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MEASUREMENT OF THE MASS FLOW RATE OF WATER IN TREES

S. Chandra
Department of Mechanical Engineering
University of Toronto,
Toronto, Ontario M5S 1A4
Canada

P. Lindsey & N. Bassuk
Urban Horticulture Institute
Cornell University
Ithaca, New York 14853
U. S. A

ABSTRACT

A gauge is described to directly measure the mass flow rate of water in a tree. Principal components of the gauge are: 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 that the heater is switched on. An energy balance shows the mass flow rate 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 water flow in a tree using the gauge are found to show good agreement with its recorded loss in weight.

NOMENCLATURE

A	-	stem cross-section area
c	-	specific heat
D	-	stem diameter
K_{sh}	-	sheath conductance
k	-	thermal conductivity
L	-	heater width
m	-	cumulative mass flow of water
$\mathring{m}$	-	mass flow rate of water
P	-	heater power
Pe	-	Peclet number [$=(\rho_w c_w U L)/k_w^z$]
q	-	heat flow
R	-	heater resistance
r	-	radial coordinate
T	-	temperature
ΔT	-	temperature rise across heater [$=T_u - T_d$]
t	-	time
t_h	-	total duration for which the heater in 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	-	on the inside of the insulation
o	-	on the outside of the insulation
r	-	radial
w	-	wood
s	-	water

Superscripts

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

INTRODUCTION

Water is needed by plants for vital metabolic and physiological processes. The water is taken from the soil by the plant roots and moves upwards through the stem, with most of it finally evaporating into the atmosphere at the surface of the leaves in a process known as transpiration. A prolonged period of water deficit will lead to reduced growth for the plant, and eventually to premature mortality. The effect of water usage on plant growth and development, and the strategies used by plants to cope with water stress are of interest in plant biology and ecology. Methods to prevent water stress are of fundamental concern to commercial producers in fields such as agronomy and forestry. Plant transpiration may also have significant environmental impact, since adding or removing vegetation can influence the rate at which water is lost from the soil, altering local climate patterns. Any research into this interplay between climatic, plant, and soil factors requires an accurate technique to measure plant water use. On a more practical level, this information will promote the breeding of plants for water use efficiency and help direct more effective irrigation management strategies. Motivated by the significance of the application, extensive research has been conducted to develop methods of measuring water flow rates in growing plants.

The movement of heat within the plant stem was used by many early investigators to trace the flow of water (e.g., Marshall, 1958). Heat was applied to a point on the tree stem as 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. However, when used to calculate the mass flow rate, this method was limited by the need for additional information about the stem area through which water was transported.

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 (figure 1). A known heat input (q_i) is provided to this section using an electrical heater. Insulation is wrapped around the stem, extending above and below the heated segment. Energy transport from the control volume can then take place by either 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 due to the water flow in the stem (q_s). The conductive heat 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 then 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.

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

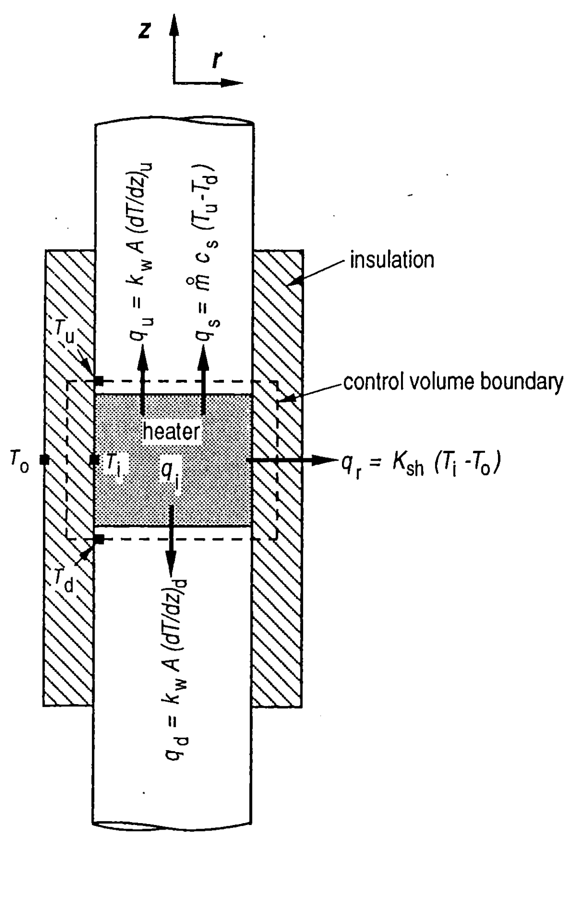


FIGURE 1 Stem heat balance method

The constant heat input technique was first implemented by Sakuratani (1981,1984) and developed further by Baker and van Bavel (1987), Steinberg, van Bavel, and McFarland (1989, 1990), Steinberg, McFarland, and Worthington (1990) and Ham and Heilman (1990). The gauge consisted of an electric band heater that provided a steady, known heat input to the section of the stem around which it was wrapped. Stem temperatures above (T_u) and below (T_d) the heater, and temperatures on the inner (T_i) and outer (T_o) surfaces of the insulation were measured using thermocouples whose outputs were recorded continuously by means of a datalogger. Temperature gradients along the stem were estimated from the difference between the output of two thermocouples separated by a known distance.

This gauge has the advantages of being non-intrusive and simple to construct. However, the gauge needs calibration to obtain a value of the sheath conductance (K_{sh}), which is a heat transfer coefficient that relates the radial heat conduction to the temperature difference across the insulation so that $q_r = K_{sh}(T_i - T_o)$. Calculation of axial conduction heat losses require values for the thermal conductivity of the wood (k_w) and the stem cross-sectional area (A), 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 temperature sensors. Also, steady state conditions have to be re-established after a change in water flow, causing a lag in the response of the gauge to rapid changes in the flow rate (Steinberg, van Bavel, and McFarland 1989). The inability to control the heat input to the stem is another major 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. Consequently the stem temperature rises, possibly damaging the plant. This increase in T_i also increases radial losses such that q_r may become an order of magnitude greater than q_s (Ham and Heilman 1990), magnifying uncertainties in the measurement of K_{sh}. Conversely, at high flow rates ΔT becomes small, making accurate measurement of temperature differences more difficult (Shackel et al., 1992).

An alternate implementation of the heat balance method, which avoids many of the drawbacks of the constant heat input technique, is one in which ΔT is held constant by varying q_i. In the gauge developed by Cermak, Deml and Penka (1973) and Cermak, Kucera and Penka (1976) a section of the stem is heated by the insertion of vertical stainless steel plates that act as electrodes. An electric current passed through the electrodes heats the wood in the space between them. The current is varied continuously so as to keep a constant temperature difference between the heated and unheated section of the stem; the energy input q_i is measured by continuously recording the magnitude of the 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, 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. Furthermore, only the mass of water that flows through the space between the electrodes is measured, and an extrapolation has to be made to give the water flow through the entire stem. It is also not certain if q_u and q_r can always be neglected, as conduction losses may be significant if flow rates are low.

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 non-intrusive measurement technique that would require no calibration; be independent of physical properties or dimensions of the plant; be insensitive to the location of the temperature sensors; would respond rapidly to changes in the flow rate; and could be adapted to different stem sizes. Finally, to permit use of the gauge in the field, the associated electronic control and measuring unit was required to be portable, inexpensive, and simple to use.

GAUGE DESIGN

The gauge was based on a design in which ΔT was held constant; the requirement that the measurement need no calibration or estimation of physical properties precluded use of the constant heat input technique. Figure 2 is a schematic of the gauge, showing the dimensions and layout of its components. A thin flexible band heater (labelled 'lower heater' in figure 2) was wrapped around a section of the stem. When a constant voltage V was placed across the heater, it provided a power input $P=V^2/R$ to the stem, where R was the heater resistance. The stem temperature above (T_u) and below (T_d) the heated segment was measured using thermistors. An analog temperature controller (described below in §3) switched the current to the heater on and off so as to hold steady the difference ΔT between the temperature measured by the upper and lower thermistors. ΔT could be set at any value from 0° to 10°C. The controller activated a clock whenever power was supplied to the heater; a digital display indicated the cumulative time in seconds that 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 in on for a total duration t_h, an energy balance gives (neglecting conduction losses):

$$P\, t_h = m\, c_s\, \Delta T \qquad (2)$$

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.

The power of the heater has to be enough to raise the temperature of the water by the required ΔT. Designing for maximum values of $\mathring{m}$=200 gm/hr and ΔT=5°C, and assuming that the heater is switched on for 50% of the total time, the energy balance equation (2) gives the required heater power $P \geq 2.32$ W.

Holding ΔT constant using a single heater proved difficult in practice, for two reasons. Firstly, at low flow rates the temperature rise sometimes exceeded the required value of ΔT. Figure 3*a* shows the axial temperature profile when a single heater is wrapped around the stem. At high flow, the maximum stem temperature is at the upper edge of the heater. When the flow is low, however, the maximum temperature occurs before the edge of the heater. In the limiting case of zero flow, heat transfer is by conduction alone, and the temperature profile is symmetric about the center of the heated section. The peak stem temperature is then greater than T_u, causing possible overheating of the stem (see figure 3*a*).

The second difficulty in holding ΔT constant with a single heater arose because the temperature rise in response to the heater being switched on occured first at the mid-point of the heated length of the stem. The upper thermistor, which was above the edge of the heater, detected this temperature change after a significant delay. This caused a lag in the response of the temperature controller, leading to a temperature overshoot.

Both these problems were solved by placing a second heater (labelled 'upper heater' in figure 2), around the stem a small distance above the first. The two identical heaters were connected in parallel, and switched on and off simultaneously. Figure 3*b* shows axial temperature profiles for the case of two heaters. The center of the heated section now lies between the two heaters, close to the location of the upper thermistor. Since the thermistor is near the point where the stem temperature first responds to a heat input, the controller response is rapid. Also, in the absence of any flow the peak temperature occurs near the thermistor location, preventing any excessive temperature rise.

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

The greatest heat loss occurs by radial conduction through the insulation surrounding the heated section of the stem (Ham and 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 figure 2) was wrapped around the outside of the insulation. A secondary temperature controller switched this outer heater on and off so as to maintain T_o=T_i, the two temperatures being measured by means of thermistors placed on the inner and outer faces of the insulation.

Heat loss due to axial conduction in the downward direction (q_d) may be eliminated from the energy balance (2), if the reference

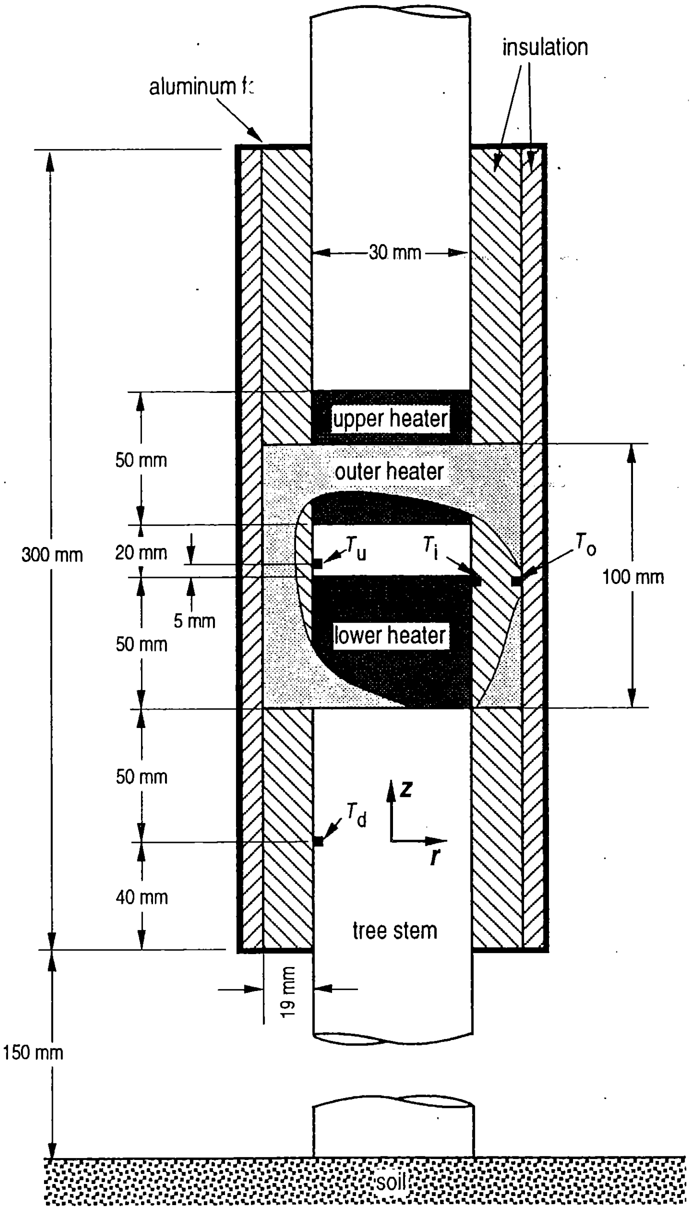
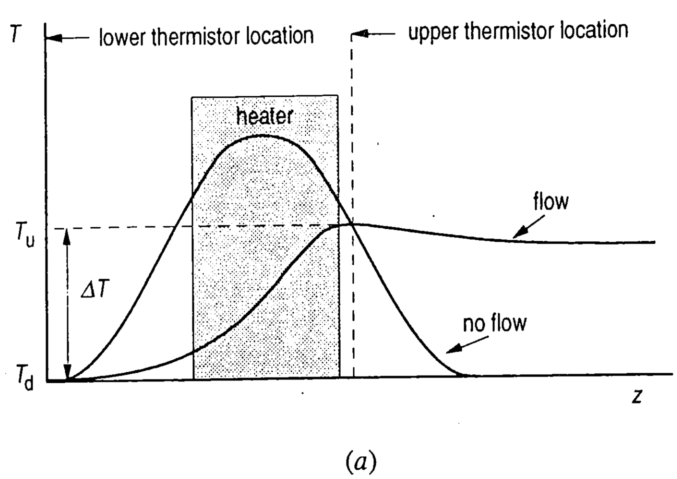


FIGURE 2 Schematic of the gauge



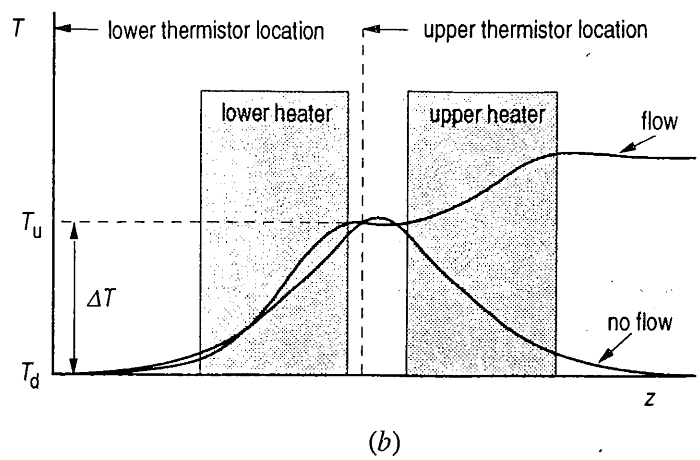


FIGURE 3 Axial temperature distribution along the stem with and without water flow for the case of (*a*) one heater and (*b*) two heaters.

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 from the heater. Then, at that position $(dT/dz)_d \rightarrow 0$ and accordingly $q_d \rightarrow 0$. Experiments and numerical calculations indicated that measuring T_d at a distance equal to the width of the heater 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). Suitable selection of the heater width can ensure that $q_u << q_s$. Heat transfer in the stem is governed by the energy transport equation, written in axisymmetric, cylindrical coordinates as:

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

with boundary conditions:

$$T - T_d = 0 \text{ at } z \rightarrow -\infty \qquad (4a)$$

$$\frac{\partial T}{\partial z} = 0 \text{ at } z \rightarrow \infty \qquad (4b)$$

$$\frac{\partial T}{\partial r} = 0 \text{ at } r=0 \qquad (4c)$$

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

and the initial condition:

$$T - T_d = 0 \text{ at } t = 0 \qquad (4e)$$

The energy equation (3) may be non-dimensionalized using 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 as $U=\mathring{m}/\rho_s A$. We can then write (3) in the form:

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

in which Pe is the Peclet number, defined by:

$$Pe = \frac{\rho_w c_w U L}{k_w^z} \qquad (6)$$

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

$$Pe >> \frac{\rho_w c_w}{\rho_s c_s} \qquad (7)$$

Increasing the magnitude of Pe therefore reduces the measurement error due to axial conduction. The value of Pe is proportional to $\mathring{m}$ (which is large at high flow) and L (increased by selecting a wider heater). Experimental measurements (Ham and Heilman 1990) confirm that axial conduction losses are negligible 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 and Whitfield 1981): k_w^r=0.38 W/m°C; k_w^z= 0.76 W/m°C; ρ_w=435 kg/m^3; c_w= 3180 J/kg°C; ρ_s=1000 kg/m^3; and c_s=4186 J/kg°C. The tree diameter was taken to be D=30 mm (corresponding to our experimental set-up), with a stem of circular cross-section so that $A=\pi D^2/4$. For a flow rate $\mathring{m}$ =100 gm/hr, (7) reduces to the requirement that L>>5 mm; selecting L=50 mm satisfies this condition. At lower values of $\mathring{m}$ (<20 gm/hr), though, axial conduction would become more significant, increasing the error in measurement. In practice, however, the presence of the upper heater worked to our advantage since it reduced temperature gradients at the edge of the lower heater (see figure 3*b*), further diminishing axial conduction.

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

$$\frac{1}{Pe}\frac{L^2}{D^2}\frac{k_w^r}{k_w^z} >> \frac{\rho_s c_s}{\rho_w c_w} \qquad (8)$$

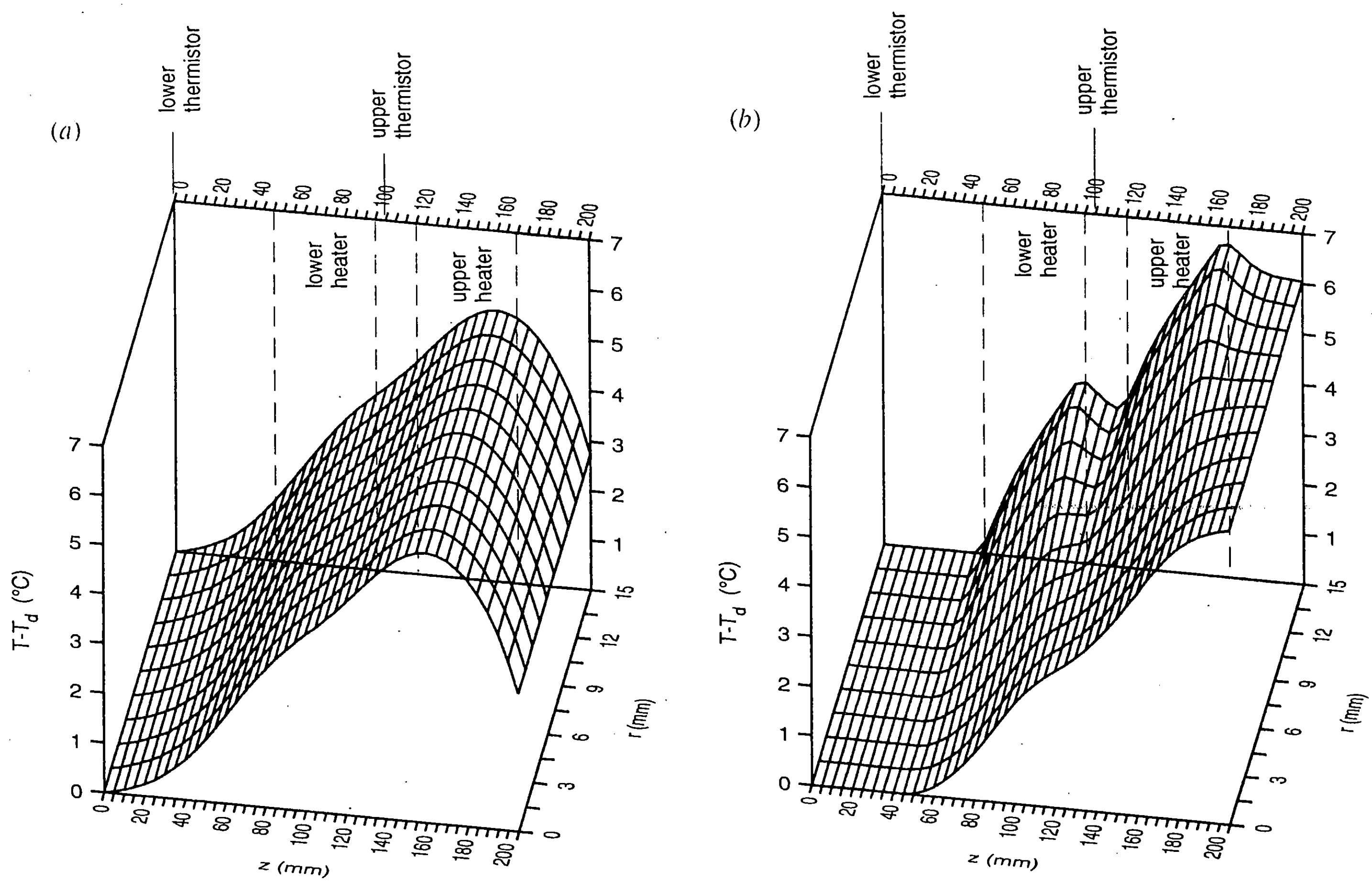


FIGURE 4 Temperature distribution in the stem for a water flow rate of (*a*) 20 gm/hr, and (*b*)175 gm/hr.

Simplification of (8) results in the condition that:

$$L \gg \frac{4}{\pi}\frac{c_s}{k_w^r}\mathring{m} \qquad (9)$$

Substituting in (9) the physical property data listed above, we find that for $\mathring{m}=100$ gm/hr we need L>>400 mm. Physical limitations on the size of the gauge prevent this condition from being satisfied; significant radial temperature gradients will therefore 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 error in the water flow measurement because of them. A numerical simulation of the gauge was also useful in estimating the magnitude of axial conduction losses, and in selecting the size and location of the heaters. The transient energy equation in axi-symmetric, cylindrical coordinates (3) and the boundary and initial conditions (4*a*-*e*) were discretized using a finite difference approximation, and then solved with 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 center-line. A uniform mesh spacing of 1.5 mm in the radial direction and 5 mm in the axial direction, and a time step of 10 s was adopted for the discretization. The water flow velocity was assumed to be uniform across the stem cross-section, so that $u=U$. The physical properties of wood and water were assumed to be constant, with the values listed above. Radial conduction losses were neglected; the insulation around the stem was assumed perfect. Results of the simulation are reported in this paper for a gauge with the dimensions shown in figure 2, with the upper and lower heater each having a power of 2.32 W. The heaters were switched on and off in the numerical model so as to hold ΔT=3.5°C.

The model predicted that radial temperature gradients increase with greater water flow 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 figures 4*a* and *b* for water flow rates of 20 gm/hr and 175 gm/hr, 90 minutes after the heater was switched on (after which time the temperature field showed little further change). The difference between the temperature at the stem surface (r=15 mm) and the stem center (r =0) was less than 0.01°C for $\mathring{m}$=20 gm/hr (figure 4*a*), whereas it reached values of 1.6°C for $\mathring{m}$=175 gm/hr (figure 4*b*).

Figure 5 shows the gauge measurement as a function of water mass flow rate, with T_u and T_d being measured on the stem surface. The error in measurement is seen to increase with $\mathring{m}$, until the gauge under-predicts the flow by approximately 14% at $\mathring{m}$ =175 gm/hr. This error could be attributed largely to the radial temperature gradient, since axial conduction losses were found to be negligible for $\mathring{m}$ > 20 gm/hr, and radial conduction losses through the insulation had been postulated to be zero in the model. The accuracy of the gauge may be 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 stem surface. In the experiment, therefore, temperature sensors were inserted into radial holes drilled into the stem.

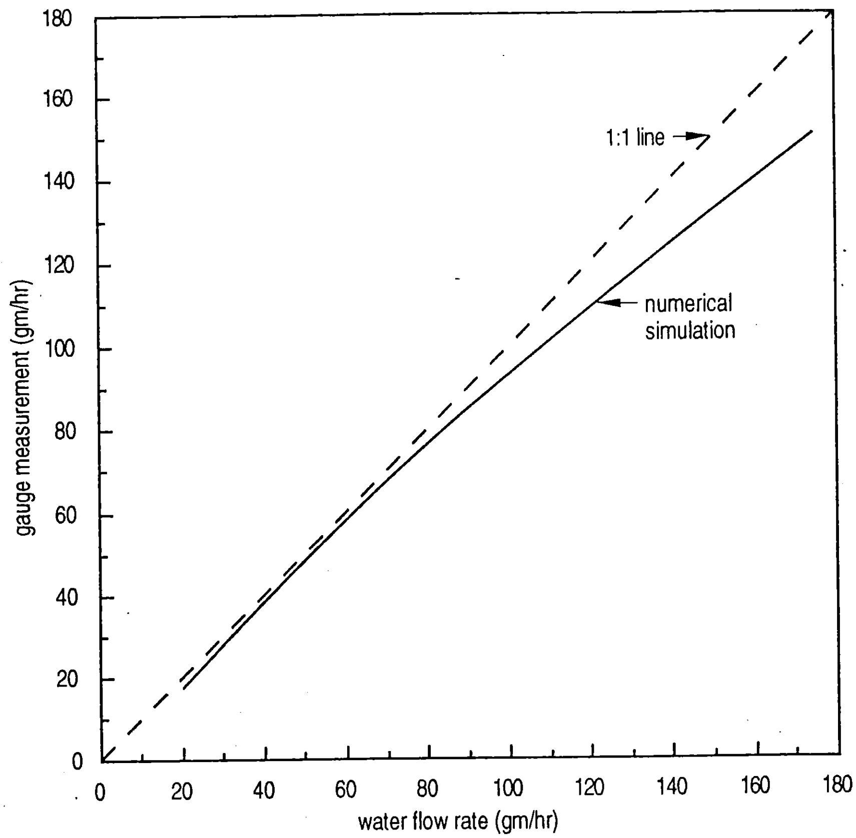


FIGURE 5 Results of the numerical simulation, showing the predicted error in the gauge measurement as a function of the water flow rate.

EXPERIMENTAL METHODS

Experiments were performed to test the accuracy of the gauge in measuring water flow in a crab apple (*Malus*) tree during October and November 1991. The tree was planted in soil contained in a 76 liter plastic container and placed in a greenhouse in Cornell University, Ithaca, NY. The gauge was mounted on the trunk such that the bottom edge of the insulation was at a height of 150 mm above soil level. The trunk diameter was approximately 30 mm over the section where the gauge was located. The location of the heaters and temperature sensors are shown in figure 2.

Flexible etched foil Kapton heaters (Minco Products Inc.) 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 62Ω; the outer heater was 100 mm x 300 mm, with a resistance of 35Ω. A regulated 12 V DC power supply (Leader model LPS-164A) 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 Armaflex pipe insulation (Armstrong Insulation Products) was wrapped around the heated portion of the stem (figure 2). 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 (YSI Inc.), 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.) 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 an Omega HH-23 digital thermometer with a resolution of 0.1°C. Values of ΔT measured with the themocouple and thermistors agreed to within 0.1°C.

Figure 6 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 YSI 44204 linear thermistors, which have a positive temperature coefficient and give an output of 0.01 V/°C when supplied an excitation voltage of 1.775 V. An instrumentation amplifier took the difference between the output of the two thermistors and amplified it with a gain of 10, providing a linear signal of 0.1 V/°C proportional to ΔT. This signal was connected to the negative input of a comparator; the positive input 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 go 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 heater 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 went higher than that of the positive input, the comparator output would go low, switching the heater off. A clock with a resolution of 0.0001 s was connected to the comparator output, and activated whenever the heater was switched on. The cumulative time of operation of the heater 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 YSI 44004 thermistors which have a negative temperature coefficient. The thermistors were placed in a Wheatstone bridge circuit whose nodes were connected to the inputs

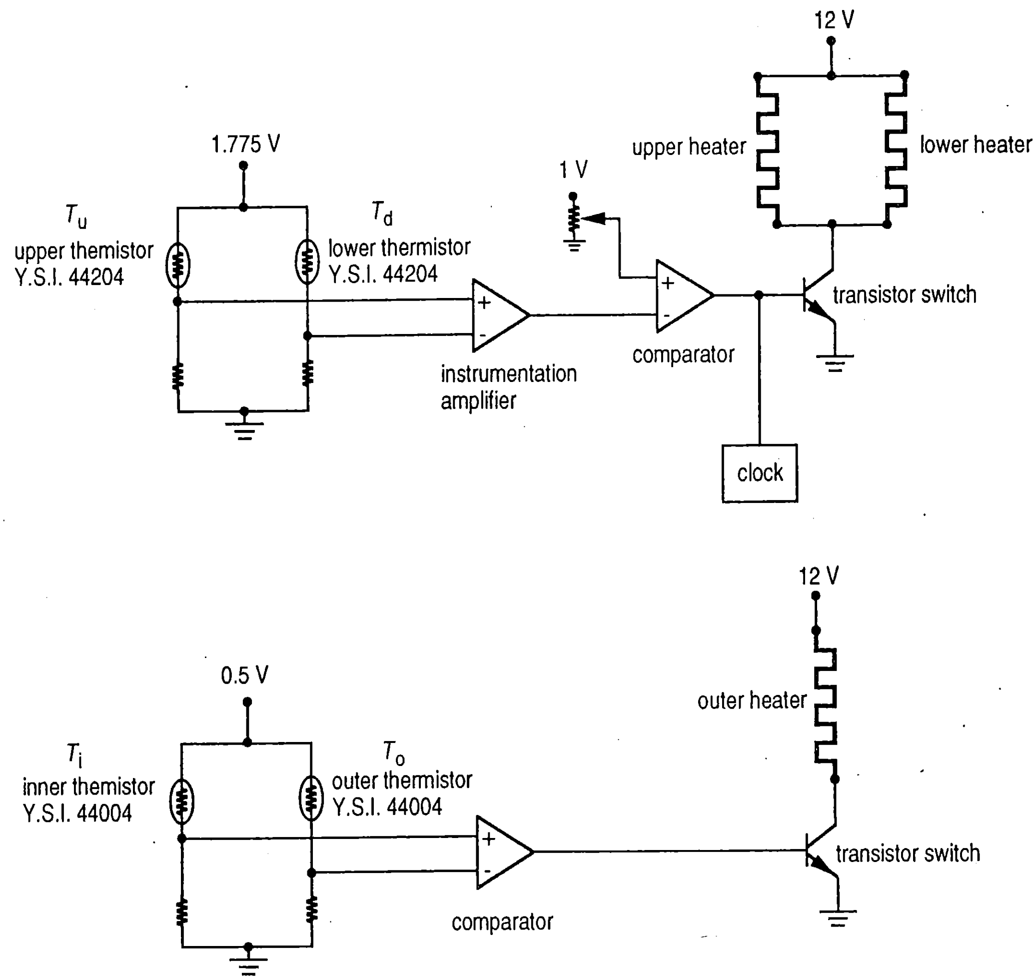


FIGURE 6 Schematic of the temperature controller

of a comparator (figure 6). 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 ±0.05°C of the preset value, and $|T_i-T_o|\leq 0.1$°C, as measured by both the thermistors and thermocouples.

RESULTS AND DISCUSSION

A flow measurement test was started by watering the soil in which the tree was planted, and allowing the container to drain overnight. The surface of the soil was covered with a layer of 3 mm diameter plastic pellets to reduce water evaporation; the container top was then covered with a plastic sheet. The tree and container were placed on a Sauter EB60 weighing scale which had a 54 kg capacity and a resolution of 1 gm. All weight loss recorded was assumed to be because of transpiration from the tree foliage.

Results are reported in this paper from a test conducted over a 72 hr period, from 10th to 13th November. The temperature controller and heaters were switched on at 10:00 am on 10th November. After 90 minutes 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 loss were then noted periodically during daylight hours for the next three days.

Table 1 lists the recorded tree weight loss and clock reading, as well as the calculated water flow. The cumulative water mass flow was calculated as being m=0.1541t_h (with m in grams and t_h in seconds), with the constant of proportionality calculated by re-writing (2) as $m=(P/c_s\,\Delta T)t_h$ and substituting values of P=2.323 W, ΔT=3.6°C, and c_s= 4.186 J/gm°C. The water flow and tree weight loss over the 72 hr period are plotted in figure 7.

The calculated water mass flow integrated over a long time period (>2 hrs) agrees with the tree weight loss to within 3% (see table 1). Measurements over an interval shorter than 2 hrs can 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 (Steinbeg, van Bavel, and McFarland 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. It was observed that during intervals when T_d increased suddenly (as happened when the ambient temperature rose) some of the energy from the heater would be used to raise the temperature not only of the water, but also of the insulation; the gauge would then read high. Conversely, when T_d dropped rapidly the stem withdrew heat stored in the insulation; the gauge then read low. Averaged over periods longer than two hours, 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. The use of insulation with a lower thermal capacity should improve the time response of the gauge.

A final caveat should be added concerning another potential source of error in the gauge. Our experiments were conducted in the fall, when the ambient air was always cooler than the water drawn from the soil. Ambient temperatures were always lower than T_i, and radial losses could be controlled by means of the outer heater which

Date	Time of day	Clock reading (s) t_h	Weight loss (gm)	Water flow (gm) $\dot{m}$=0.1541 t_h	Difference
10 November	11:30 am	0	0	0	0%
	12:01 pm	307	47	47	0%
	12:33 pm	558	103	86	-16.5%
	1:01 pm	1004	179	155	-11.2%
	1:31 pm	1546	245	238	-0.9%
	2:42 pm	2598	409	400	-2.2%
	3:02 pm	2957	459	456	-0.7%
	3:32 pm	3312	509	510	0.2%
11 November	10:24 am	8144	1254	1255	0.1%
	11:03 am	8512	1301	1312	0.8%
	11:30 am	8794	1338	1355	0.3%
	1:51 pm	10778	1617	1661	2.7%
	2:53 pm	11599	1736	1787	2.9%
	3:55 pm	12139	1823	1871	2.6%
	4:16 pm	12326	1852	1899	2.5%
12 November	8:48 am	16809	2560	2590	1.2%
	9:20 am	17193	2611	2641	1.1%
	10:07 am	17740	2694	2734	1.5%
	10:44 am	18281	2775	2817	1.5%
	11:24 am	18907	2865	2914	1.7%
	12:40 pm	19954	3012	3075	2.1%
	1:16 pm	20542	3099	3166	2.2%
	2:48 pm	21693	3266	3343	2.4%
	3:20 pm	22025	3312	3394	2.5%
	4:17 pm	22560	3392	3476	2.5%
13 November	8:37 am	27468	4146	4233	2.1%
	11:17 am	29432	4426	4535	2.1%

TABLE 1 Experimental measurement of water flow and plant weight loss over a 72 hr period.

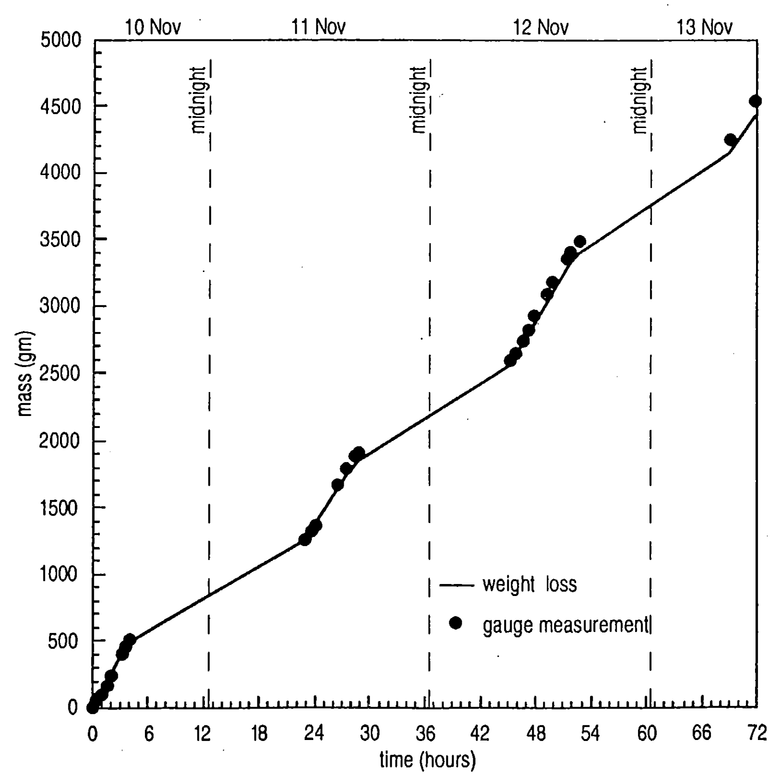


FIGURE 7 Comparision of water flow measured by the gauge with weight loss from the plant

increased T_0 to make it equal to T_i. In a warmer climate it is possible that the ambient temperatures may be greater than the soil water temperature so that we have $T_i<T_0$. There would then be radial heat conduction inwards from the air to the tree stem through the insulation, which the outer heater would be ineffective in preventing. It is therefore important to leave a sufficient portion of the stem below the gauge uninsulated, to ensure that the water rising in the stem warms up enough to at least reach ambient temperatures before it enters the gauge. Further work is planned during the summer to determine the best location for the gauge.

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