

Determination of thermal expansion of green wood and the accuracy of tree stem diameter variation measurements

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Sevanto, S., Hölttä, T., Hirsikko, A., Vesala, T. & Nikinmaa, E. 2005: Determination of thermal expansion of green wood and the accuracy of tree stem diameter variation measurements. *Boreal Env. Res.* 10: 437–445.

The coefficient of thermal expansion in the radial direction for wet fresh wood was determined for two coniferous species *Pinus sylvestris* and *Picea abies* and three broad-leaved species *Acer platanoides*, *Betula pendula* and *Alnus incana*. The diameter variation of 7–11 samples of each species was measured in a water heat bath with a linear variable displacement transducer (LVDT). The temperature range was 5–45 °C. The average values for the coefficient of thermal expansion varied between 7.9×10^{-6} and 17.5×10^{-6} °C⁻¹. Heating and cooling gave similar results for all the species and no hysteresis was observed. The results show that the coefficient of thermal expansion for wet green wood is a positive number as for dry wood and timber, contrary to values mentioned in literature. The coefficient is lower than that of dry timber and of the same order of magnitude as the coefficient of many commonly used metals and alloys. In field measurements of tree stem diameter variations an LVDT is usually attached to a metal frame. The similar magnitude of the coefficients means that the accuracy of absolute values of tree stem diameter variations is dominated by the temperature difference between the stem and the surrounding air. However, if both the temperatures are measured, the error in stem diameter variation measurements resulting from the thermal expansion can be corrected.

Introduction

Tree stem diameter variation measurements are a good indicator of water status of the stem and they are widely used in both physiological and environmental studies of water relations of trees (see e.g. Brough *et al.* 1986, Roberts 1987, Herzog *et al.* 1995, Génard *et al.* 2001, Offenthaler *et al.* 2001, Perämäki *et al.* 2001, Sevanto *et al.* 2001, Ueda and Shibata

2001, Zweifel *et al.* 2001, Zweifel and Häslér 2001, Hölttä *et al.* 2002, Sevanto *et al.* 2005). Xylem diameter variations have a strong connection with water tension and transpiration (Irvine and Grace 1997, Perämäki *et al.* 2001) and combining xylem measurements with measurements over bark seems to give a tool to analyze water flow between the xylem and the phloem (Sevanto *et al.* 2002, 2003). Stem diameter variation measurements have thus a potential for

becoming an inexpensive tool to observe tree-level transpiration and sap flow.

The most accurate diameter variation measurements are nowadays usually made with a pen-like linear displacement transducer (LVDT) attached to a frame, which is mounted around the stem (*see e.g.* Neher 1993, Irvine and Grace 1997, Perämäki *et al.* 2001 or Sevanto *et al.* 2002). All these measurement setups use rectangular frames made of four metal bars. The LVDT is attached to one of the bars and the direction to which the diameter variation is measured is perpendicular to that bar. With that setup, the thermal expansion of the bars parallel to the measurement direction have an effect on the diameter variations. These bars are often made of stainless steel or invar (an alloy with a very low coefficient of thermal expansion).

The order of magnitude of the diurnal amplitude of the diameter variation *e.g.* in Scots pine (*Pinus sylvestris* L.) below bark is about 0.01–0.1 mm and above bark 0.1–0.5 mm (Sevanto *et al.* 2002). The coefficient of thermal expansion of steel is of the order of magnitude of $10^{-5} \text{ }^{\circ}\text{C}^{-1}$ (CRC Handbook of Chemistry and Physics), which means that a change of one degree in temperature would result in a change of 0.001 mm if the parallel distance of the steel frame is about 10 cm. Since a typical variation in temperature during a summer day may be well over 10 degrees in boreal zone, the effects of thermal expansion have to be taken into account when analyzing the data.

The thermal expansion of wood affects the diameter variation likewise. However, values from literature can be found only for dry wood or timber (for a review, *see e.g.* Kubler *et al.* 1973). Moist wood is most often reported to shrink when heated due to the migration of water out of the cells (*see e.g.* Simpson and TenWolde 1999). Only Kubler *et al.* (1973) and Salmén (1990) reported measurements of thermal expansion of moist wood. Salmén used preheated, sulfonated, water-saturated wood in temperatures between 20 °C and 90 °C. He got a negative coefficient for thermal expansion when the temperature was under the softening temperature of lignin (60 °C) and a positive coefficient when the temperature exceeded that. On the other hand Kubler *et al.* (1973) found the coefficient to be a function of

moisture content peaking at 12% and decreasing towards 30%–40% moisture contents. With wetter wood than that the coefficient of thermal expansion was close to zero or negative independent of species and Kubler *et al.* (1973) argued the reason to be the water loss from the samples.

Theoretically, the properties of water-fiber compound could differ from those of water or dry fibers and that might make the coefficient of thermal expansion of moist wood to differ from that of dry wood. However, it is rare among materials that the bond distance of the atoms decreases when the internal energy is increased by heating. There are only some special liquids (*e.g.* water between 273 and 277 K), some quartz compounds, ceramics and polymers that have negative coefficient of thermal expansion over a certain temperature range or to a specified direction (*see e.g.* Evans *et al.* 1996, Evans 1999). In general in solids with no empty space in the structure the shrinkage in size with increasing temperature results from an increase in disorder (entropy) when the material is packed tighter. This behavior is most often due to the lattice structure (*see* Evans 1999) or the special atomic composition of the material. In porous, net-structured materials, such as wood, thermal shrinkage could be possible because the expansion of certain cell walls could lead to shrinkage of the overall network in some direction (Lakes 1996).

Experimental evidence in controlled environment shows that transpiration induced tension in wood is causing it to shrink (Irvine and Grace 1997). Similarly, as wood sample diameters are measured in different temperatures, there are bound to be water phase transitions that could result into water vapor loss from the measured sample and reflect on the water tension and diameter of the measured wood sample as suggested by Kubler *et al.* (1973). For these reasons we set to determine the thermal expansion of fresh wood in a water bath. In this paper, we report the coefficients of thermal expansion determined in a water bath for wood samples of five different tree species. We also discuss the impact of these effects on the accuracy of field measurements of stem diameter variations. Generally, the problems of heat transfer between different materials are case specific depending strongly on the

properties of the materials and the geometry of the situation. In this study we concentrate on the special case of the measurement system for tree stem diameter variation measurements. Thus, the results will enhance understanding of the behavior of water in wood and improve the accuracy of tree stem diameter variation measurements.

Theory

Thermal expansion of any material is described by the coefficient of thermal expansion, α , which gives the range of the change in the size of the object due to change in temperature when pressure p is kept constant.

$$\alpha = \frac{1}{X} \left(\frac{\partial X}{\partial T} \right)_p \quad (1)$$

where X represents any measure of size e.g. volume, length or area (see e.g. Hook and Hall 1995).

The variation in tree stem diameter (dD) detected by the sensor consists of four different parts:

$$dD = dD'_{el} + dD'_{th} + dD'_{water} + dL_{frame} \quad (2)$$

where D' is the diameter of the sample and L is the length of the steel bar between the two attachment points A and B in Fig. 1. The first term (subscript "el") represents changes resulting from the changing water tension, which depend on the transpiration rate and the elasticity of wood. The second and third terms are the variations due to changes in temperature of the wood (th) and the water (water) and the fourth represents the thermal expansion of the steel frame (frame).

If the water content of the sample is kept constant, the elastic term can be neglected since the elastic changes are due to changes in the water potential of the stem. The thermal expansion coefficient of water is of the order of magnitude of 10^{-3} K^{-1} (Otero *et al.* 2002). However, water moves relatively easily in the vertical direction in wood thus the thermal expansion of water does not contribute to the diameter variation and we neglect the third term on the right side.

With these assumptions, combining Eqs. 1 and 2 gives

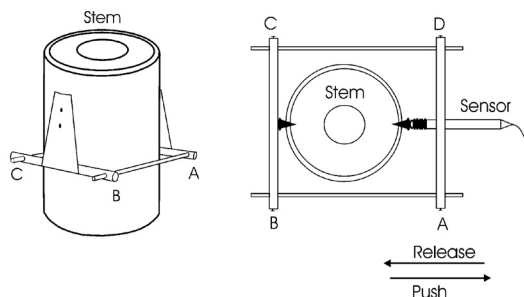


Fig. 1. Schematic illustration of the stem diameter measurement system seen from the side (left) and from the top (right) (not in scale). A rigid metal frame is mounted around the stem and attached by screws (marked with solid black). The sensor is attached to one of the metal bars through a hole. To measure only the variation of xylem diameter small screws are screwed to opposite sides of the stem and the sensor tip and the metal bar opposite to that rest on the screws. When the length of metal bars AB and CD increases (e.g. due to thermal expansion) the spring in the sensor is released and the sensor value decreases. On the other hand, if the sensor tip is pushed (e.g. due to positive thermal expansion of wood) the value increases.

$$dD = \alpha_w D'_0 dT_w + \alpha_F L_0 dT_F \quad (3)$$

for the measured diameter variation dD . Here T is the temperature, D'_0 and L_0 are the original diameter of the wood sample and the length of the frame bar (see Fig. 1) and the subscripts W and F refer to wood and frame, respectively.

Material and methods

We measured thermal expansion of fresh blocks of tree stems in a heat bath. The samples were cut from low parts (< 1.5 m from the ground) of fairly young stems and the size varied between 8.3 to 13.6 cm in diameter. The water bath was built of a refrigerating bath circulator (Lauda RC 6 CS) with an external bath. We used distilled, de-ionized water as bath liquid. The radial expansion of wood was measured using a system used to measure tree stem diameter variations in the field (Fig. 1) (see e.g. Sevanto *et al.* 2002). A rigid rectangular frame consisting of four round metal bars was mounted around a tree block. A linear displacement transducer (LVDT; Solartron AX/5.0/S; Solartron Inc., West Sussex, UK) was

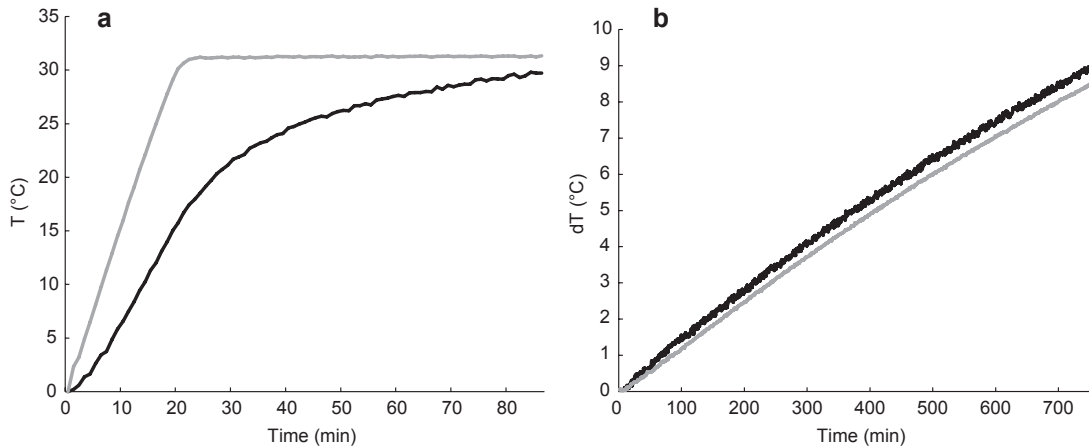


Fig. 2. Change of the temperature of the heat bath (gray) and the stem sample (black) in (a) quick and (b) slow heating. The temperature in the stem is measured at the depth of 1.5 cm from the surface. In the slow heating the ratio of the change of temperature of the bath to that of the stem is 1.012 after a 300 min relaxation time.

attached to the frame through a hole in one of the bars and the tip of the sensor was placed on a screw drilled through the bark tissue about 5 mm into the wood tissue. Another screw was placed on the opposite side of the block and the bar opposite to the sensor bar rested on that screw. With that setup the LVDT measured the diameter variation of the block. The screws eliminated the effects of bark tissue on the diameter.

The wood samples were set into the water bath so that the sample was completely immersed in the water. The temperature of the bath and the stem blocks (1.5 cm below the wood surface) was measured with copper constantan-thermocouples. Before setting the samples to the heat bath each block was wetted by forcing water flow through the block with hydrostatic pressure and the wetness of the blocks was tested by floating them in water (density was close to 1000 kg m^{-3}). The measurements were taken once every minute.

The LVDT was calibrated using a 1.00 ± 0.05 mm thick aluminum plate, which gave a 103 mV signal. The coefficient of the thermal expansion of the frame bars was determined by taking the tree sample away and placing the sensor tip on the bar BC in Fig. 1. To eliminate possible heating effect on the LVDT sensor the thermal expansion of the frame was also measured in a separate heat bath, where the LVDT remained outside the liquid in constant temperature. Both procedures gave similar results and the mean of

six repetitions with the frame was $(15.8 \pm 0.3) \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ (S.D. = $2.7 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$) and for the separate water bath $(15.6 \pm 0.3) \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ (S.D. = $2.0 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$). We used the value $15.8 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ for α_F in our calculations. We also tested the measurement system by inserting a bar of aluminum (Alumec, Uddeholm, Helsinki) in the place of the stem sample. The manufacturer gives $23 \times 10^{-6} \text{ K}^{-1}$ for the linear coefficient of thermal expansion of this compound and our measurements gave $(26.6 \pm 0.3) \times 10^{-6} \text{ K}^{-1}$.

According to Eq. 3, the coefficient of thermal expansion can be most easily and accurately determined with two different procedures: (1) changing the temperature of the bath (and frame) quickly and keeping it constant until the temperature of the stem reaches that of the bath (Fig. 2a), or (2) changing the temperature of the bath slowly and adjusting the rate of change so that the temperature of the wood sample changes with the same rate (Fig 2b). In the first case, the second term in Eq. 3 becomes zero and α_w can be calculated directly from the slope of D versus T_w . In the second the ratio dT_F/dT_w gets close to one and the slope of the D versus T_w line becomes $\alpha_w D_0' + \alpha_F L_0$ (note that the sample does not have to be in the temperature of the bath). Generally, dT_w and dT_F depend on the thermal conductivities of wood and steel as well as on the heat transfer coefficients between those and the surrounding fluid and the ratio dT_F/dT_w can be a non-linear function of time.

From these procedures the second one — slow heating and cooling — proved to be the best one (see Fig. 2b) and we used a heating/cooling rate of $0.01\text{--}0.1\text{ }^{\circ}\text{C min}^{-1}$. The results from the first procedure — quick heating and cooling — were unsatisfactory. That procedure led to an irregular behavior of the diameter most probably resulting from releases of tensions in the sample. Hence the coefficient of thermal expansion could not be determined based on this approach. However, the quick heating and cooling showed that the sensor for detecting the temperature of the stem was deep enough to give a representative value for the temperature of the sample. It took 130 minutes for the temperature of the sample to reach a value less than 1% different from that of the bath. Theoretically, with corresponding values (time 130 min, temperature at the depth of 1.5 cm less than 1% from the surface temperature, sample cylinder diameter 15 cm, thermal diffusivity of wood $0.0026\text{ cm}^2\text{ s}^{-1}$ (Simpson and TenWolde 1999)) the temperature profile inside the cylinder is such that the temperature in the middle of the cylinder differs less than 3% from the surface temperature (Carslaw and Jaeger 1990).

Results and discussion

The thermal expansion coefficients of all the species were positive (Table 1). We calculated the coefficients by fitting a line with the least-squares method to the measured diameter data as a function of the temperature of the wood sample (Fig. 3). The slope equals $\alpha_w D'_0 + \alpha_F L_0$ (Eq. 3) and α_w was calculated from that. The frame was considered to be in the temperature of the bath. We estimated that it would take less than a second for the temperature in the middle of a frame bar (steel, diameter 6 mm) to differ less than 1% from the surface temperature of the bar (see e.g. Bird *et al.* 1960).

The lowest mean value of the measurements ($7.9 \times 10^{-6}\text{ }^{\circ}\text{C}^{-1}$) was obtained for *Pinus sylvestris* L. and the highest ($17.5 \times 10^{-6}\text{ }^{\circ}\text{C}^{-1}$) for *Acer platanoides* L. The coefficients of *Pinus sylvestris* L. and *Alnus incana* L. were statistically significantly lower than the others (*t*-test: $p < 0.02$) and they also differed significantly from each other ($p < 0.05$). The differences between the other species were statistically insignificant. All the samples showed a highly linear dependence of diameter on temperature (Fig. 3) and

Table 1. Measured values for coefficient of thermal expansion of fresh wet wood. α_w is the coefficient of thermal expansion calculated from each measurement by fitting a line to the measurements of diameter change as a function of temperature. R^2 values are given to describe the goodness of the fit ($R^2 = 1$ means a perfect fit). Mean values of all measurements and standard deviations (S.D.) are also given. The line numbers refer to the individual samples of each species and the columns are not of equal length because the amount of samples of all species was not equal.

Measurement	<i>Pinus sylvestris</i>		<i>Picea abies</i>		<i>Acer platanoides</i>		<i>Alnus incana</i>		<i>Betula pendula</i>	
	α_w 10^{-6} K^{-1}	R^2	α_w 10^{-6} K^{-1}	R^2	α_w 10^{-6} K^{-1}	R^2	α_w 10^{-6} K^{-1}	R^2	α_w 10^{-6} K^{-1}	R^2
1	8.4	0.96	10.1	0.97	18.6	0.998	12.4	0.99	10.5	0.98
2	7.2	0.94	20.0	0.99	17.4	0.99	8.2	0.93	14.3	0.995
3	6.0	0.96	16.6	0.97	19.6	0.998	11.9	0.98	12.0	0.99
4	9.3	0.99	16.0	0.99	21.3	0.998	5.2	0.94	15.9	0.99
5	9.4	0.97	20.0	0.997	21.6	0.996	4.0	0.90	11.1	0.96
6	7.0	0.85	11.7	0.99	10.7	0.96	12.8	0.97	22.0	0.99
7	8.1	0.80	7.1	0.99	13.6	0.99	13.7	0.98	16.7	0.997
8	8.6	0.98	17.4	0.98			20.3	0.99	19.2	0.99
9	6.7	0.95	18.7	0.99					19.7	0.98
10	9.3	0.89	10.7	0.99						
11	7.4	0.92								
Mean	7.9		14.8		17.5		11.1		15.7	
S.D.	1.2		4.5		4.1		5.2		4.0	

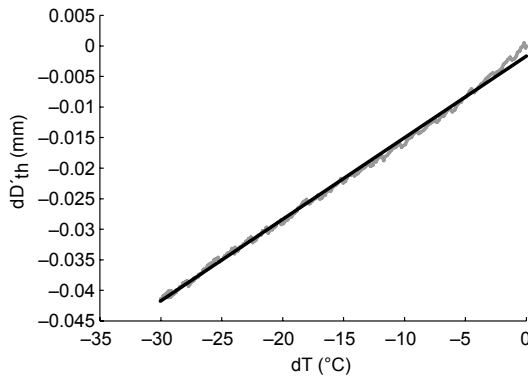


Fig. 3. Example of a fitted line to measured temperature and diameter change data (*Betula pendula*, measurement 7 in Table 1). The axes are set to begin at zero at the beginning of the measurement. The sample was cooled down from 36.6 °C to 6.6 °C. The line ($y = 1.339 \times 10^{-3} - 1.643 \times 10^{-3}x$; $R^2 = 0.997$) is fitted in the sense of least squares. The thermal expansion of the frame is subtracted from the data. The slope of the line ($1.336 \times 10^{-3} \text{ mm } ^\circ\text{C}^{-1}$) equals $\alpha_w D_0'$ (Eq. 3). In this measurement D_0' was 80 mm, which gives $16.7 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ for α_w .

both cooling and heating gave a similar result. No hysteresis was observed.

The values we got for the coefficient of thermal expansion were lower than those reported for dry wood or timber. Simpson and TenWolde (1999), for example, gave an empirical equation for calculating the radial coefficient of thermal expansion as a function of specific gravity. With that equation the coefficients for pine, spruce, maple, alder and birch using the specific gravity of green samples would be $22.9 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$, $23.2 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$, $26.1 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$, $21.9 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ and $27.7 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$, respectively. However, our values were in agreement with the trend observed by Kubler *et al.* (1973), who showed that the coefficient of thermal expansion was lower in wet wood than in dry one. In that light, the thermal expansion of wood seems to decrease as a function of water content even without the loss of water from the stem.

The samples in this study were taken from fairly young stems of diameters 8.3–13.6 cm. The conifer samples that were most likely to have heartwood (*see e.g.* Tsoumis 1991) were the smallest ones and no heart wood formation was observed. However, if heartwood were present and the water content there was considerably lower than in sapwood (usually the

case in conifers), the thermal expansion of the wood (first term in Eq. 3) would consist of two parts, one coming from the sapwood and the other from the heartwood. In that case the coefficients of thermal expansion for timber could be used as a first approximation for the coefficient of heartwood. In field conditions however, the temperature variation deep inside the stem (*i.e.* in heartwood) is smaller than in the surface and although the coefficient of expansion would be higher for heartwood, its contribution to the total thermal expansion may not be significant unless talking about large stems (*see* discussion below).

The accuracy of our measurement system can be considered high. The maximum error in the coefficients of thermal expansion due to the inaccuracy of temperature, diameter change and length measurements was estimated to be $0.3 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$. However, the measurement results, except for *Pinus sylvestris* L., had unexpectedly high deviation.

The cell walls of xylem cells consist mainly of cellulose, hemicellulose and lignin (*see e.g.* Kramer and Kozlowski 1979: pp. 445–493). The molecules of these substances are built up from chains of carbohydrates. Thus, the molecular structure of wood material resembles the structure of polymers. Cellulose and hemicellulose molecules are packed together and organized to form microfibrils. In different layers of the cell wall the microfibrils are oriented to different directions (*e.g.* Bidlack *et al.* 1992) forming a net-like ordered structure. In larger scale also the xylem cells form an oriented net structure where the directions are not similar. In polymers, this type of a structure may lead to negative thermal expansion due to the bending of void walls, although the actual length of the unit elements of the material increases (Lakes 1996). A similar behavior may lead to the decrease in the coefficient of thermal expansion in wood saturated with water. Also the high deviation of the measurement results could be explained by the complex net-like structure that differs from sample to sample. This might as well explain the problems with quick heating and cooling.

The coefficients for thermal expansion of wood presented here are of the same order of magnitude as the thermal expansion of steel. The measurement setup in Fig. 1 is such that the

effects of thermal expansion of wood and frame bars have an opposite influence on the sensor. In this experiment that sets additional requirements for the accuracy of the measurement of thermal expansion of the steel bars. Our two independent measurement setups for α_F (one with frame without a wood sample, the other with separate heat bath with LVDT outside) gave similar results and the inaccuracy in those measurements add an error of $\pm 0.5 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ to determined α_w . However, the coefficient of thermal expansion of metal alloys varies with the composition and if we used the value $10 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ given for steel in tables the example in Fig. 3 would give $7.5 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for α_w .

In the case of field measurements of stem diameter variations the thermal expansion of the frame is nearly balanced by that of the wood and the total thermal correction (wood and frame) required for the diameter measurements is considerably smaller than when using the negative thermal expansion coefficients in the literature. In fact, if the coefficient for wood exceeds that of the frame, the sign of the correction changes so that the measured amplitude increases after the temperature correction (compare e.g. Irvine and Grace 1997).

The temperature of the stem might differ from that of the air (and the frame), especially when the sun is warming some parts of the stem or cool water is moving from the soil to the stem. The most thorough study of the temperature field inside a stem we found was made by Stockfors (2000), who measured the temperature of tree stem (*Picea abies*) from 40 positions (four heights) taking sample weeks around a whole year. He found that the mean variation of the temperature inside the stem was $3.7 \text{ }^\circ\text{C}$. However, the variation was greater than $10 \text{ }^\circ\text{C}$ for more than 8% of the time and the maximum variation was $21.5 \text{ }^\circ\text{C}$. The temperature profile at each height was quite homogenous in the mornings. In the afternoons, especially in the summer, the temperature could vary even $6 \text{ }^\circ\text{C}$ depending on the warming of the sun. In addition to that, Leikola (1969) reported that the difference between air temperature and the temperature of the cambium layer was $3 \text{ }^\circ\text{C}$ at maximum in pine trees (*Pinus sylvestris*). The stem was usually warmer than the air. The only case when the

stem was cooler was on very warm mornings (air temperature $> 15 \text{ }^\circ\text{C}$). However, Leikola reported results from measurements at the height of 1.3 m measured only three times a day during summertime. Also Silins *et al.* (2000) showed results for measurements of stem temperature. They measured lodgepole pine at 1.3 m height and 3.5 cm depth in winter. The temperature of the stem followed that of the air with a time lag of about 6 h. In spring the maximum temperature of the stem started to exceed the air temperature by $2\text{--}3 \text{ }^\circ\text{C}$.

Calculating the stem temperature from the air temperature is a highly complicated task requiring knowledge of parameters such as solar radiation, wind speed and direction inside the forest, heat conductivity of different wood tissues and convective heat transfer between the stem surface and the air. Derby and Gates (1966) presented a fairly simple simulation model for that purpose, but the amount of initial parameters listed above makes the use of this method unsuitable for simple correction of diameter variation measurements.

The measurements of Stockfors (2000) showed that, in most cases, the temperature field inside a stem consists of coaxial isothermal circles and the temperature decreases towards the center of the stem. Only at the top where the warming of direct radiation is high and the stem relatively thin, the temperature zones cut the stem linearly, so that the highest temperatures are in the direction of the sun.

If we limit the acceptable inaccuracy of diameter variation due to thermal expansion of wood to $1 \text{ } \mu\text{m}$ and, to give a conservative estimate, take $\alpha_w = 20 \times 10^{-6} \text{ K}^{-1}$, temperature variation in the stem should exceed $5 \text{ }^\circ\text{C}$ over a length of 1 cm and $1 \text{ }^\circ\text{C}$ over 5 cm to become important. This means that local temperature variation in the scale of 1 cm and smaller can be totally ignored and at each measurement height the stem can be assumed to be isothermal most of the time. Thus one point measurement of xylem temperature close to a diameter variation sensor is sufficient for correcting diameter variation measurements. Only at locations where direct radiation warms the stem considerably or with stems that exceed 15 cm in diameter special attention should be paid to stem temperature measurements. In the first case, use of proper shades homogenizes the temperature field inside the stem and by install-

ing the sensors perpendicular to the direction of incoming radiation measuring over varying temperature field can be avoided. In the second case installation of two temperature sensors in different depths gives the required information. If accurate values for diameter variation of the bark tissue are wanted, the temperature of bark surface should be detected as well.

Conclusions

The negative coefficients of thermal expansion for moist wood reported in literature (Kubler *et al.* 1973, Salmén 1990) have been argued to result from the changes in the water content of the samples when heated. We used a water bath for heating the samples and they were all the time totally in the water. Thus, the water content of the samples remained constant.

This study showed that the coefficient of thermal expansion of moist wood is positive. The values presented here were of the same order of magnitude as the coefficient for steel. Thus, the correction for the effects of thermal expansion in field measurements of tree stem diameter variations are dominated by the difference in the temperature of the frame and the stem. This emphasizes the importance of proper shading of the measurement system where direct sunlight might lead to inhomogeneous temperature profiles. To obtain reliable values for stem shrinkage and swelling, temperature profiles of the stem should be measured and compared with the air temperature. With the above-mentioned setup, diameter variations can be detected with reasonable accuracy and used e.g. for calculating water tensions in different tissues (*see e.g.* Perämäki *et al.* 2001). However, comparisons of diameter variations can be made reliably in the cases when the temperatures of the frames are known and the temperature profile of the stem can be assumed to be similar in the compared measurement locations.

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Received 29 March 2005, accepted 29 June 2005