Plant, Cell and Environment (1994) **17**, 867–874

TECHNICAL REPORT

A gauge to measure the mass flow rate of water in trees

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ABSTRACT

A gauge that measures the mass flow rate of water in a growing tree is described. The gauge consists of an electric band heater wrapped around a section of the stem, a temperature controller that switches the current to the heater on and off so as to maintain a constant temperature rise across the heated section, and a timer to record the total time for which the heater is switched on. An energy balance shows the mass flow of water to be proportional to the time of operation of the heater. The magnitude of measurement errors is estimated using dimensional analysis and a numerical model. Experimental measurements of the flow rate of water in a tree using the gauge agree well with its recorded loss of weight.

Key-words: heat balance; sap flow; transpiration; water use.

INTRODUCTION

The movement of heat within a plant stem has been used by many researchers as an indicator of the flow rate of water in the xylem. The first application of this technique was the heat pulse method, the theoretical basis of which is described by Marshall (1958) and Swanson & Whitfield (1981). Many of the early studies carried out using this method have been listed by Cermak, Deml & Penka (1973). Typically, heat was applied to a point on the tree stem in a brief pulse; a temperature sensor placed downstream of the heat source detected the passage of this pulse. The time taken for the heat to travel from the source to the detector could be correlated with the flow velocity of water in the stem. Although this gave a measure of the velocity, the stem area through which water was transported had to be known to calculate the mass flow rate.

Difficulties in accurately estimating the flow area led to the adoption of the stem heat balance technique, which provides a direct measurement of water mass flow rates. This method uses an energy balance over a control volume consisting of a section of the tree stem. An electrical heater provides a known heat input (q_i) to this section. Insulation is wrapped around the stem, extending above and below the heated segment. Heat transfer from the control volume takes place either by heat conduction axially along the stem in the upward (q_u) or downward (q_d) direction, by radial conduction (q_r) through the insulation, or by convection in the water flow in the stem (q_s). The conduction fluxes are estimated by measuring the temperature gradients at the control volume boundaries. Assuming steady-state conditions, the water mass flow rate ($\mathring{m}$) may be calculated from the energy balance equation

$$q_s = q_i - (q_u + q_d + q_r) = \mathring{m}\, c_s\, (T_u - T_d), \qquad (1)$$

where T_u and T_d are the stem temperatures measured above and below the heated section (see 'Appendix' for abbreviations).

Two different approaches to implementing the heat balance method have been proposed. One method is based on providing a constant heat input (q_i) to the stem, and continuously monitoring temperature variations along the stem. An alternate procedure is to vary q_i, so as to hold the temperature increase ($\Delta T = T_u - T_d$) across the heated section constant.

The constant heat input technique was first implemented by Sakuratani (1981, 1984), and has since been used in several other studies (Baker & van Bavel 1987; Steinberg, van Bavel & McFarland 1989, 1990b; Ham & Heilman 1990; Steinberg, McFarland & Worthington 1990a). The gauge consists of an electric band heater that provides a steady, known heat input to the section of the stem around which it is wrapped. Temperatures along the stem and insulation are measured using thermocouples whose outputs are recorded continuously by a datalogger. Temperature gradients are estimated from the difference between temperatures measured by two thermocouples separated by a known distance.

This gauge has the advantages of being non-intrusive and simple to construct. However, each gauge needs individual calibration to obtain a value of the sheath conductance, which is a heat transfer coefficient that relates radial heat conduction to the temperature difference across the insulation. Calculation of heat losses by axial conduction requires values for the thermal conductivity of the wood and the stem cross-sectional area, properties that may vary with wood porosity and moisture content. Precise placement of thermocouples is required, since the measurement of temperature gradients is sensitive to the spacing between the temperature sensors. Also, steady-state conditions have

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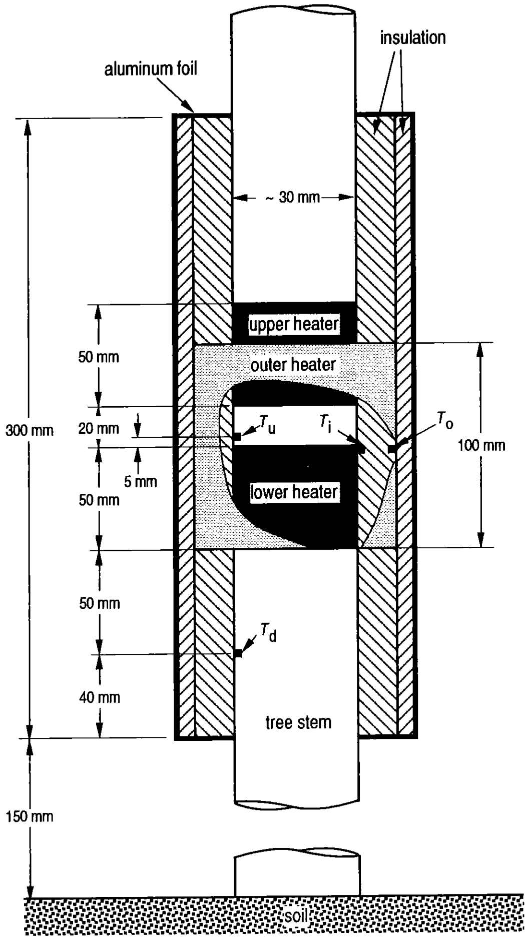

Figure 1. A diagram of the gauge. T_u and T_d are the temperatures measured by thermistors above and below the lower heater. T_i and T_o are the temperatures measured on the inner and outer faces of the insulation.

to be re-established after a change in water flow, causing a lag in the response of the gauge to rapid changes in flow rate (Steinberg, *et al.* 1989). Inability to control heat input to the stem is another disadvantage of using a constant heat input method, because under low flow conditions little heat is carried away from the heated section of the stem by convection so that the stem temperature may increase, possibly damaging the plant. An increase in T_i also increases radial losses such that q_r may become an order of magnitude larger than q_s (Ham & Heilman 1990), magnifying uncertainties in the measurement of the sheath conductance. Conversely, at high flow rates ΔT becomes small, making accurate measurement of temperature differences more difficult (Shackel *et al.* 1992). Extensive testing of a constant heat input gauge (Devitt *et al.* 1993) found an average error of 18% in the measurement of cumulative flow over periods ranging from 14 to 72 h.

An alternate implementation of the heat balance method that avoids many of the drawbacks of the constant heat input technique is to hold ΔT constant by varying q_i. In the gauge developed by Cermak *et al.* (1973) and Cermak, Kucera & Penka (1976), vertical stainless-steel plates inserted into a section of the stem act as electrodes. An electric current passed through the plates heats the wood in the space between them. The voltage across the electrodes is varied continuously so as to keep a constant temperature difference between the heated and unheated section of the stem, and the energy input q_i is measured by continuously recording the magnitude of the voltage and current. The energy balance equation (1) then shows ($\mathring{m}$) to be proportional to q_i for constant ΔT, if radial and axial conduction losses are neglected.

Since the water temperature rise is controlled, overheating of the stem is prevented. Also, because ΔT remains constant, the gauge response is not limited by the time needed to re-establish steady-state conditions after a change in flow rate. However, the method is intrusive, requiring insertion of electrodes, which makes it unsuitable for smaller stem sizes. Only the mass of water that passes between the electrodes is measured and the data have to be extrapolated to give the water flow through the entire stem. Also, the control unit required continuously to vary and to record the voltage supplied to the electrodes is quite complex and requires an AC power supply, which may restrict the use of this method in the field.

The limitations of the available techniques motivated our attempt to develop a gauge that would provide a direct measure of the mass flow of water in an intact plant stem. Our objective was to provide a measurement technique that would require no calibration; be independent of the physical properties or dimensions of the plant; be insensitive to the location of the temperature sensors; respond rapidly to changes in the flow rate; and be adaptable to different stem sizes. Finally, to permit use of the gauge in the field, the associated electronic control and measuring unit had to be portable, inexpensive, and simple to use.

MATERIALS AND METHODS

Gauge design

Figure 1 is a diagram of the gauge, showing the dimensions and layout of its components. A thin flexible band heater (labelled 'lower heater') was wrapped around a section of the stem. The stem temperatures above (T_u) and below (T_d) the heated segment were measured using thermistors.

The gauge was based on a design in which ΔT was held constant. However, rather than continuously varying the heater voltage, a temperature controller (described below) switched the heater on and off so as to hold steady the difference (ΔT) between the temperatures measured by the upper and lower thermistors. The controller activated a clock whenever power was supplied to the heater, and a digital display indicated the cumulative time in seconds for which the heater had been switched on.

If m is the mass of water that flows through the heated section of the stem in a given time interval, during which the heater supplies power P for a total duration t_h, an energy balance (neglecting conduction losses) gives

$$P\,t_h = m\,c_s\,\Delta T. \tag{2}$$

For constant (and known) P, ΔT and c_s, m is directly proportional to t_h, which can be read directly from the clock display. Since there is no need to record temperatures or voltages, the cost and complexity of the equipment required are greatly reduced, making it a robust technique for field use.

Holding ΔT constant using a single heater proved difficult in practice. The temperature rise in response to the heater being switched on occurred first at the mid-point of the heated length of the stem. The upper thermistor – located at the edge of the heater – detected the temperature change after a significant delay, giving rise to a lag in the response of the temperature controller. This problem was solved by placing a second heater (labelled 'upper heater' in Fig. 1) around the stem a small distance above the first. The two identical heaters were connected in parallel, and switched on and off simultaneously. Since the thermistor was now near the point where the stem temperature first responded to a heat input, the controller response was rapid.

Heat losses by conduction are neglected in the energy balance equation (2). This allows direct measurement of water flow, without the use of any correction factors. For this assumption to be valid, the gauge has to be designed so that conduction losses are negligible compared to convective heat transport.

The largest heat loss occurs by radial conduction through the insulation surrounding the heated section of the stem (Ham & Heilman 1990). The conduction rate (q_r) is proportional to the temperature difference ($T_i - T_o$) across the insulation, and can be minimized by forcing the temperature on the outside of the insulation to match that on its inside. To achieve this, a heater (labelled 'outer heater' in Fig. 1) was wrapped around the outside of the insulation. A second temperature controller switched this outer heater on and off so as to maintain $T_o = T_i$, the two temperatures being measured by thermistors placed on the inner and outer faces of the insulation.

Heat loss by axial conduction in the downward direction (q_d) may be eliminated from the energy balance if the reference temperature T_d is measured at a point sufficiently far below the heater that the temperature field at that location is not influenced by heat conducted along the stem. Experiments and numerical calculations indicated that measurement of T_d at a distance equal to the heater width was adequate to achieve this.

Axial conduction losses in the upward direction (q_u) cannot be eliminated directly from the heat balance. However, a simple order-of-magnitude analysis shows that the axial conduction heat flux is a function of the heater width (L), and that selection of a suitable heater width can ensure that $q_u \ll q_s$. Heat transfer in the stem is governed by the energy transport equation, written in axisymmetric, cylindrical coordinates as (Baker & Nieber 1989)

$$k_w^r \frac{1}{\rho}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + k_w^z \frac{\partial^2 T}{\partial z^2} - \rho_s c_s u \frac{\partial T}{\partial_z} = \rho_w c_w \frac{\partial T}{\partial t} \tag{3}$$

with boundary conditions

$$T - T_d = 0 \qquad \text{at } z \to -\infty, \tag{4a}$$

$$\frac{\partial T}{\partial z} = 0 \qquad \text{at } z \to \infty, \tag{4b}$$

$$\frac{\partial T}{\partial r} = 0 \qquad \text{at } r = 0, \tag{4c}$$

$$-k_w^r \frac{\partial T}{\partial r} = P/\pi DL \qquad \text{at } r = D/2, \text{ over the heated portion of the stem}$$
$$= 0 \qquad \text{at } r = D/2, \text{ over the insulated portion of the stem,} \tag{4d}$$

and the initial condition

$$T - T_d = 0 \qquad \text{at } t = 0. \tag{4e}$$

The energy equation (3) is non-dimensionalized by defining the dimensionless variables $r^* = r/D$, $z^* = z/L$, $u^* = u/U$, $t^* = Ut/L$, and $T^* = (T - T_d)/(T_u - T_d)$. U is a characteristic velocity for water flow in the stem, defined by $U = \mathring{m}/\rho_s A$. We can then write equation (3) in the form

$$\frac{1}{Pe}\frac{L^2}{D^2}\frac{k_w^r}{k_w^z}\frac{1}{\rho^*}\frac{\partial}{\partial r^*}\left(r^*\frac{\partial T^*}{\partial r^*}\right) + \frac{1}{Pe}\frac{\partial^2 T^*}{\partial z^{*2}} - \frac{\rho_s c_s}{\rho_w c_w} u^* \frac{\partial T^*}{\partial z^*} = \frac{\partial T^*}{\partial t^*}, \tag{5}$$

in which Pe is the Peclet number, defined as

$$Pe = \frac{\rho_w c_w U L}{k_w^z} \tag{6}$$

(Incropera & DeWitt 1990).

The three terms on the left-hand side of equation (5) represent heat fluxes by radial conduction, axial conduction and convection, respectively. Since the dimensionless variables are of order unity, axial conduction losses are negligible compared to convection if

$$Pe \gg \frac{\rho_w c_w}{\rho_s c_s}. \tag{7}$$

An increase in the magnitude of Pe therefore reduces the measurement error resulting from axial conduction. The value of Pe is proportional to $\mathring{m}$ (which is large at high flow rates) and L (which is increased by selecting a wider heater). Experimental measurements (Ham & Heilman 1990) confirm that axial conduction losses are negligible compared to convective heat transfer for all but the smallest flow rates, and decrease as the heater width is increased.

A suitable value for the heater width (L) was calculated assuming typical values for the physical properties of water and moist wood to be (Swanson & Whitfield 1981; Incropera & DeWitt 1990) $k_w^r = 0{\cdot}38$ W (m °C)$^{-1}$; $k_w^z = 0{\cdot}76$ W (m °C)$^{-1}$; $\rho_w = 435$ kg m^{-3}; $c_w = 3180$ J (kg °C)$^{-1}$; $\rho_s = 1000$ kg m^{-3}; and $c_s = 4186$ J (kg °C)$^{-1}$. The tree diameter was taken to be $D = 30$ mm (the size used in our experiments), with a stem of circular cross-section so that $A = \pi D^2/4$. For a flow rate $\mathring{m} = 100$ g h^{-1}, equation (7) reduces to the requirement that $L \gg 5$ mm; selection of $L = 50$ mm satisfies this condition. Conduction losses would therefore be expected to be negligible at flow rates equal to or greater than 100 g h^{-1}. At very low values of $\mathring{m}$ (< 20 g h^{-1}), however, axial conduction may become more significant, increasing the error in measurement. In practice we found that the upper heater reduced temperature gradients at the edge of the lower heater, minimizing axial losses even at low flow rates.

The energy balance equation (2) neglects any radial temperature gradients in the stem, assuming instead that the temperatures T_u and T_d are uniform across the entire cross-section. This assumption is reasonable if radial heat conduction fluxes are much larger than axial fluxes; i.e., comparing the radial conduction and convection terms in the dimensionless energy equation (5), if

$$\frac{1}{Pe}\,\frac{L^2}{D^2}\,\frac{k_w^r}{k_w^z} >> \frac{\rho_s c_s}{\rho_w c_w}. \tag{8}$$

Substituting in equation (8) the physical property data listed above, we find that for $\mathring{m} = 100$ g h^{-1} we need $L >>$ 400 mm. Physical limitations on the size of the gauge prevent this condition from being satisfied, so that significant radial temperature gradients will be present, and will grow larger as $\mathring{m}$ increases.

A numerical solution of the energy transport equation was required to calculate the magnitude of the radial temperature gradients and to estimate the resulting error in the water flow measurement. A finite difference approximation of the transient energy equation (3) in cylindrical coordinates, combined with the boundary and initial conditions (4*a–e*), was solved using an alternating direction implicit (A.D.I.) method (Ferziger 1981). The origin of the coordinate system was established such that $z = 0$ corresponds to the axial location of the lower thermistor, and $r = 0$ to the stem centre-line. We adopted a uniform mesh spacing of 1·5 mm in the radial direction and 1·67 mm in the axial direction, and a time-step of 5 s. The physical properties of wood and water were assumed to be constant, with the values listed above. Results of the simulation are reported in this paper for a gauge with the dimensions shown in Fig. 1, with the upper and lower heaters each having a power of 2·32 W. The heaters were switched on and off in the numerical model so as to hold $\Delta T = 3{\cdot}5$ °C.

The model was initially run assuming the water flow velocity to be uniform across the stem cross-section, with the temperature sensors placed on the stem surface, leading to the prediction that radial temperature gradients increase

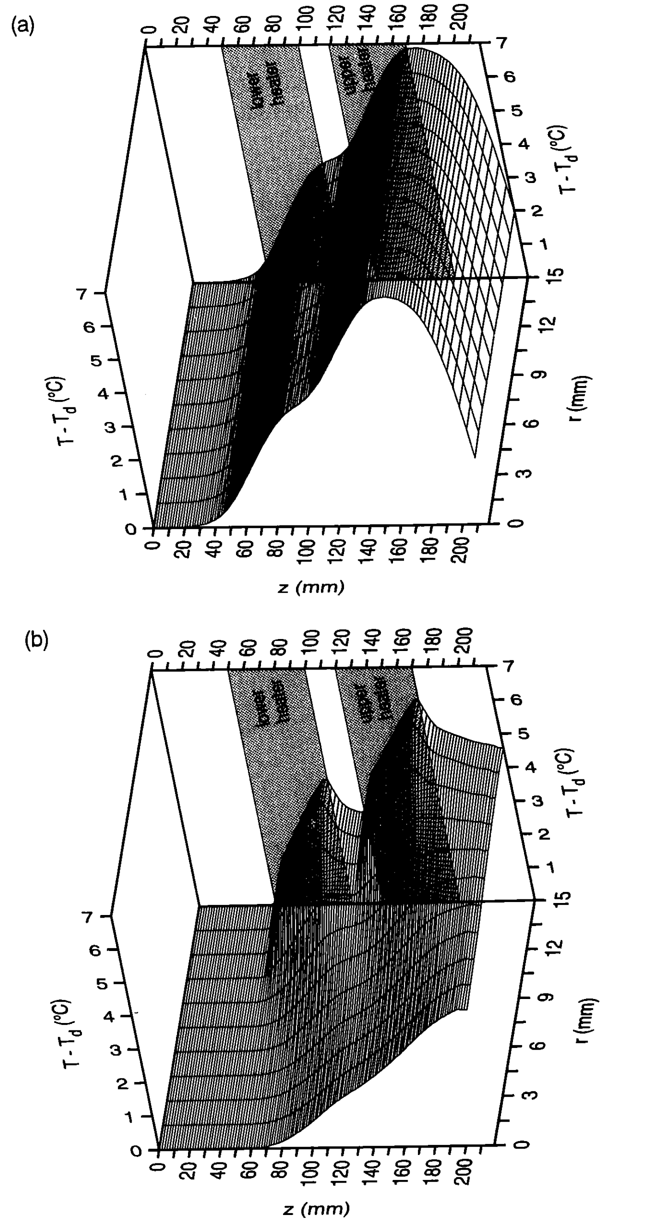

Figure 2. Temperature distribution in the stem for a water flow rate of (*a*) 50 g h^{-1}, and (*b*) 400 g h^{-1}. r is the radial coordinate, measured from the stem centre-line; z is the axial coordinate, measured from the location of the lower thermistor; T is the stem temperature, and T_d is the temperature measured by the thermistor below the heaters.

with larger water flows in the stem. Physically, as flow increases more energy from the heaters is convected downstream instead of being conducted to the axis of the stem. The calculated stem temperature distribution is shown in Figs 2a and b for water flow rates of 50 and 400 g h^{-1}, 90 min after the heater was switched on (after which time the temperature field showed little further change). The difference between the temperatures at the stem surface ($r = 15$ mm) and the stem centre ($r = 0$) was less than 0·2 °C for $\mathring{m} = 50$ g h^{-1} (Fig. 2a), whereas it exceeded 3·0 °C for

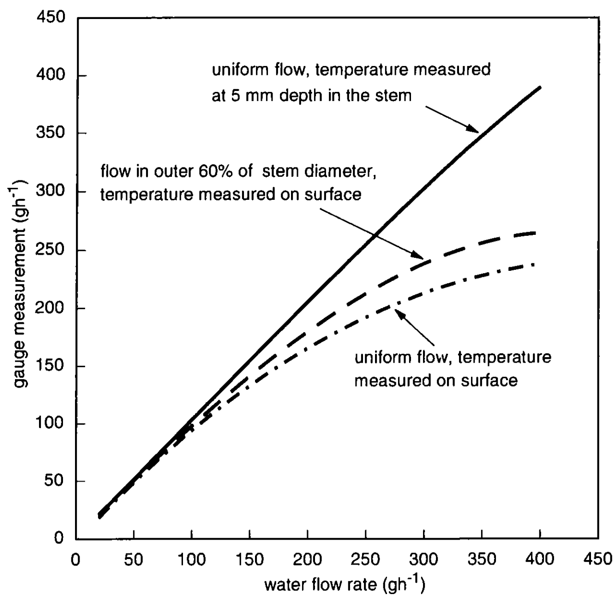

Figure 3. Results of the numerical simulation, showing the measurement error as a function of the flow rate.

$\mathring{m}=400\,g\ h^{-1}$ (Fig. 2*b*). These temperature gradients can cause large measurement errors at high flow rates. Figure 3 shows that the simulated gauge measurement underestimates the flow by almost 40% at $\mathring{m}=400\,g\ h^{-1}$.

We next considered the case where flow in the stem was assumed not to be uniform, but to be confined to an annular region. The central area of the stem was considered to be heartwood, through which no flow occurs (Cermak *et al.* 1992). Narrowing of the flow area reduces the radial temperature gradients, improving the measurement accuracy. Figure 3 shows the predicted gauge measurements when water flows only in the outer 60% of the stem diameter.

The accuracy of the gauge could be greatly improved by using a better estimate of the average temperature across the stem, obtained by measuring T_u and T_d at some depth in the stem, rather than at the surface. When the model was run with the temperature sensors placed at a depth of 5 mm, the predicted measurement error was reduced to less than 3% (Fig. 3). In the experiment, the thermistors were therefore inserted into radial holes drilled into the stem.

Gauge construction

The positions of the heaters and temperature sensors in the gauge are shown in Fig. 1. Flexible etched foil Kapton heaters were used to provide the heat input. The lower and upper heaters were both 50 mm x 135 mm in size, with a resistance of 62 Ω (Model No. 5413, Minco Products Inc., Minneapolis, MN); the outer heater was 100 mm x 300 mm, with a resistance of 35 Ω (Model No. 5491, Minco Products Inc., Minneapolis, MN). The heater length was slightly greater than the circumference of the tree, so that the ends overlapped when they were wrapped around the stem; the overlap did not appear to affect the measurements. A regulated 12 VDC power supply provided current to the heaters, so that the power ($P=V^2/R$) of the lower heater was 2·323 W.

A 19 mm thick layer of polyurethane foam insulation, with a density of 64 kg m^{-3}, was wrapped around the heated portion of the stem. The outer heater was placed over this insulation, and covered with another thin layer of insulation. The entire gauge was then covered with aluminum foil, to eliminate any radiant heating effects.

Stem temperatures were measured using thermistors with a bead diameter of 2·5 mm. The thermistors were inserted in 3 mm diameter holes, drilled radially in the tree trunk to a depth of approximately 8 mm. The thermistor beads were coated with a thermal compound (Omegatherm 201, Omega Engineering Inc., Stamford, CT) to provide good thermal contact with the stem. An independent measurement of the temperature was provided by 0·13 mm diameter copper–constantan (type T) thermocouples which were positioned with their beads touching the thermistors. The thermocouple temperatures were read using a digital thermometer (Model No. HH-23, Omega Engineering Inc., Stamford, CT) with a resolution of 0·1 °C. Values of ΔT measured with the thermocouple and thermistors agreed to within 0·1 °C.

Figure 4 shows a schematic diagram of the temperature control circuit used to regulate the heaters so as to hold ΔT constant and $T_i = T_o$. T_u and T_d were measured by linear thermistors (Model No. 44204, YSI Inc., Yellow Springs, OH) which have a positive temperature coefficient and give an output of 0·01 V °C^{-1} when supplied an excitation voltage of 1·775 V. An instrumentation amplifier took the difference between the outputs of the two thermistors and amplified it with a gain of 10, providing a linear signal of 0·1 V °C^{-1} proportional to ΔT. This signal was connected to the negative input of a comparator, the positive input of which could be held at any voltage from 0–1 V, corresponding to setting the required value of ΔT between 0 and 10 °C. The comparator output would be high if the difference between its two inputs was positive (i.e. if ΔT was lower than the required value), switching the upper and lower heaters on. The resulting heat input to the stem would increase ΔT, raising the voltage at the negative input of the comparator. When the negative input voltage was higher than that of the positive input, the comparator output decreased, switching the heaters off. A clock with a resolution of 0·0001 s was connected to the comparator output, and activated whenever the heaters were switched on. The cumulative time of operation of the heaters was rounded off to the nearest second and displayed on a six digit display. A similar circuit was used to control the outer heater. T_i and T_o were measured using thermistors (Model No. 44004, YSI Inc., Yellow Springs, OH) with a negative temperature coefficient. The thermistors were placed in a Wheatstone bridge circuit whose nodes were connected to the inputs of a comparator (Fig. 4). The comparator switched the outer heater on and off as required to hold $T_i=T_o$. The controller was found to be capable of holding ΔT constant to within ±0·1 °C of the pre-set value, and $|T_i - T_o| \leq 0.2$ °C, as measured by both the thermistors and the thermocouples.

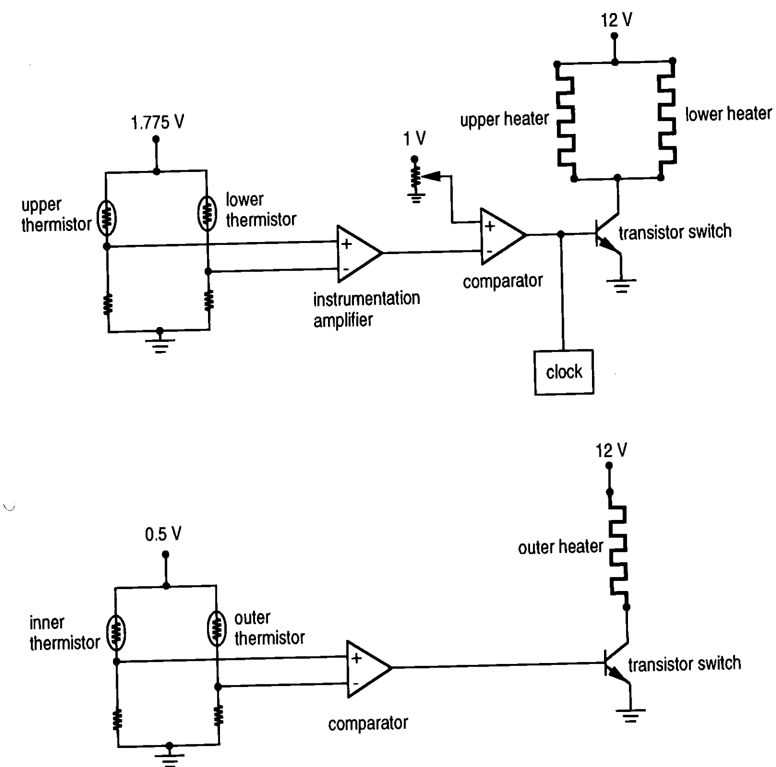

Figure 4. Diagram of the temperature control circuit.

Two sets of tests were performed to evaluate the gauge performance. The first set was conducted in October and November 1991 on a crab apple tree (*Malus* 'Spring Snow') with a trunk diameter of approximately 30 mm over the section where the gauge was located. Experiments in the period May to July 1992 were carried out on a green ash (*Fraxinus pennsylvanica*) with a trunk diameter of 36 mm. Both trees were planted in 0·076 m^3 plastic containers and placed in a greenhouse at Cornell University. The only modification made to the gauge when it was transferred from the first tree to the second was that the thickness of the polyurethane insulation was reduced from 19 mm to 12 mm.

A flow measurement test was started by watering the soil in which the tree was planted and allowing the container to drain overnight. The soil surface was covered with a layer of 3 mm diameter plastic pellets to reduce water evaporation, and the container top covered with a plastic sheet. The tree and container were placed on a weighing scale which had a 54 kg capacity and a resolution of 1 g. All weight loss recorded was assumed to be the result of transpiration from the tree foliage.

RESULTS AND DISCUSSION

Results from a test conducted over a 72 h period, from 10 to 13 November 1991, are shown in Table 1. The temperature controller and heaters were switched on at 10:00 am on 10 November. After 90 min, a steady state was reached, at which time ΔT was constant at 3·6 °C. The clock reading (t_h) was zeroed at 11:30 am. The clock reading and the tree weight were noted periodically during daylight hours for the next 3 d.

Table 1 lists the tree weight loss recorded and the clock reading, as well as the calculated water flow. The cumulative mass flow of water was calculated as being $m = 0{\cdot}1541 t_h$ (with m in grams and t_h in seconds), where the constant of proportionality was calculated by substituting values of $P = 2{\cdot}323$ W, $\Delta T = 3{\cdot}6$ °C, and $c_s = 4{\cdot}186$ J (g °C)$^{-1}$ in equation (2).

The calculated mass flow of water, integrated over a time period longer than 2 h, agreed with the tree weight loss to within 3% (see Table 1). Measurements over a shorter interval (<30 min) could differ by as much as 20%. One possible explanation for this disagreement may be the existence of a time lag between stem flow and transpiration from the foliage (Steinberg *et al.* 1989). A second source of error may lie in the time taken for the insulation in the gauge to adjust to changes in the stem temperature below the gauge. We observed that during intervals in which T_d increased suddenly (as happened when the ambient temperature rose) some of the energy from the heater was used to raise the temperature not only of the water, but also of the insulation, so that the gauge read high. Conversely, when T_d dropped rapidly, the stem withdrew heat stored in the insulation and the gauge read low. Averaged over periods

Date	Time of day	Clock reading (s) t_h	Weight loss (g)	Flow (g) $m=0{\cdot}1541t_h$	Difference (%)
10 Nov	11:30	0	0	0	0
	12:01	307	47	47	0
	12:33	558	103	86	−16·5
	13:01	1004	179	155	−11·2
	13:31	1546	245	238	−0·9
	14:42	2598	409	400	−2·2
	15:02	2957	459	456	−0·7
	15:32	3312	509	510	0·2
11 Nov	10:24	8144	1254	1255	0·1
	11:03	8512	1301	1312	0·8
	11:30	8794	1338	1355	0·3
	13:51	10778	1617	1661	2·7
	14:53	11599	1736	1787	2·9
	15:55	12139	1823	1871	2·6
	16:16	12326	1852	1899	2·5
12 Nov	8:48	16809	2560	2590	1·2
	9:20	17193	2611	2641	1·1
	10:07	17740	2694	2734	1·5
	10:44	18281	2775	2817	1·5
	11:24	18907	2865	2914	1·7
	12:40	19954	3012	3075	2·1
	13:16	20542	3099	3166	2·2
	14:48	21693	3266	3343	2·4
	15:20	22025	3312	3394	2·5
	16:17	22560	3392	3476	2·5
13 Nov	8:37	27468	4146	4233	2·1
	11:17	29432	4426	4535	2·1

Table 1. Experimental measurements of water flow and plant weight loss over a 72 h period.

longer than 1 h, these errors cancelled out. This influence of ambient temperatures on gauge accuracy has been noted by Shackel *et al.* (1992), in experiments with a gauge based on a constant heat input design.

To reduce the thermal capacity of the insulation we decreased its thickness from 19 mm to 12 mm. The improvement in the time response can be seen in Fig. 5, where flow rate measurements – averaged over 1 h intervals – are compared with the weight loss of the tree. The stem, soil and ambient air temperatures measured with thermocouples over the same period are also shown; thermocouple outputs were recorded by a datalogger at 15 min intervals. The maximum difference between the flow rate measured by the gauge and weight loss was 11% (at 1:00 pm). However, the cumulative mass flow measured over the 24 h period was within 0·6% of the total weight lost by the tree.

A certain amount of caution needs to be exercised when the gauge is used in very hot weather, when flow measurement errors can arise. Radial heat losses from the gauge were controlled by the outer heater, which increased T_o to make it equal to T_i. This assumes, though, that ambient air temperatures will always be less than T_o. However, on some very hot days (air temperature >42 °C), water taken from the soil cooled the stem so much that the temperature on the outside of the insulation was lower than that of the air. Heat was conducted radially inwards from the air to the tree stem through the insulation, and the outer heater was ineffective in preventing this. This heat input was

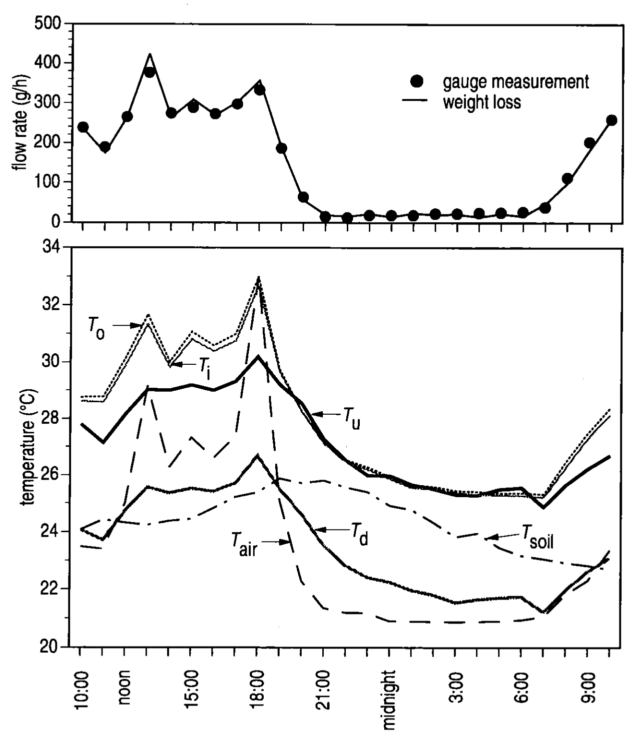

Figure 5. Variation of flow rate and temperatures on 16/17 May. T_u and T_d are the temperatures measured above and below the lower heater, while T_i and T_o are those measured on the inner and outer faces of the insulation. T_{air} and T_{soil} denote the temperatures of the ambient air and of the soil in the container that the tree was planted in.

unaccounted for in the energy balance, so that the gauge measurement was lower than the actual water flow in the tree. To minimize the possibility of erroneous measurements it is important to leave a sufficient portion of the stem below the gauge uninsulated, to ensure that water flowing in the stem warms up sufficiently to reach ambient temperatures before it enters the gauge. If a sufficient stem length is unavailable, a band heater placed around the stem could be used to heat the water. We have not, however, found it necessary to do this in our experiments so far. Further field tests are being carried out to determine the best location for the gauge.

CONCLUSIONS

A gauge has been constructed to measure the mass flow rate of water through a tree, using an energy balance method. A band heater is used to provide a known heat input to a section of the stem. The flow rate is calculated by equating this energy input to heat convection by the water; heat conduction is neglected.

Dimensional analysis shows that, for the heater width used (50 mm), axial conduction along the stem is negligible for significant water flow rates. Radial temperature variations could, however, be significant. A numerical model of the gauge was developed using a finite-difference approximation of the energy equation. Model predictions were used to estimate potential errors in measurement resulting from radial temperature gradients in the stem.

The gauge has been used to measure water flow in trees with stem diameters of approximately 30 mm. An independent measure of the water transpiration rate was obtained from the weight reduction of the potted trees. Gauge measurements agreed well with the recorded weight loss.

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APPENDIX: ABBREVIATIONS

A	stem cross-sectional area
c	specific heat
D	stem diameter
k	thermal conductivity
L	heater width
m	cumulative mass flow of water
$\mathring{m}$	mass flow rate of water
P	heater power $[= V^2/R]$
Pe	Peclet number $[= (\rho_w\, c_w\, U\, L)/k_w^z]$
q	heat flow rate
R	heater resistance
r	radial coordinate
T	temperature
ΔT	temperature rise across heater $[= T_u - T_d]$
t	time
t_h	total time for which the heater is switched on
U	characteristic velocity $[= \mathring{m}/(\rho_s A)]$
u	velocity of water flow
V	heater voltage
z	axial coordinate

Subscripts

u	above the heater
d	below the heater
i	inside the insulation
o	outside the insulation
r	radial
w	wood
s	water

Superscripts

r	in the radial direction
z	in the axial direction
*	dimensionless variable

Received 4 November 1993; received in revised form 21 December 1993; accepted for publication 18 January 1994