International Journal of Thermal Sciences 76 (2014) 200–207

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

# Nonlinear finite element analysis of thermal inertia in heat-balance sap flow measurement

M. Trcala [a,*], J. Čermák [b]

[a] Department of Wood Science, Mendel University in Brno, Brno, Czech Republic
[b] Department of Forest Botany, Dendrology and Geobiocenology, Mendel University in Brno, Brno, Czech Republic

A R T I C L E  I N F O

*Article history:*
Received 5 April 2013
Received in revised form
5 September 2013
Accepted 24 September 2013
Available online 26 October 2013

*Keywords:*
Sap flow measurement
Trunk heat balance method
Thermal inertia
Nonstationary and nonlinear heat transfer model
Finite element analysis

A B S T R A C T

This paper deals with the numerical solution of a three-dimensional model of nonstationary nonlinear heat transfer in the sapwood of trees during sap flow measurement by a thermodynamic method based on volumetric heating of a stem segment (Trunk Heat Balance – THB – method). The model respects the dependence of physical properties on temperature and moisture and also the anisotropic nature of wood. The corresponding partial differential equation is then solved by finite element method.

The main aim of this study was to analyze the thermal inertia of the THB method with horizontal references thermocouples. We compared the results of the simpler stationary and the more complex nonstationary model and we can conclude that the thermal inertia of the THB method is not negligible (mainly for smaller flows around 0.01 kg m$^{-2}$ s$^{-1}$). In addition, the authors have shown that the influence of moisture on the recorded sap flow data $Q_{rec}$ is negligible but there is small influence on $Q_{fic}$ and hence on the resulting sap flow measurement as was shown in their previous work. We also tested two new variants of temperature sensors arrangement and proved that the difference between them is very small and can be ignored.

## 1. Introduction

The water flow represents the biggest energy flow in vegetation which also causes its magnificent climatic effect. Plants can only survive when their exposed parts (needed to absorb the radiant energy and $CO_2$) are effectively conditioned, i.e. cooled. From all the water taken up by plants, the majority is transpired, leading to leaf cooling (associated with the heat of vaporization) and only minor amounts of water is consumed to all the other processes (such as photosynthesis transport of assimilates, growth, etc.). The transpiration can be estimated through measurement of sap flow rates in a tree stem. We do not need any additional constructions (towers, greenhouses), the measurement can be done automatically, practically in all tree species and under any terrain and environmental conditions. The sap flow measurement equipment is quite small and can be easily moved from one site to another [3,9].

Sap flow is a very convenient variable especially because of the possibility of long-term automatic and direct measurement of water movement through plants. When water is absorbed by fine roots, it is transported through xylem to the foliage. Therefore, the measurement of water flow provides data for an entire tree analysis. A series of measurement methods were developed for this purpose. The main methods developed for sap flow measurement (presented in chronological order) are: (1) heat pulse velocity [2,4,5,14–17,24,25,36,42]; (2) trunk segment heat balance [7,6]; (3) stem heat balance [30,31,1]; (4) heat dissipation [13] and (5) heat field deformation [26,27,43].

In this work we deal with the trunk heat balance (THB) method that has been successfully applied for many years in different field conditions and tree species [6–9,20,21], being theoretically analyzed later [37,38]. The THB method was designed especially for large trees with the stem diameter over 15 cm and found quantitative when compared with other methods, such as gravimetric [29], gas-exchange [33], volumetric and other techniques [3,10,11,19]. It has also been applied as a standard for testing other methods [28,32,22].

Thermal inertia of the THB method has never been analyzed despite the fact that the heated volume is not small and thus there is a real danger that the thermal inertia is not negligible. Thermal inertia can play an important role in this case, where nonstationary effects can be significant in mathematical model, and a stationary calculation can yield inaccurate results. For this reason, we

---

[*] Corresponding author.
*E-mail addresses:* miroslavtrcala@seznam.cz (M. Trcala), cermak@mendelu.cz (J. Čermák).

1290-0729/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ijthermalsci.2013.09.007

performed numerical solution of nonstationary nonlinear conduction–convection heat transfer model and compared results of the stationary and the nonstationary models to analyze the thermal inertia of the THB method. We also compared two new variants of the method and assessed the influence of the moisture on the results.

### 1.1. *Theory of THB method*

The original THB method is characterized by direct internal electric heating and internal sensing of the generated temperature field. Heat is released uniformly within the bulk xylem tissue between electrodes situated at 2 cm distances. Measured stem segments are 8 cm wide (when using 5 electrodes) or 4 cm (when using 3 electrodes). Heat does not escape much through the thick (insulating) bark neither does it enter the heartwood much, provided that it is dry enough (although e.g. wet rotten heartwood causes problems). Both, power ($P$ – which is directly proportional to sap flow) or temperature difference ($dT$ – indirectly proportional) can be held constant by electronic circuits, while the other variable is recorded. The electrodes, i.e. stainless steel plates (usually 2.5-cm wide and 0.1-cm thick) are hammered in at short distances (2 cm) into approximately the depth of sapwood (therefore, they are of different length). They are inserted in parallel into the sapwood keeping the central electrode in the radial direction relative to the tree trunk. The power usually 0.6 or 1 W (of 3 or 5 electrodes) is applied by l kHz alternating current. The temperature difference $dT$ between the upper heated plates and the reference plates about 10 cm below (around 5 K for constant $P$ and around 2 K for constant $dT$) is measured by a battery of 0.1 cm thin needle thermo-sensors (usually thermocouples Cu–Cst). By this method the heat balance of a defined heated space is calculated. Basically, the input energy has to be split between the conductive heat losses and the warming of water passing through, according to the following simplified equation [12]

$$P = QdTc_\mathrm{w} + \mathrm{d}T\lambda, \tag{1}$$

where $dT$ is temperature difference (K) between heated and non-heated measuring points, $Q$ is sap flow through the measured part of xylem (kg s$^{-1}$), $\lambda$ is a coefficient of heat conduction from measured plant part to its environment (W K$^{-1}$), $c_\mathrm{w}$ is specific heat of water (J kg$^{-1}$ K$^{-1}$), $P$ is the heat input into the measured part of xylem (W).

From this, we can derive the basic relation for the calculation of the sap flow rate through the measured part of the xylem

$$Q = \frac{P}{\mathrm{d}Tc_\mathrm{w}} - \frac{\lambda}{c_\mathrm{w}}. \tag{2}$$

The heat loss magnitude ($\lambda$) is not clearly specified but is included in the "fictitious flow" $Q_\mathrm{fic}$, which is recorded when the actual flow is zero. Based on Eq. (2), we can write

$$Q = Q_\mathrm{rec} - Q_\mathrm{fic}, \text{ which means that } Q_\mathrm{fic} = Q_\mathrm{rec} \text{ when } Q = 0, \tag{3}$$

where $Q_\mathrm{rec} = P/\mathrm{d}Tc_\mathrm{w}, \quad Q_\mathrm{fic} = \lambda/c_\mathrm{w}$.

The new version of the THB method [38] has a horizontal arrangement (Fig. 1) of temperature sensors to be able to measure

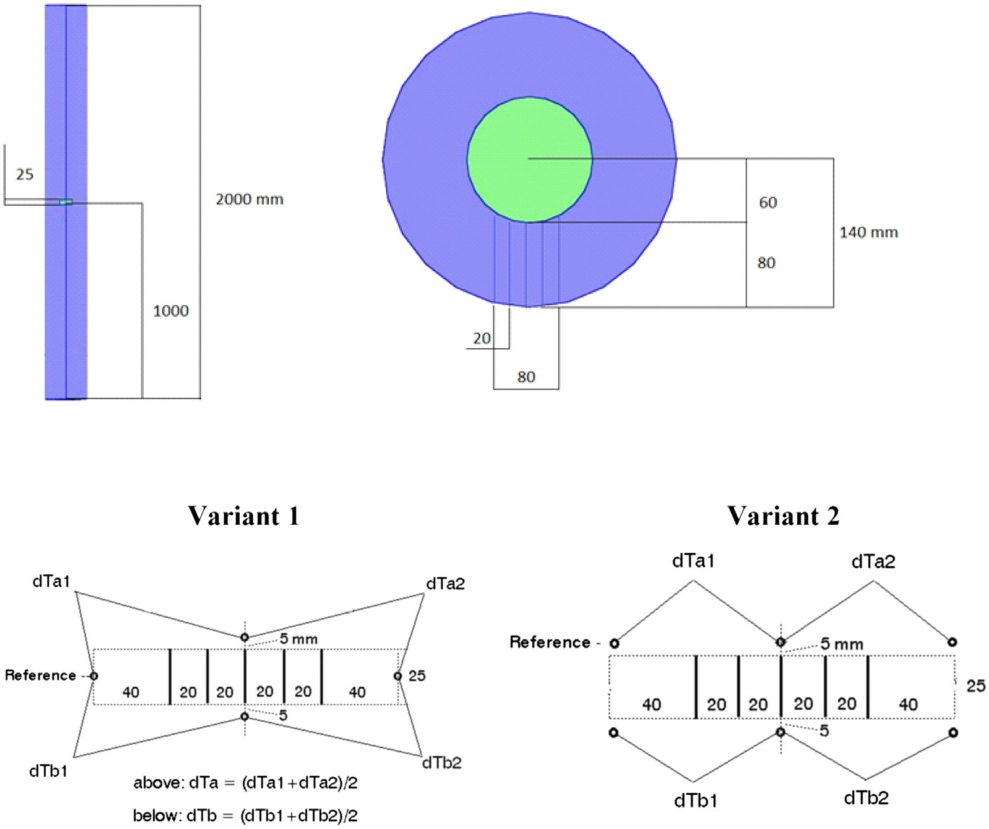

**Fig. 1.** Geometry of the tree used in numerical simulations (upper panel) and scheme of the measuring points (lower panel). Upper panel: tree stem part used to analyze the THB method by numerical simulations (frontal view on the left side, cross section on the right side). Lower panel: variant 1 and variant 2 of horizontal geometry of the trunk heat balance (THB) sensor. Electrodes are marked by thick vertical lines, the position of thermocouples is marked by large dots. Distances between electrodes and thermocouples are given in mm. The sensors are symmetrical in respect to the central vertical axis and the references are shown here on the left for the 5 electrodes system.