous line-source of heat H (W m^{-1}) along the length of heated needle is based on Green's function theory [17] and is the following:

$$\mathrm{d}T = T(\mathrm{d}x_1, \mathrm{d}y_1) - T(\mathrm{d}x_2, \mathrm{d}y_2) = \frac{H}{2\pi\sqrt{\lambda_L \lambda_T}} ln \sqrt{\frac{\lambda_L \mathrm{d}x_2^2 + \lambda_T \mathrm{d}y_2^2}{\lambda_L \mathrm{d}x_1^2 + \lambda_T \mathrm{d}y_1^2}} \tag{3}$$

where $T(x, y)$ is temperature (K) at point $[x, y]$ (origin [0, 0] of coordinate system is in place of heating), and H is heat power per unit length along the line (W m^{-1}).

After modifications we can use the derived analytical equation (Eqn. (3)) in this way:

$$(\mathrm{d}T_{\mathrm{above}})_0 = (T_{\mathrm{above}} - T_{\mathrm{side}})_0 = \frac{H}{2\pi\sqrt{\lambda_L \lambda_T}} ln \left(\frac{\mathrm{d}x}{\mathrm{d}y} \sqrt{\frac{\lambda_L}{\lambda_T}} \right), \tag{4}$$

where dx is horizontal distance of side thermocouples from heater (m) and dy is vertical distance of above thermocouples from heater (m). Note: $(\mathrm{d}T_{\mathrm{above}})_0 = (T_{\mathrm{above}} - T_{\mathrm{side}})_0 = -(T_{\mathrm{side}} - T_{\mathrm{below}})_0 = -(\mathrm{d}T_{\mathrm{below}})_0 = -\mathrm{K}$ is the temperature difference under zero sap flow condition that is recorded (extrapolated) during HFD measurement (see Introduction and Fig. 1).

Both thermal conductivities λ_T and λ_L are functions of water content WC and it is proved that $\lambda_L = k\lambda_T$, where often and also here we assume $k = 2$ [13] and thus we can use the following formula for calculating λ_T:

$$\lambda_T = \frac{H}{2\pi(\mathrm{d}T_{\mathrm{above}})_0\sqrt{k}} ln \frac{\sqrt{k}\mathrm{d}x}{\mathrm{d}y}. \tag{5}$$

You can see the dependence of thermal conductivity on the temperature difference in an additional figure (Fig. 7).

Therefore the calculated thermal conductivity λ_T can be used to derive the water content WC through the physical quantity called moisture M in wood ($\lambda_T \rightarrow M \rightarrow$ WC), using the following relations:

2.1.2. Derivation of water content from thermal conductivity

Some important physical quantities describing material properties of wood are described below. Moisture M (mass definition) [23] and water content (volume definition) WC are defined as [22]:

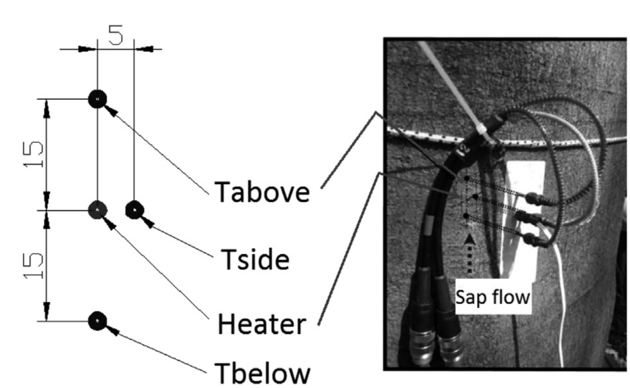

Fig. 1. Scheme of sensor (HFD configuration).