History of the Development of the Trunk Heat Balance Method in Last Forty Years

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Abstract

The aim of this contribution is to describe the step-wise improvement of the trunk heat balance method (THB) from the first idea to the actual sophisticated instrumentation. Both technical and theoretical aspects of the development of the method are considered. The original idea of heating trunk tissues with an electrical current passing between inserted plate electrodes has been accepted as an optimal arrangement despite the misleading original idea of energy distribution. The first important improvement eliminated the significant influence of highly electrically conductive phloem on the accuracy of the measurement in trunks with thick phloem tissues. Following fundamental physical analysis of both power field and heat field showed false conception of the homogeneous energy distribution between two parallel plate electrodes in an electrically conductive environment. Besides, the physical analysis confirmed the presumption that the stability of the flow measurement based on heat balance increases with the size of heated volume. The actual measuring layout uses three stainless plates for direct heating of plant tissues and the needle temperature sensors are inserted in slots of those plates. This way uses the averaging effect of metal plates and reduces an error caused by a radial temperature gradient that makes a lot of troubles especially by point-shaped temperature sensors. The electronics maintains stable temperature difference between heated and non-heated parts of the measuring points. This arrangement substantially improves the response of the measuring system to fast sap flow changes and last but not least greatly reduces the power consumption.

INTRODUCTION

Heat balance method was probably one of the first attempts of the measurement of stem water flow (Daum, 1967) in terms of volumetric amount. One of the first modifications giving the results directly in kilograms of water per hour is the tissue heat balance method developed by Jan Čermák in early seventies of the last century (Čermák et al., 1973) and theoretically explained by Kučera et al. (1977). The revolutionary idea of this method consisted in the direct heating of the xylem by electric current. As it was confirmed many years later (Tatarinov et al., 2005), this point was highly important with respect to the accuracy and reliability of results. The Trunk Heat Balance (THB) method is somewhat sophisticated, installation of the measuring point needs some skills (see Cienciala et al., 1999, for practical recommendations on installation) and it has some limits of use but because the linearity between the sensor output and real water flow and only negligible dependence of the result on radial water velocity the method has still some hard-core users.

PREHISTORY

The first modification of the THB method used five stainless electrodes providing the contact of conductive xylem tissues, mostly sapwood, with a power unit generating alternating heating current. The use of alternating current brings a lot of difficulties concerning the electronics but it must be used in order to avoid polarization of the electrodes. The authors of that arrangement supposed more-less regular power density distribution in the space between neighboring electrodes. Five electrodes defined a heated block eight centimeters wide along the trunk circumference that was artificially heated with a controlled power. A part of heated power was drained by the running water. The rest of heat dissipates as a heat loss.

The temperature inside the heated space was measured in two different depths by two needle shaped temperature sensors. The calculation of the volumetric water flow was based on a simple heat balance equation describing the relation between the temperature, the input power and the water flow:

$$P = Q.dT.c_w + dT.\lambda \quad [W; kg^{-1}, K, J.kg^{-1\ -1}, K, W\ s^{-1}] \tag{1}$$

where
P - input power [W]
Q - sap flow [kg s^{-1}]
dT - temperature difference between heated space and the surrounding xylem tissue [K]
c_w - specific heat of water [J kg^{-1} s^{-1}]
λ - heat loss from the measuring point [W]

After rearranging the formula (1) the total amount of water passing through each centimeter of eight centimeters wide heated segment (see Tatarinov et al., 2005, for theoretical development of the effective width of measured segment - d) can be calculated as follows

$$Q = \frac{P}{c_W * dT * d} - \frac{\lambda}{c_W} \quad [kg\ s^{-1}\ cm^{-1}] \tag{2}$$

It should be emphasized that the result is (theoretically) independent of the sap flow depth and there is no empirical coefficient involved in the calculation. The λ represents heat losses from the heated part of the measuring point. Those heat loses are estimated as the heat losses at the period when there is certainly no sap flow through the stems (i.e. during rainy periods or during the night with longer duration of zero vapor pressure deficit). This heat loss is usually constant in the longer time period (i.e. several weeks). Even the positive night flows can be estimated this way. A schematic of the original instrumentation is shown in Figure 1.

Since the heating power has to be kept on the constant level, it was manually adjusted when the xylem electrical conductivity had changed. Two temperature sensors measuring the temperature inside the heated space was completed with additional two lateral sensors connected up-side-down in order to compensate for natural (vertical) temperature gradients along the trunk axis. The output from the temperature sensor was recorded by a highly sensitive (and capricious) chart recorder. It follows from Eqn (2) that one records smaller temperature differences at higher flow rates, all other factors being equal.

HISTORICAL INSTRUMENTATION

The first “fully grown” equipment was finished in 1976. It operated with variable heating power maintaining a constant temperature difference (dT = 1K) between the heated space and the surrounding xylem. The system also calculated the xylem resistance, which mostly depends on a xylem water content and sap ion concentration. The output was recorded with a line recorder. Figure 3 shows a facsimile of an original record displaying a fast response to a rainy event. However, for technical and mainly economical reasons, following four-channel systems manufactured since 1978 were based on a measurement with constant heating power (Fig. 4). These systems worked up to the end of the 1980s when the political revolution turned us to the normal world. Electronic compounds normally used in the western countries became available in the

Czechoslovakia after 1989 and enabled construction of more sophisticated instruments.

THE NEW DEAL

A new battery operated system was developed in 1990. The system, using twelve channels and constant power modification, was housed in an extremely sturdy aluminum alloy enclosure with a built-in datalogger and PC software involving graphically-supported subtraction of heat loses from the measuring points. The overall design was clumsy but acceptable for any field measurement (Fig. 5). Later, in 1998, the systems finally got an up-to-date outfit (Fig. 6).

METHODICAL IMPROVEMENTS

Once the instrumentation was developed for routine measurement, there came a good time for a thorough investigation of the methodological background that had remained largely unchanged since 1973. Strange and unstable results of our sap flow measurement in big trees on the west coast of USA in 1996 had made us recognize the importance of phloem tissue that was quite thick in these large coniferous trees (three meters of circumference). We found the electric conductivity of phloem was three to five times higher than the xylem conductivity. Therefore, since the electrodes touch the phloem over a relatively large fraction of their surface area, most of the electric current actually passes through phloem tissue so that the water-conductive xylem was heated more or less indirectly from the outside. Consequently, the actual sap flow was strongly overestimated.

Another issue with the original THB method involved measurement of the temperature representing somehow the average temperature within the heated space. There were some persisting doubts since in some cases a small change in the depth of the temperature sensor resulted in large difference in measured value of the sap flow rate. It was clear that the THB method required a more thorough understanding of the heat field distribution and its dependence on other factors such as the radial water conductive profile, water content, sap flow rate etc. Also, from the point of view of a sense of the next system development, a thorough analysis seemed to be a crucial issue.

Such an analysis was performed in first years of this millennium and published in a journal of physics in 2005 (Tatarinov et al., 2005). This analysis was not directly concentrated on a special arrangement of THB method. We were looking for an optimal way of applying the heat and for the assumption of a representative measurement of temperature within the heated space. The most important result from that theoretical work was a fact, that the accuracy, reliability and stability of the sap flow measurement are directly proportional to the heated volume. This result encouraged us to continue our analysis of the existing arrangement with direct volumetric heating. Our theoretical calculations showed that the heating-power field between the neighboring electrodes is not homogeneous. Rather, it is concentrated around the electrodes.

Fortunately, the heat conductivity of xylem contributed to rather homogeneous temperature field along the trunk circumference. However, under higher sap flow rates (>ca 0.15 kg/hr per 1 cm of stem circumference) a significant drop in temperature occurred just in the position where both temperature sensors were located, and this drop consequently led to the overestimation of measured flow rates. Following all those findings, a totally new arrangement of THB method with direct heating of xylem tissues was designed. The original idea with heating via plate electrodes remained but the sensor design was totally changed. The number of electrodes was reduced to three and each electrode was covered with an insulating foil in that part of the probe that was in direct contact with the phloem and the living bark layer. Furthermore, the needle temperature sensors were inserted into slots in the electrode in such a way that the sensing element is placed in center of that part of the electrode bellow the cambium. A drawing of the actual arrangement of the measuring points is shown Figure 7. In addition, we added a fourth (lower) electrode that is used just for the thermal symmetry of the temperature difference measurement.

ACTUAL INSTRUMENTATION

With respect to the theoretical analysis mentioned above, and following more than forty years of experience with the THB approach, it was decided to design a completely new electronics system to drive the sap flow measurements. Amongst other factors, the new systems had to be

- flexible in terms of number of measuring channels
- compatible with any data logging system
- extremely power efficient
- compatible with all electromagnetic compatibility rules (EMC)
- operate with variable power under constant temperature difference which could be set to more levels.

The last factor was important not only because of good dynamics and accuracy but also from the point of view of powering the system. With such an arrangement, the energy consumption principally follows the sap flow rate, and this is under common conditions proportional to incoming solar radiation. Thus, the new design fits nicely with solar powering and basically saves the battery energy during rainy (cloudy) periods of both low sap flow and low battery recharge. EMC compatibility also required the electronic units to be located close to the measuring point because of the relatively high-frequency alternating current used for xylem heating. The overall look of the actual system is shown on pictures Figures 8, 9, 10 and 11.

CONCLUSIONS

The actual arrangement and instrumentation of THB method is sophisticated, needs some operator skills and experience and takes a time for installation (ca 20 minutes). In return it gives the values independent on the radial sap velocity profile and it is not based on empirical coefficients. Last but not least, even the usually hyper-critical authors of this contribution have finally started to trust the measured values.

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Figures

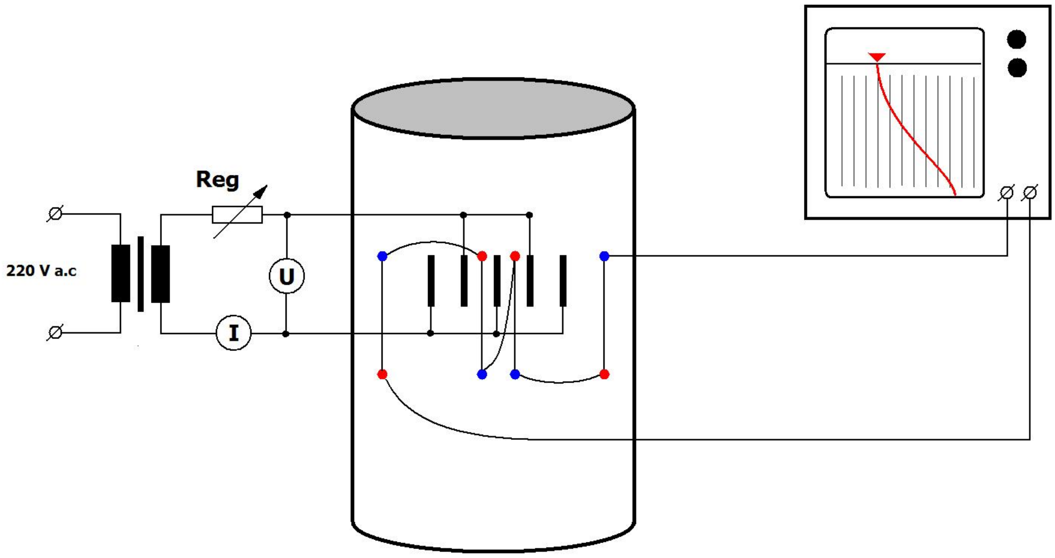

Fig. 1. Original instrumentation – 1973 consisted from the transformer and manually adjusted voltage regulator (left hand side of the picture), five-electrode measuring point (centre) with thermocouple arrangement automatically compensating for the natural temperature gradients and one-channel recorder (right).

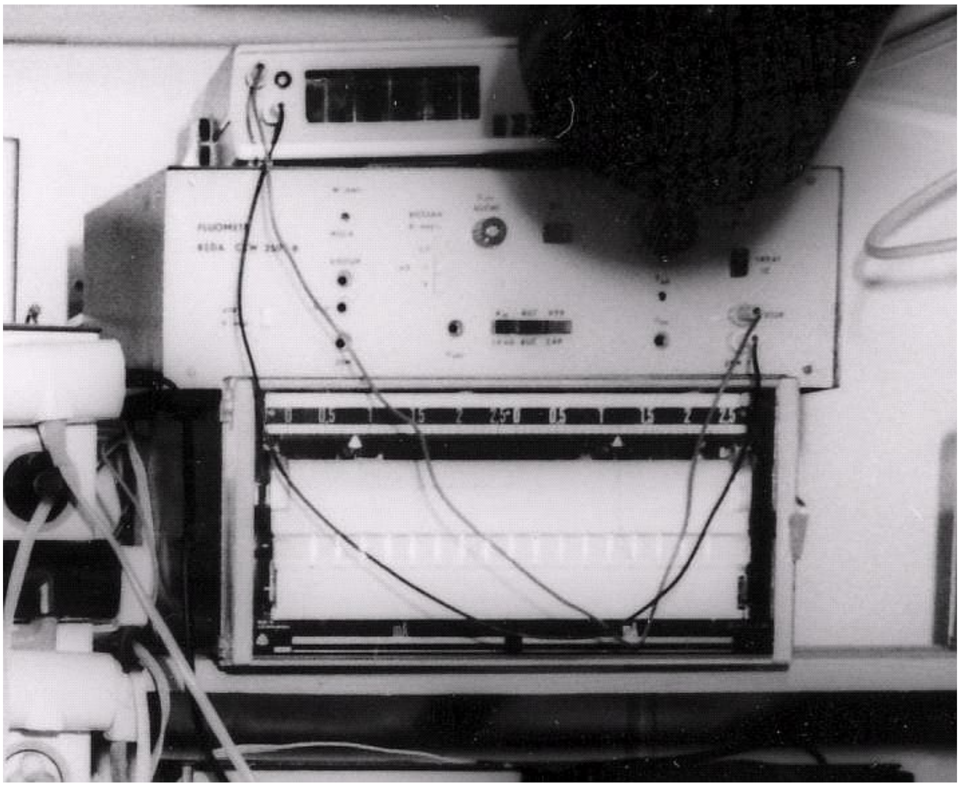

Fig. 2. Single-channel THB sap flow system with variable power and producing a constant temperature difference (dT=1K).

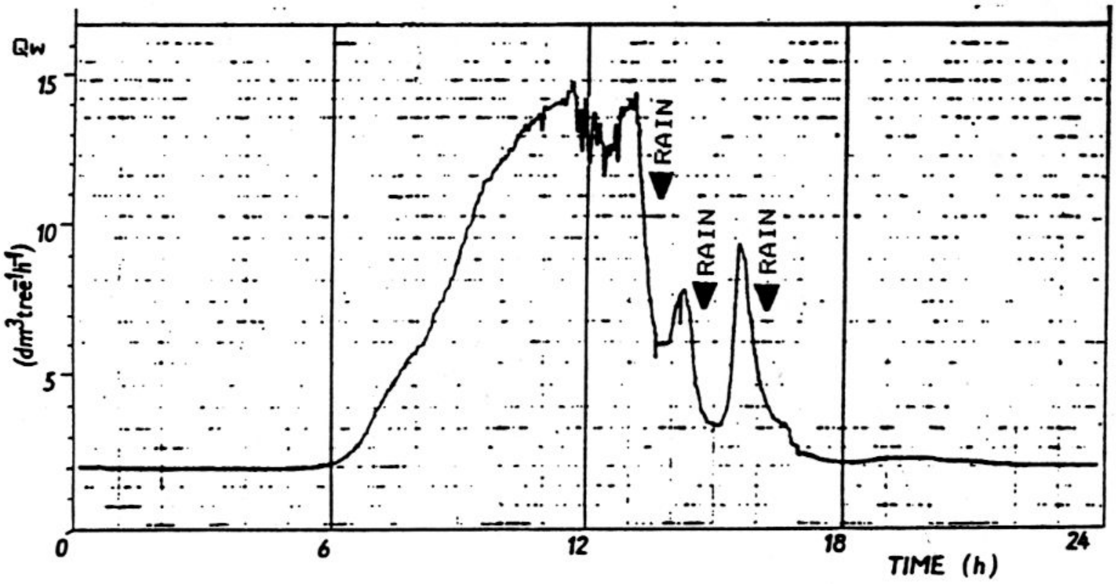

Fig. 3. A one-day record of sap flow rate measured with the system maintaining a constant temperature difference, dT.

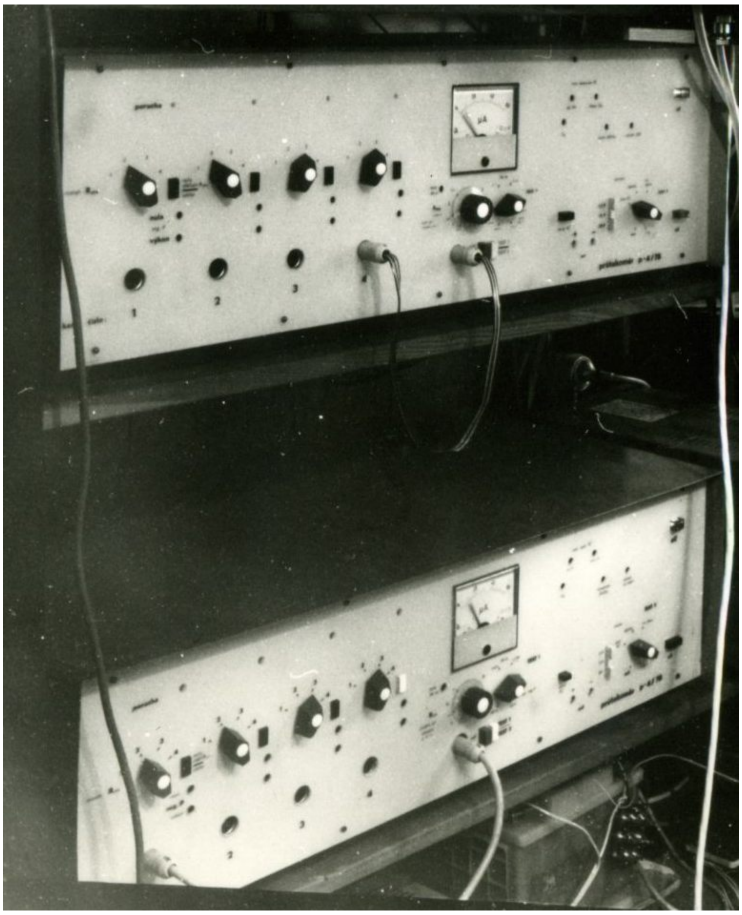

Fig. 4. Four-channel sap flow systems used to maintain a constant heating power (1W).

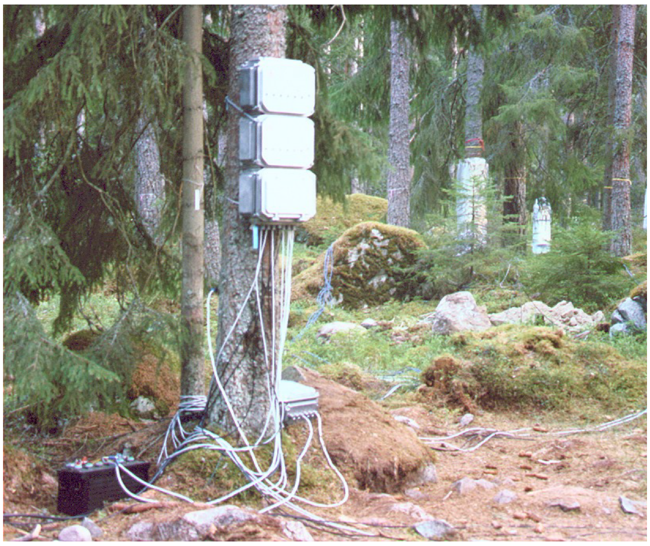

Fig. 5. 12-channel battery operated sap flow system maintaining constant power (0.63 or 1W).

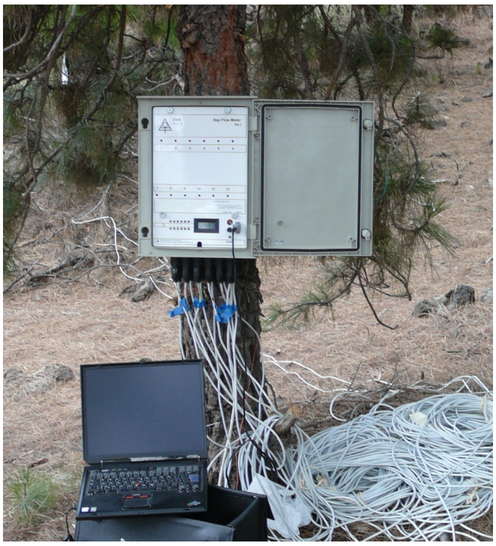

Fig. 6. 12-channel system. Last model using constant power heating.

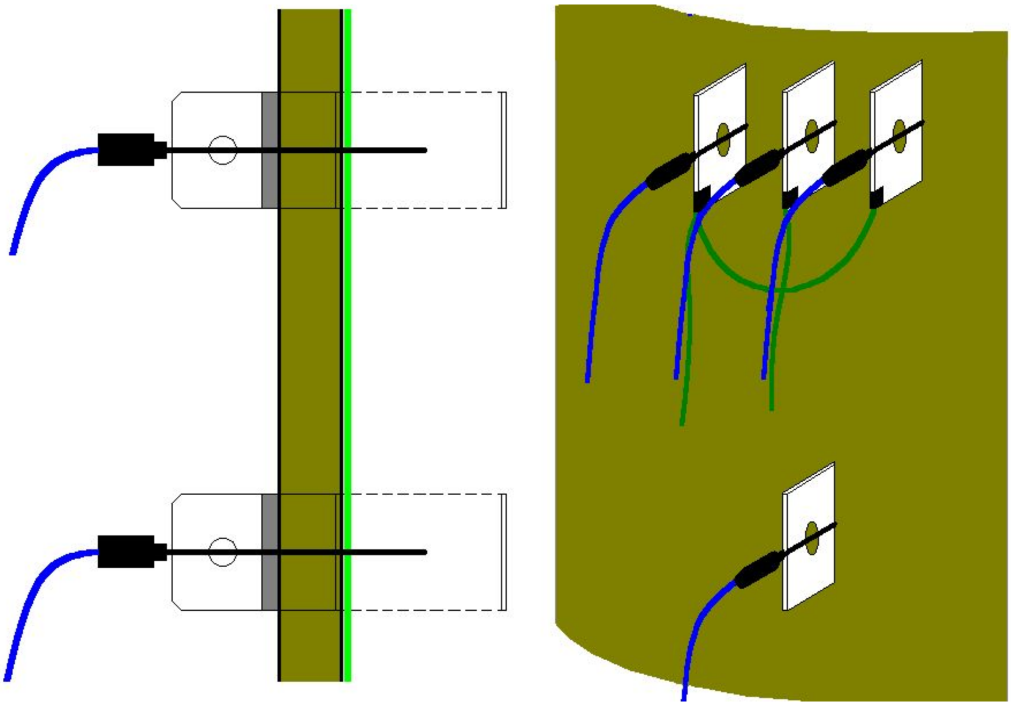

Fig. 7. Actual arrangement of THB measuring point (sensor).

Fig. 8. Sap flow module.

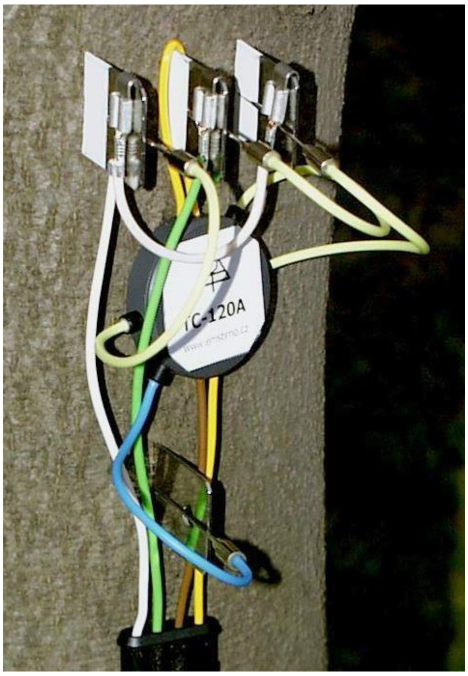

Fig. 9. Measuring point.

Fig. 10. Installed measurement.

Fig. 11. Insulation against solar irradiation.