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Research paper

Influence of stem temperature changes on heat pulse sap flux density measurements

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While natural spatial temperature gradients between measurement needles have been thoroughly investigated for continuous heat-based sap flow methods, little attention has been given to how natural changes in stem temperature impact heat pulse-based methods through temporal rather than spatial effects. By modelling the theoretical equation for both an ideal instantaneous pulse and a step pulse and applying a finite element model which included actual needle dimensions and wound effects, the influence of a varying stem temperature on heat pulse-based methods was investigated. It was shown that the heat ratio (HR) method was influenced, while for the compensation heat pulse and T_{max} methods changes in stem temperatures of up to 0.002 °C s^{-1} did not lead to significantly different results. For the HR method, rising stem temperatures during measurements led to lower heat pulse velocity values, while decreasing stem temperatures led to both higher and lower heat pulse velocities, and to imaginary results for high flows. These errors of up to 40% can easily be prevented by including a temperature correction in the data analysis procedure, calculating the slope of the natural temperature change based on the measured temperatures before application of the heat pulse. Results of a greenhouse and outdoor experiment on *Pinus pinea* L. show the influence of this correction on low and average sap flux densities.

Keywords: heat dissipation, sap flow, sensor, transpiration.

Introduction

Sap flux density can be measured with thermometric sap flow sensors that deliver continuous or pulsed heating to the plant (Vandegehuchte and Steppe 2013). Moving sap will transport the applied heat in the direction of the sap flow, altering the temperature of the xylem tissue surrounding the heater element. Based on these temperature changes, heat pulse velocity and, by derivation, sap flux density can be assessed. In addition to these intentionally induced temperature changes, both spatial and temporal natural temperature gradients (NTGs) may occur. These NTGs have mainly been attributed to differences in thermal heat storage in the soil, the stem and the root tissues (Cermak and Kucera 1981, Köstner et al. 1998, Do and Rocheteau 2002) and to the influence of direct solar radiation (Lu et al. 2004), resulting in temperature gradients in the stem.

While many studies have addressed the influence of varying stem temperatures on sap flow or sap flux density determination with continuous heating methods (e.g., Cermak and Kucera 1981, Groot and King 1992, Gutierrez et al. 1994, Do and Rocheteau 2002, Ayutthaya et al. 2010, Lubczynski et al. 2012, Reyes-Acosta et al. 2012), this issue has received less attention for heat pulse methods (Cohen et al. 1988, Clearwater et al. 2009). This is not surprising as, unlike the continuous heating methods which measure temperature differences between different positions in the xylem, these heat pulse methods rely on relative temperature changes measured at different positions in the stem. Hence, absolute temperature differences between the measurement needles do not affect the sap flux density measurements. However, as indicated by Vandegehuchte and Steppe (2012*b*, 2012*c*), measured relative temperature profiles are also affected by changing stem temperatures and need to be corrected for in the sap flow method. Indeed, altering ambient temperatures will cause the stem temperature to vary. These stem temperature variations are not accounted for in the theoretical thermodynamic approach on which the heat pulse methods are based (Vandegehuchte and Steppe 2012*d*). Clearwater et al. (2009) showed that the sap flow measured in small-diameter stems and petioles by an external heat pulse method was particularly noisy during daylight hours when ambient temperatures were highly variable, unlike the measurements conducted in a controlled laboratory environment. This variability could be reduced, although not eliminated, by more thoroughly insulating the stem and the sensor. These authors also mentioned that some of the noisy data could be excluded or corrected based on temperature measurements prior to initiation of the heat pulse, but no further elaboration on this correction procedure is provided (Clearwater et al. 2009).

In this study, we wanted to investigate how changes in stem temperature, resulting from changing ambient temperatures, affect heat pulse velocity and sap flux density measured with the compensation heat pulse (CHP), T_{max} and heat ratio (HR) methods. To this end, the equations for both an ideal and non-ideal heat pulse (step pulse) were implemented and a finite element model incorporating wound effects was applied. Our modelling results showed that the HR method was negatively affected by varying stem temperatures. Therefore, a correction for the HR method was proposed which was tested in a greenhouse and outdoor experiment on 3-year-old *Pinus pinea* L. with diameter at breast height of 50 mm at Crawley, Western Australia. The correction procedure determines the slope and intercept of changes to the sapwood temperature profile due to NTGs for the 30-s period immediately prior to the initiation of the heat pulse. The slope and intercept are used to predict changes to stem temperatures in the post-pulse period. The predicted temperature changes due to NTGs are then subtracted from the actual measured temperatures which include both the influence of NTGs and the rise of temperature due to the release of the heat pulse.

Materials and methods

Temperature changes in the stem following an ideal heat pulse were modelled with and without the influence of changes in underlying stem temperature, based on the standard heat conduction–convection equation for an ideal pulse in anisotropic wood (Vandegehuchte and Steppe 2012*d*):

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

where ΔT (K) is the difference between the temperature at position (x,y) before application of the heat pulse and a time t (s) after application of the heat pulse, q (J m^{-1}) is the amount of heat liberated per unit length of the heater, K_{ax} and K_{tg} the axial and tangential thermal conductivity (W m^{-1} K^{-1}), respectively, ρc the volumetric heat capacity (J m^{-3} K^{-1}) and V_h the heat pulse velocity (m s^{-1}), directly related to sap flux density. Based on these temperature differences, the CHP method (Swanson and Whitfield 1981, Green and Clothier 1988) (Eq. 2), the T_{max} method (Cohen et al. 1981) (Eqs 3 and 4) and the HR method (Burgess et al. 2001) (Eq. 5) could be tested for errors due to changing stem temperature:

$$V_{h\_CHP} = (x_d - x_u)/(2t_c), \quad (2)$$

$$D_{ax} = {x_d}^2(4t_{m0})^{-1}, \quad (3)$$

$$V_{h\_Tmax} = ({x_d}^2 - 4D_{ax}t_m)^{1/2}(t_m)^{-1}, \quad (4)$$

$$V_{h\_HR} = (D_{ax}/x)\ln(\Delta T_{down}/\Delta T_{up}), \quad (5)$$

with x_d and x_u being distances, taken at 10 mm downstream and 5 mm upstream of the heater, respectively, t_c the time at which ΔT at x_d and at x_u are equal, t_m the time at which ΔT at x_d is maximal (with t_{m0} at zero flow), D_{ax} the axial thermal diffusivity (m^2 s^{-1}), and ΔT_{down} and ΔT_{up} the relative temperature differences averaged over a certain time interval (usually 60–100 s) after application of the heat pulse, measured at x mm downstream and upstream, respectively, with x usually taken at 5 mm.

In practice, pulses are never ideal and, depending on the thermal wood properties and the thermal properties of the heater, pulses of several seconds have to be applied to obtain sufficient temperature rises for accurate measurement. Therefore, the influence of changing stem temperature was also investigated for pulses of finite length. Temperature differences were modelled based on Vandegehuchte and Steppe (2012*d*) and Kluitenberg and Ham (2004):

$$\Delta T = \frac{q_t}{4\pi\sqrt{K_{ax}K_{tg}}}\int_0^t \frac{1}{t}\exp\left(-\frac{\rho c}{4t}\left(\frac{(x-V_h t)^2}{K_{ax}}+\frac{y^2}{K_{tg}}\right)\right)dt \quad \text{for} \quad 0<t<t_0, \quad (6)$$

$$\Delta T = \frac{q_t}{4\pi\sqrt{K_{ax}K_{tg}}} \int_{t-t_0}^{t} \frac{1}{t} \exp\left(-\frac{\rho c}{4t}\left(\frac{(x-V_h t)^2}{K_{ax}} + \frac{y^2}{K_{tg}}\right)\right) dt \quad \text{for} \quad t_0 < t, \tag{7}$$

where t is the time after application of the heat pulse with a duration of t_0 (s) and q_t is the energy input per unit length of the heater per unit time (W m^{-1}). For the T_{max} method, formulae for a non-ideal heat pulse as mentioned in Vandegehuchte and Steppe (2013) were applied. For the CHP and HR methods, Eqs (2) and (5) were applied, respectively, even though they are theoretically not applicable for non-ideal pulses. However, it is mentioned in Burgess et al. (2001) that there was no significant difference when applying heat pulses of 6 s compared with shorter pulses. This was also confirmed by comparing the theoretical results of applying the original HR equation to the temperatures as modelled by Eqs (6) and (7) for heat pulses ranging between 1 and 10 s for which no significant difference ($P<0.05$) between results was obtained. For the CHP method, V_h is slightly underestimated proportional to the length of the heat pulse, resulting in an underestimation of V_h of 15% for a pulse length of 6 s.

To assess the influence of stem temperature changes when wound effects occur due to the interruption of the vessels when measurement needles and heater are installed, a finite element model was developed. This model simulates flow in a stem segment in which a T_{max}, CHP or HR sensor was installed, and is based on standard conduction–convection partial differential heat equations (Incropera and DeWitt 1996). To this end, the needles and heater were modelled as cylinders with 1.5 mm diameter and with the properties of stainless steel ($\rho=7850$ kg m^{-3}, $c=475$ J kg^{-1} K^{-1}, $K=44.5$ W m^{-1} K^{-1}). For the stem segment, the density was taken as 980 kg m^{-3} and thermal heat capacity as 2400 J kg^{-1} K^{-1}, while for the axial and tangential thermal conductivity 0.66 and 0.44 W m^{-1} K^{-1} were applied, respectively. The wound effect was modelled as a rectangular zone surrounding the needles in which no flow occurred with a total width of 2.0 mm (0.5 mm wider than the measurement needles) and a length ranging from 0.25 mm below the lower needle until 0.25 mm above the upper needle. The thermal properties of this wound zone were taken as identical to the remainder of the sapwood. The initial stem temperature, needle temperatures and outer boundaries of the system were taken at a temperature of 20 °C. For the outer boundaries of the stem segment, thermal insulation was chosen as the boundary condition while for the inner boundaries, between the sensor needles and the wound zone and the rest of the stem segment, thermal continuity was applied as the boundary condition. For the heater needle, the boundary condition consisted of a pulsed outward heat flux.

We chose two practical tests of the influence of changes in stem temperature, resulting from varying ambient temperatures, on HR results as the model results indicated a clear influence of varying stem temperatures on the HR method. Firstly, we investigated a fairly extreme case by placing a potted tree (*P. pinea* L.) outdoors (31°59′S, 115°49′E) under conditions of hot sunny days and cold clear nights where the diel temperature variation exceeded 20 °C. The tree had a small stem (50 mm diameter and a height of ~2 m) which was able to change temperature quite rapidly in response to the diel thermal regime. The second test was less extreme, with a potted *P. pinea* of similar dimensions placed in a glasshouse with reasonably stable temperature regulation (±5 °C) but had the advantage of an independent gravitational measurement of sap flow. This was achieved by placing the tree on a logging digital balance (WSM1 Weigh Scale Meter, ICT International, Armidale, Australia), which measured the amount of weight loss due to transpiration of water. For both experiments, HR needles (SFM1 Sap Flow Meter, ICT International) were shielded from radiation by a white polyester insulating material and covered with a reflective foil.

For both practical tests, a procedure to correct for varying stem temperatures was applied to the HR measurements. Temperatures were corrected by first determining the slope and intercept for natural temperature changes measured over a 30-s period prior to the application of each heat pulse and then subtracting the projected values of temperature change from the values recorded during and after heat pulse application. The heat pulse velocities determined from these corrected temperature data were compared with the uncorrected heat pulse velocities.

Results

Without wound effects

Figure 1 shows that for an ideal pulse, both the T_{max} and the CHP method were hardly influenced by a stem temperature change of ±0.002 °C s^{-1} (the average morning stem temperature variation measured during the greenhouse experiment on *P. pinea*). For low heat pulse velocities (<5 cm h^{-1}), the T_{max} method led to imaginary results for the positive temperature change due to the small error in calculated D_{ax} (Eq. 3). For heat pulse velocities >5 cm h^{-1}, the errors remained <1.5% for both the T_{max} and the CHP method. For the HR method, however, NTG influenced the ratio $\Delta T_{down}/\Delta T_{up}$ over the course of the measurement period following the application of the heat pulse, which led to errors in the results. For negative temperature changes (Figure 1a), this resulted in an overestimation or even imaginary results for average and high heat pulse velocities (data which appear to be missing in the figure). For positive temperature changes (Figure 1b), average-to-high heat pulse velocities were underestimated. These underestimations increased for increasing heat pulse velocities and increasing temperature changes. These deviating results were due to the disproportionally affected ΔT_{up} signal for average and high heat pulse velocities. Moreover, Figure 2 shows that the

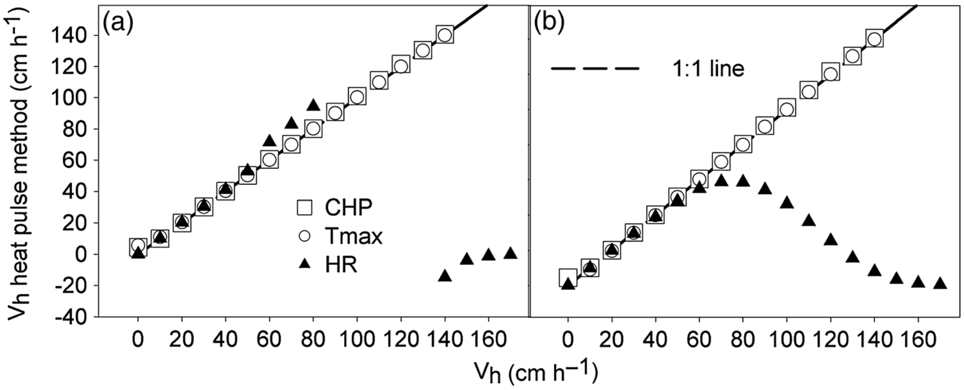

Figure 1. Heat pulse velocity (V_h) determined according to the compensated heat pulse (CHP), T_{max} and heat ratio (HR) methods based on an ideal heat pulse for a stem temperature gradient of −0.002 (a) and +0.002 °C s^{-1} (b), respectively, versus the actual heat pulse velocity as implemented in the model (Eq. 1). For the HR method, the average $\Delta T_{down}/\Delta T_{up}$ signal between 60 and 100 s after the application of the heat pulse was applied in Eq. (5). K_{ax} and K_{tg} were taken as 0.66 and 0.44 W m^{-1} K^{-1}, respectively, while for ρc a value of 2.352 10^6 J m^{-3} K^{-1} was applied. Initial stem temperature was taken at 20 °C.

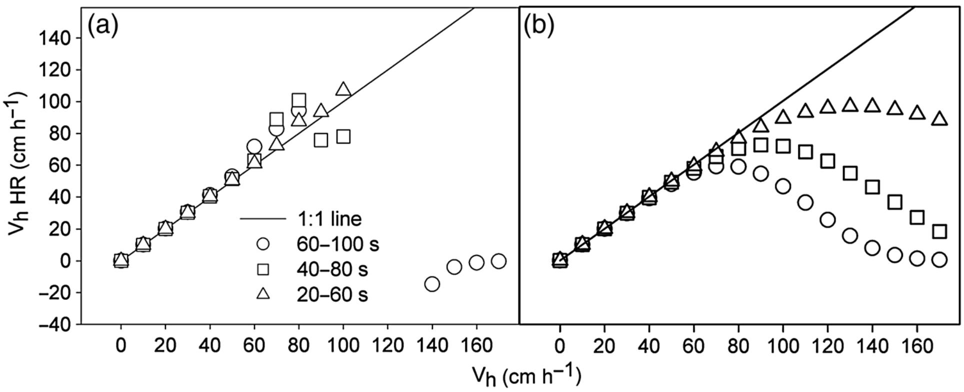

Figure 2. Heat pulse velocity (V_h) determined according to the heat ratio (HR) method based on an ideal heat pulse for a stem temperature gradient of −0.002 (a) and +0.002 °C s^{-1} (b) versus the actual heat pulse velocity as implemented in the model (Eq. 1). The $\Delta T_{down}/\Delta T_{up}$ signal was averaged for three different time ranges, 20–60, 40–80 and 60–100 s, respectively. K_{ax} and K_{tg} were taken as 0.66 and 0.44 W m^{-1} K^{-1}, respectively, while for ρc a value of 2.352 10^6 J m^{-3} K^{-1} was applied. Initial stem temperature was taken at 20 °C.

errors obtained due to changing stem temperatures are not only dependent on V_h, but also on the chosen time range for which the average $\Delta T_{down}/\Delta T_{up}$ signal is calculated. While for negative stem temperature changes, the errors were rather unpredictable, an averaging period taken closer to the start of the heat pulse led to better results and fewer imaginary values. For positive temperature changes, the underestimation clearly decreased for averaging periods shifted toward the start of the heat pulse. Similar results were obtained for higher temperature gradients. When modelling temperatures according to the non-ideal heat pulse equations (Eqs 6 and 7), similar responses were obtained for the T_{max} and the HR method, while for the CHP method underestimations occurred. These underestimations were, however, not due to changing stem temperatures but due to the fact that the CHP method is based on the ideal heat pulse theory (Eq. 1) and is not strictly applicable for non-ideal pulses (Eqs 6 and 7), which resulted in slight underestimations, proportional to the length of the pulse, resulting in errors of up to 15% for pulses of 6 s. The above-mentioned conclusions remained valid also when different wood thermal properties (K_{ax}, K_{tg} and ρc) were applied.

Including wound effects

The results for ideal and non-ideal pulses were confirmed with the finite element model when wound effects were included. Wound effects induced underestimations of V_h for all methods (Figure 3a) as was previously reported (Swanson and Whitfield 1981, Burgess et al. 2001, Green et al. 2009, Vandegehuchte and Steppe 2012*b*). The magnitude of negative V_h values, only determinable by the HR method, was also underestimated because of the wound effect.

For the T_{max} method, low values could not be determined as t_m values of the temperature curves at these V_h values were larger than the t_m value for zero flow, leading to imaginary results when applying Eqs (3) and (4). For the CHP method, stem temperature gradients had a negligible effect on V_h calculations

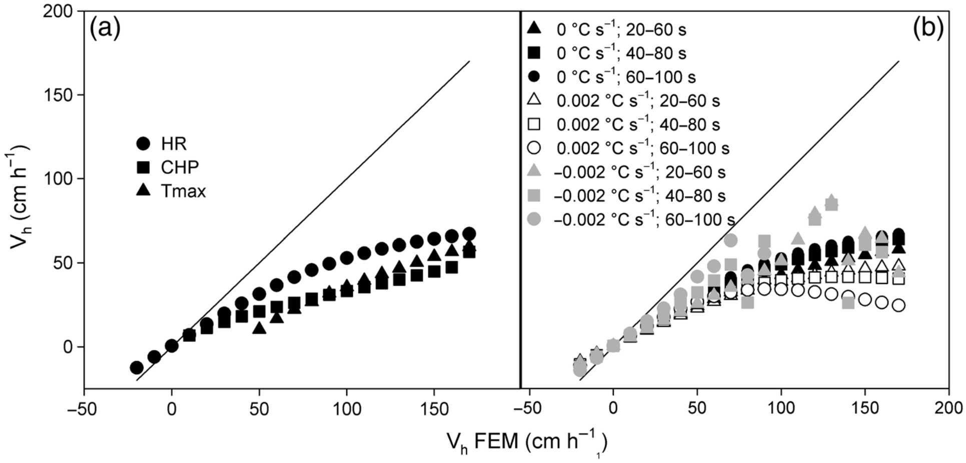

Figure 3. (a) Heat pulse velocity (V_h) determined according to the compensated heat pulse (CHP), T_{max} and heat ratio (HR) method based on the finite element model (FEM) including wound effects without stem temperature gradients. (b) V_h according to the HR method for different averaging periods of the temperature signals (20–60 s, 40–80 s, 60–100 s) and different stem temperature gradients (0 °C s^{-1}, +0.002 °C s^{-1}, −0.002 °C s^{-1}), including wound effects.

(on average 0.9±3% difference for a positive or negative gradient of 0.002 °C s^{-1} compared with no stem temperature gradient for a V_h range of 0–170 cm h^{-1}). For the T_{max} method, a gradient of ±0.002 °C s^{-1} led to an average difference of 6±7% compared with no stem temperature gradient for a V_h range of 0–170 cm h^{-1} with larger differences for lower flows (up to 15% for V_h < 60 cm h^{-1}). For the HR method, a positive stem temperature gradient led to a stronger underestimation of V_h compared with no temperature gradient, especially for the higher heat pulse velocities. However, when taking the averaging period for the HR temperature signals closer to the start of the pulse, the underestimations were reduced for all stem temperature gradients (Figure 3b). Without a stem temperature gradient, however, the averaging period 60–100 s was most accurate, explaining the original choice of this period for the HR method (Burgess et al. 2001). As for the ideal heat pulse without wound effects, negative stem temperature gradients led to both under- and overestimations for the HR method including wound effects, depending on the heat pulse velocity, temperature gradient and applied averaging period (Figure 3b). For these negative stem temperature gradients, V_h could again often not be determined because of imaginary results. The magnitude of errors was proven to be dependent on stem temperature changes in combination with heat pulse velocity (and, hence, sap flux density), spacing, wood thermal properties as well as the size of the wounding zone as these factors influence the shape of the measured temperature signals. Despite the absolute differences in error magnitude, the general conclusions for the three measurement methods as described above remained similar.

Effects of the correction procedure

For all modelling cases, application of the correction procedure undid the influence of the changing stem temperature.

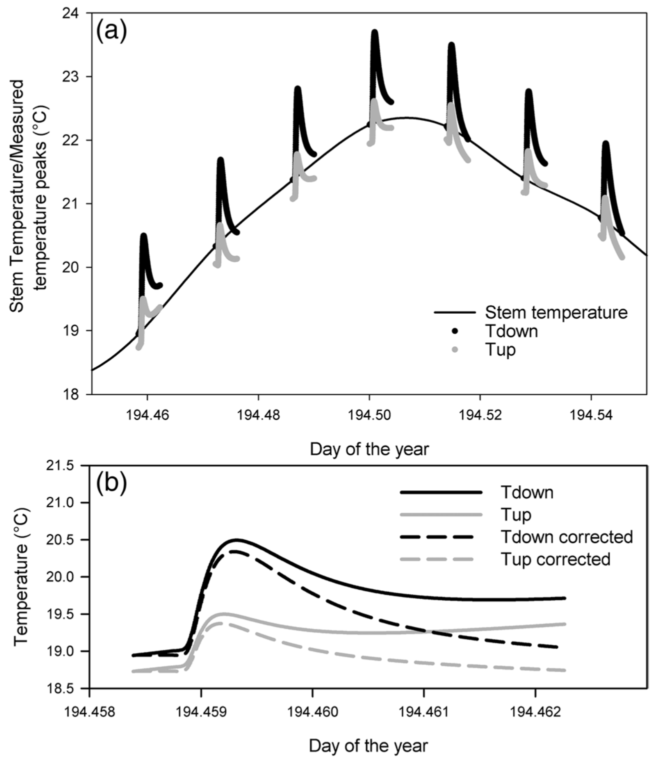

Figure 4. (a) Stem temperature and measured downstream (T_{down}) and upstream (T_{up}) temperatures during application of the HR method for *P. pinea* under greenhouse conditions. (b) An example of an uncorrected and corrected T_{down} and T_{up} measurement for a single heat pulse according to the correction procedure based on the slope of the temperature measured during 30 s prior to the pulse.

Applying this correction to the practical tests (Figure 4) led to small absolute differences in comparison with the uncorrected HR results (Figures 5 and 6) and a slightly higher correlation with gravimetric sap flow data for the greenhouse experiment (0.86 versus 0.85 for the uncorrected HR results). However, when expressed as percentage, differences of up to 40% (determined as the difference between uncorrected and corrected HR measurements divided by the corrected HR measurements) were noted.

Discussion

The HR method has the advantage that, unlike the CHP and the T_{max} method, it is able to determine very low and negative flows (Burgess et al. 2001, Vandegehuchte and Steppe 2012*a*, 2013). Since in plant physiology many research topics such as canopy water uptake, hydraulic redistribution and nocturnal sap flow necessitate the measurement of these low and negative flows, the application of the HR method has greatly increased since the publication of the methodology by Burgess et al. (2001) (e.g., Burgess and Dawson 2004, Burgess and Bleby 2006, Dawson et al. 2007, Fisher et al. 2007, Goldsmith et al. 2013). The HR method in its present formulation is, however, not capable of determining high flows (Burgess et al. 2001, Green et al. 2009, Vandegehuchte and Steppe 2012*b*) and generally an upper limit in a heat pulse velocity of 55 cm h^{-1} is assumed (Swanson 1983, Burgess et al. 2001).

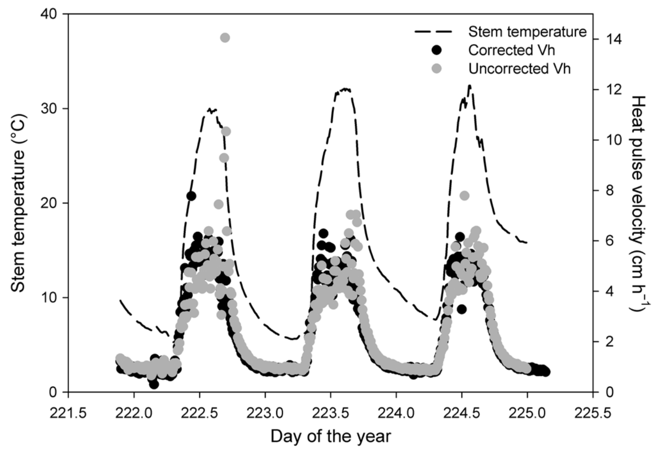

Figure 5. Stem temperature and heat pulse velocity (V_h) according to the HR method with and without correction for natural temperature gradients for *P. pinea* under outside conditions. A 7-mm needle spacing was applied.

One aspect of this upper limit relates to sensitivity problems. As the method applies to a ratio of temperature differences for which the ΔT_{up} signal in the denominator may become very small and subject to the effects of noise/instrument error, unrealistic sap flux densities can be obtained for high flows (Vandegehuchte and Steppe 2013). In our modelling results, however, imaginary results were not obtained when applying the HR method when stem temperature gradients were absent, even for high flows. This is presumably because modelled data contain less noise than actual data.

A second aspect of the limitations of the HR method, as for other methods, at high flows relates to artefacts from heat conduction in the band of wounded tissue that surrounds HR method probes inserted in the xylem (Burgess and Bleby 2008, Vandegehuchte and Steppe 2013). This issue is the subject of ongoing investigation. As a consequence, for high flows, the relation to the reference heat pulse velocity did not remain linear. Moreover, for different wood thermal properties and needle distances, imaginary results could be obtained for high heat pulse velocities as was shown previously (Vandegehuchte and Steppe 2012*b*).

In addition to these two influences, our results clearly demonstrate that stem temperature gradients, if left uncorrected, contribute greatly to errors when applying the HR method at high flows as even for the purely theoretical cases of an ideal and non-ideal heat pulse in perfectly homogenous sapwood without wounding, variations in stem temperature could induce significant errors. These errors did not occur for the CHP and the T_{max} method. This is not surprising as the HR method is based on averaged temperature changes determined during a 40-s time interval after application of the heat pulse, while for the CHP and the T_{max} method only point measurements shortly after application of the heat pulse are applied. All the three heat pulse methods are based on the temperature change relative to the temperature before the start of the heat pulse. As the temperature gradient occurs throughout the entire pulse,

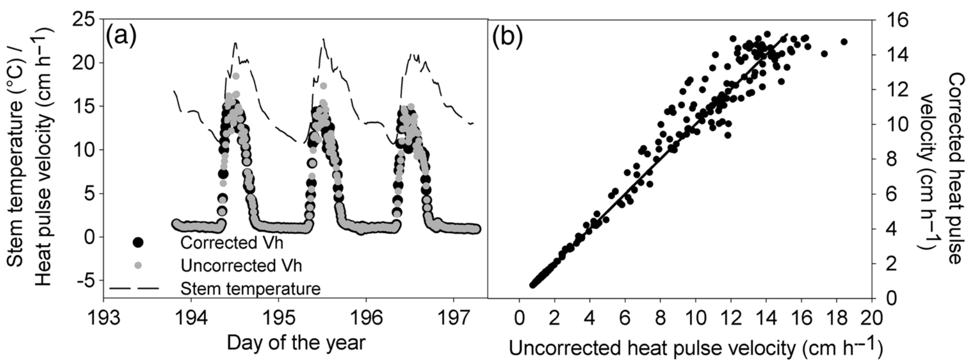

Figure 6. Stem temperature and heat pulse velocity (V_h) according to the HR method with and without correction for natural temperature gradients for *P. pinea* under greenhouse conditions (a) and corrected versus uncorrected heat pulse velocity (b). A 6-mm needle spacing was applied.

its effect accumulates, leading to larger deviations from the starting temperature of the pulse through time. As such, the temperature deviation caused by the temperature gradient is smaller when applying an averaging period for the HR temperature ratio taken closer to the start of the pulse, resulting in smaller errors. Burgess et al. (2001), however, mentioned that in practice the temperature ratios for averaging periods closer to the start of the heat pulse are less linear, which works against error reduction. If the stem temperature gradient does not remain constant throughout the pulse, additional errors may occur. Changes of stem temperature gradient during the pulse should therefore be avoided as much as possible by properly insulating and shielding the sensors, which was also mentioned by Clearwater et al. (2009).

A simple solution to NTGs that remain consistent throughout the measurement cycle is to correct measured temperatures for changes in stem temperature observed before the application of the heat pulse, as suggested by Clearwater et al. (2009). This can easily be done by subtracting the natural temperature change rate from the measured temperature data. This can practically be achieved by monitoring temperatures 30 s prior to the release of the heat pulse from which the slope and intercept are calculated, which is then forward-projected to calculate the expected baseline (i.e., the temperature profile that would occur without heat pulse) during the heat pulse release and measurement phase (Figure 4). This method was recently adopted for HR method calculations in the Sap Flow Tool software package (ICT International—Phyto-IT; Armidale–Mariakerke, Australia–Belgium). Our greenhouse and field results show that applying this correction can eliminate the up to 40% errors that have the potential to occur under conditions of rapid stem temperature change (even though absolute errors were only small in our tests). Experiments conducted on faster transpiring species could broaden our understanding of the influence of temperature gradients on the measurement of higher sap flux densities.

Conclusions

By considering the theoretical framework of the heat pulse methods and applying a finite element model to include wound effects and stem temperature gradients, the influence of a varying stem temperature was shown to be negligible for the CHP and T_{max} methods. For the HR method, however, large under- and overestimations may occur, depending on sap flux density and stem temperature gradient. A simple correction procedure was proposed which was successfully tested under greenhouse and field conditions. As this procedure can easily be implemented in the data analysis of heat pulse-based methods, we advise its consistent application to avoid errors due to changing stem temperatures.

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Conflict of interest

A.D. has a commercial interest in the Sap Flow Tool software package, SFM1 Sap Flow Meter and WSM1 Weigh Scale Meter. S.S.O.B. has a commercial interest in the SFM1 Sap Flow Meter.

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