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A THERMAL FLOW METER FOR ESTIMATING THE RATE OF XYLEM SAP ASCENT IN TREES.

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by

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ABSTRACT

Distortion in heat diffusion patterns in thermally homogenous media can be used to indicate the influence of external stimuli. Considering a living tree stem as such a medium, thermal diffusion patterns following an injected heat pulse are related to water evaporated from the leaf surfaces which results in the vertical movement of water in the stem.

The equation $v = \left[(4\pi kt)^{-1} Q\right] \exp- \left[(x-HPVt)^2 (4kt)^{-1}\right]$ describes the temperature (v) at any point (x) in a medium moving at velocity (V), initially at thermal equilibrium and of diffusivity (k) for any time greater than t = 0. The simultaneous solution of two such equations for points x, x' ($x \neq x'$), results in an equation for heat pulse velocity (HPV):

$$HPV = (x - x')\ (2t_o)^{-1}$$

where t_o is the time for v = v' following the instantaneous release of a quantity of heat (Q) at x = 0. Heat pulse velocity is a quantitative indicator of the rate of upward water movement.

Instrumentation to measure heat pulse velocity consists of a heat source, temperature detector and a timer. Practical circuits, schematics and drawings for a portable field instrument are given.

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Introduction

Distortion in heat diffusion patterns in thermally homogenous media can be used to indicate the influence of external stimuli. Measuring water flow through porus media is an application. A porus medium of interest to forest hydrologists is a tree stem. Water moves upward from the roots via the stem in response to evaporation at the leaf surfaces. The amount of water evaporated and the response of evaporation rate to various climatic parameters are useful information for managing forest as watersheds. One mean of obtaining such information is with a thermal flow meter.

Instrumentation

A thermal flow meter consists of two devices - one, a means of injecting or creating heat within a flowing medium, and two, some means of registering its rate of diffusion or tracing it downstream. A flow meter for a tree stem is shown in figure 1. Basically, it consists of a heater (H) with temperature measuring probes at (x) and (x').

In a pure convective medium, velocity between points H, x would be simply the distance H-x divided by the time from heat creation at H to its onset at x. A tree is not a purely convective medium. In fact, a greater proportion of heat will reach both points x and x' by conduction than by convection. The theoretical derivation of the formula to describe how heat both convects and conducts in this medium are covered elsewhere.[1] With the probe configuration of figure 1, heat pulse velocity (HPV), a parameter closely related to mass flow, can be obtained with simple temperature difference measurements at points x and x' and the time for equal temperature at these two points after an initial difference because of a heat pulse created at H.

The temperature (v) for any time, $t \neq 0$, at point x downstream, is described by equation (1).

$$v = \frac{Q}{4\pi kt} \exp - \left[\frac{(x - HPVt)^2 + y^2}{4kt}\right] \quad °C \qquad (1)$$

A second equation can likewise be written for an upstream point x'. Simultaneous solution for HPV at the time to when v = v' ($t \neq 0$, $x \neq x'$) yields equation (2), x, x' in cm, t in seconds.

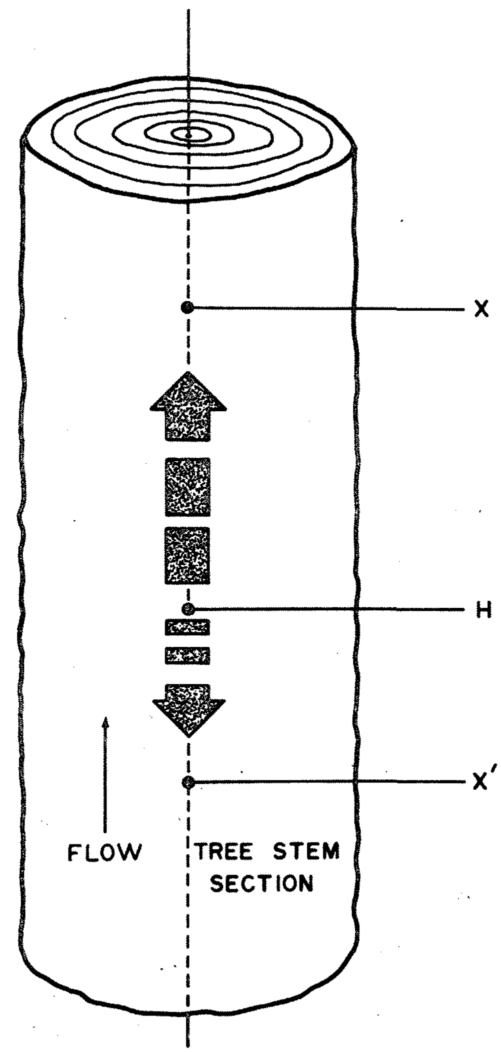


Figure 1. Thermal flowmeter for a tree stem.

$$HPV = (x - x') / 2t_o \quad cm/sec \qquad (2)$$

or

$$HPV = 1800 (x - x') / t_o \quad cm/hour \qquad (3)$$

(the "y" component is assumed zero by making all measurements in the y = 0 plane).

Instrumentation to utilize equation (2) to estimate heat pulse velocities is straightforward and simple. Probes can be any temperature sensing device. The display must be capable of detecting and indicating temperature differentials of .001°C. Thermistors have been used with the greatest success, but thermocouples are also suited if precautions are taken to eliminate thermal exchanges outside of the metered section. A one-second timer and a battery to create a momentary heat pulse are the only other requirements. A schematic diagram of the most recent complete instrument package in use by the author is shown in figure 2. Figure 3 shows heat and thermistor probe construction. These probes are best left permanently in place in a tree stem. A socket mounted at each metering point allows more than one set of probes to be serviced by a single indicating-timing package.

Flow Estimates

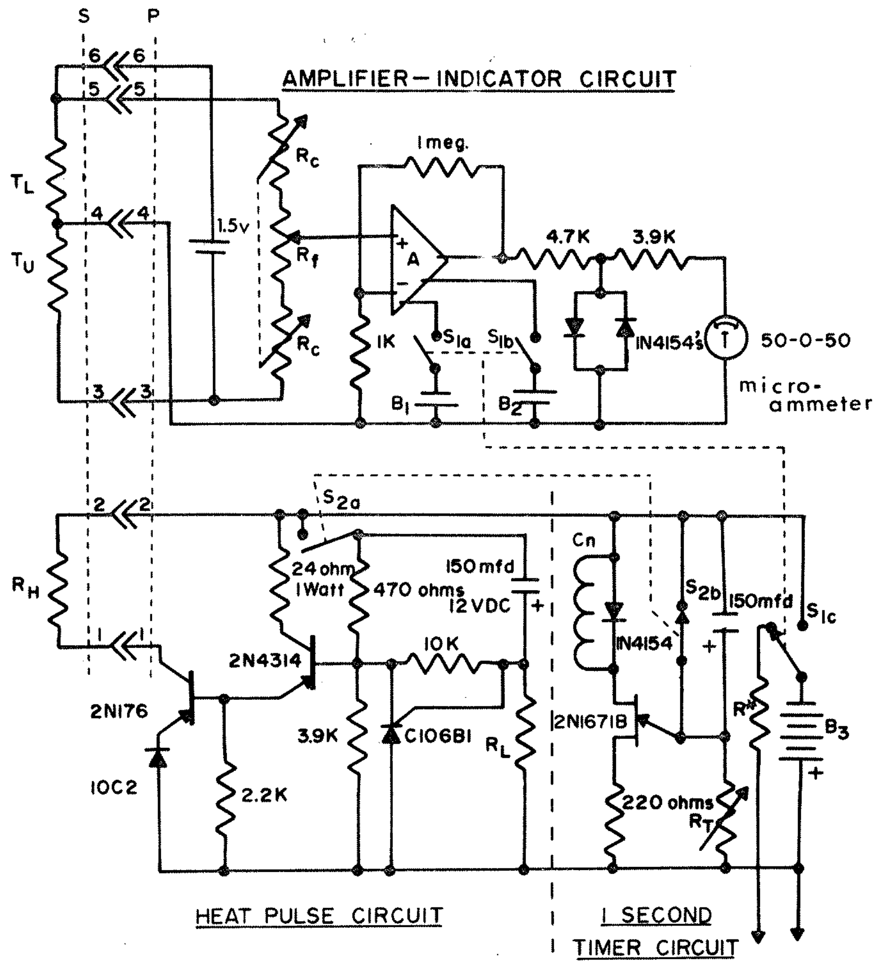
The continuity equation Q = AV required a knowledge of the average velocity V through some cross section area A in order to calculate quantity Q. In a tree stem, the same is true. Heat pulse velocity is measured with the instrumentation of figures 2 and 3. However, in order to obtain average HPV and A, we must assume some properties of the flow system. The following would apply to Lodgepole pine or Engelmann spruce tree of 10 cm diameter or larger.

First we assume that the velocity distribution across the water conducting cross section is parabolic.[2] To describe average heat pulse velocity over a radial cross section, two concurrent HPV measurements at 1.0 and 2.0 cm deep are made. A second set of measurements on the opposite side of the tree should also be made to allow for departure from circular symmetry in the stem. For each set of measurements, compute the average velocity and its physical position in the cross section. To do so it will be necessary to derive the equation for a parabola through the two measured points (1.0, HPV_1), (2.0 HPV_2) and the origin where the HPV is assumed zero (0,0). The equation for the shape factor (a), peak heat pulse velocity (PHPV) and depth at which the peak occurred (Dp) are:

$$a = -0.50 / (2HPV_1 - HPV_2) \qquad (4)$$

$$Dp = 1 - aHPV_2 \ cm \qquad (5)$$

$$PHPV = Dp^2 / -4a \quad cm/hour \qquad (6)$$



Heat Pulse Velocity Meter parts list. Only those parts not indicated on the schematic diagram are listed below.

A	= Amplifier any one of: Nexus - philbrick 2LV1, 1001, Q200; Burr-Brown 3001; Analog Devices 153C.
$B_{1,2}$	= Amplifier power - voltage to suit amplifier selected above.
B_3	= 12 volt battery for heat and timing circuit, should be rechargeable of at least 1 amp-hour capacity.
CN	= Presin FE3RA 6VDC counter - (This counter draws only 40 ma; higher current types not suitable for use in this circuit).
P	= Jones 306 - CCT plug.
Rc	= Coarse zero adjust - 10 K tandem potentiometer.
Rf	= Fine zero adjust - 1 K, 10 turn potentiometer.
R_H	= Heat source in tree.
R_L	= Heat pulse length - approximate 1500 ohms for 1 second heat pulse.
R_T	= Approx. 11 K. Adjust for 1 count/second on counter.
R*	= If 12 V battery is rechargeable, arrows should connect to charging circuit. R* adjusted for 14 hour charge rate at 1/10 ampere-hour capacity of Ni-Cad battery.
S	= Jones 306-AB socket mounted on tree.
S_1-a,b,c	= 3PDT switch entire instrument on - off.
S_2-a,b,	= DPDT toggle switch: Heat pulse - timer actuate.
T_L, Tu	= Lower and upper thermistors - 1000 ohms at 25C.

Figure 2. Schematic diagram and parts list for heat pulse velocity indicating, pulsing and timing circuits.

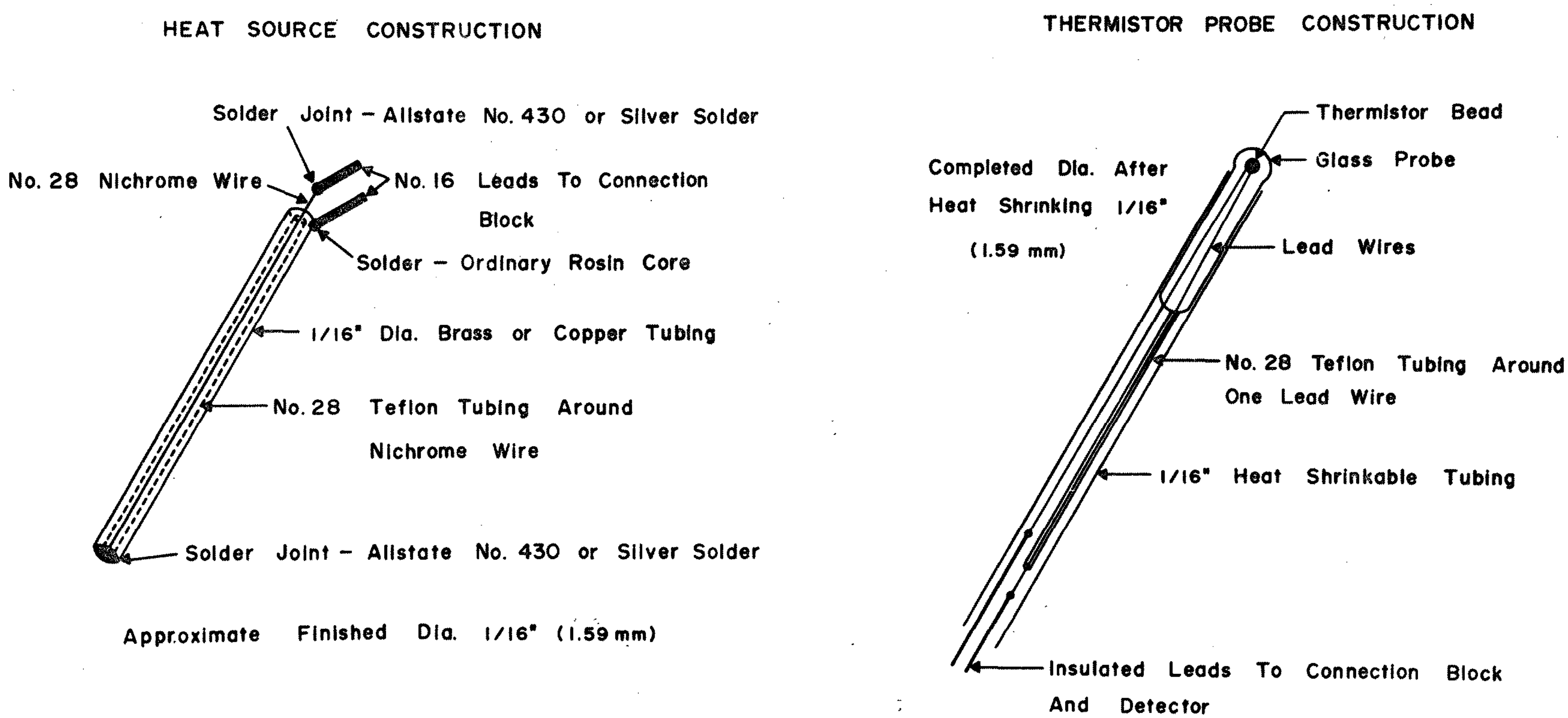


Figure 3. Heat source and thermistor probe construction.

Average heat pulse velocity ($\overline{HPV}$) is defined by (7).

$$\overline{HPV} = (2\ \overline{PHPV})/3 \qquad (7)$$

The conducting cross sectional area (CA) of the tree is computed from the overall stem diameter measurement (inside bark) and the average Dp obtained from the two measurements above.

$$CA = 2\pi Dp\ (D-2Dp) \qquad (8)$$

As an example, with actual field data for HPV and diameter:

D = 22.8 cm, side 1: $HPV_{1,2}$ = 6.0, 6.0; side 2: $HPV_{1,2}$ = 6.7, 6.4

Side 1: a = -0.083, Dp = 1.50cm, PHPV = 6.8 cm/hour.

Side 2: a = -0.0714, Dp = 1.46 cm, PHPV = 7.4 cm/hour.

$\overline{HPV}$ = (6.8 + 7.4) /3 $\cong$ 4.7 cm/hour.

CA = (6.28) (1.48) (22.8 - 2.96) = 184 cm^2

therefore Q, total flow would be: (4.7) (184) = 864.8 cc/hour.

Discussion

Relative estimates are computable directly as above. The question with this or any flow meter is how accurate are the estimates compared to actual flow? In the above estimates, there are three potential error sources: HPV may not be a valid indicator of flow/unit area cross section; HPV estimates may not be true magnitude due to the effect of the probes on the living flow system; the assumed parabolic heat pulse velocity-depth relationship may be incorrect, causing errors in both average heat pulse velocity and area.

1. Heat pulse velocity as an indicator of flow per unit cross section.

According to Marshall,[1] heat pulse velocity is a weighted average of the non-moving wood and moving sap acting together as a single medium. It is defined by equation (9).

$$HPV = auPsCs/PC \quad cm/sec \qquad (9)$$

where: a = the fraction of any plane area perpendicular to the flow axis occupied by sap streams.

u = actual sap speed cm/sec.

PsCs = density and specific heat of sap.

PC = density and specific heat of combined sap and wood.

The interpretation of HPV as a velocity stems from the interpretation of "a" as a unitless fraction. That is, a = sq. cm of sap stream divided by sq. cm of wood, i.e. sq. cm/sq. cm = 1. Thus, HPV derives its units solely from sap velocity "u".

On the other hand, HPV can be interpreted in the same manner as a flux per unit area by simply failing to cancel the units (sq. cm) (cm/sec) $(\text{sq. cm})^{-1} = (\text{cc})\ (\text{sec})\ (\text{sq. cm})^{-1}$.

The correct interpretation may never be resolved. There is evidence for both. Marshall[1] derived a second term, sap flux (SF) that he intended heat pulse velocities to be converted to before they were used to compare flow between or compute actual flow within tree stems.

$$SF = au = HPV\ (Mc + 0.33)P \quad \text{cc/sec} \tag{10}$$

Where Mc = moisture content expressed as a decimal fraction measured on a dry weight base.

P = oven-dried weight of wood divided by green volume.

Both Mc and P vary with time. Thus, both "a" and "u" of equation (9) vary with time too. A comparison of actual and calculated flows using (HPV) X(A) and (SF) X(A) is shown in figure 4. The relationship is rectilinear with heat pulse velocity, curve linear with sap flux. During the study conducted to obtain the data for figure 4, the moisture content varied from 1.01 to 0.75, the density from 0.46 to 0.52. My conclusion from figure 4, is that heat pulse velocity measurements already vary in magnitude in accordance with changes in moisture content and density, and that conversion to sap flux introduces this variation a second time, creating the curve linearity.

More important than the curve linearity, is the lack of 1:1 correspondence between either (HPV) X (A) or (SF) X (A). Both underestimate the actual amount of water flowing through the measurement cross section. Heat pulse velocity x area underestimates actual flow by 75%; sap flux x area by 65%. A reason for these underestimates is discussed below.

2. Effect of probes size on measured magnitude.

Upward flow in a living tree stem is in response to evaporation at the leaf surfaces. The water is pulled upward in coniferous trees via a series of conducting cellular structures called tracheids. In pine, tracheids are 4 to 6 mm long. Water flows from tracheid to tracheid both vertically and to a much lesser extent, horizontally, through bordered pits at the tapered junctions. Each pit is equipped with a valve-like structure that remains open as long as the pressure on both sides of it remains relatively equal. Any disruption of flow through a tracheid or group of tracheids results in closing of the disturbed flow path.

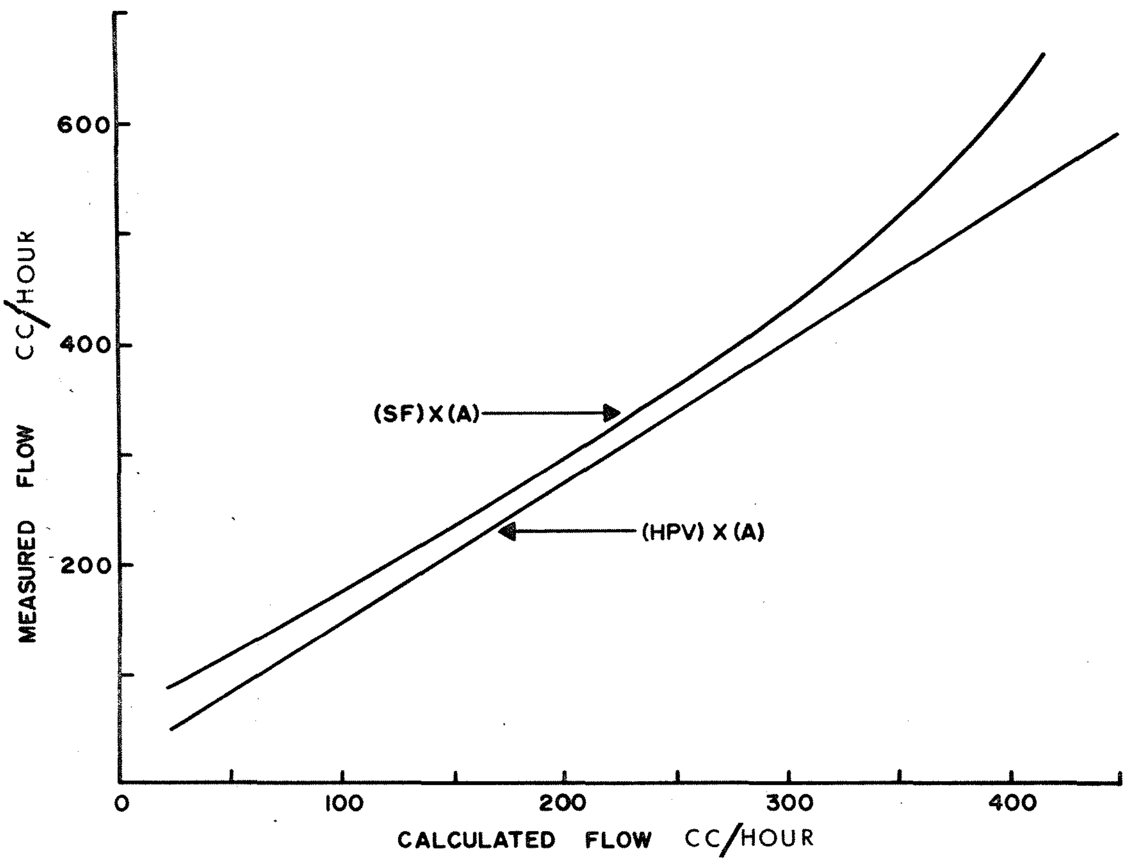


Figure 4. Flow volume versus (sap flux) x (area) and (heat pulse velocity) x (area).

Both thermistor and heat probes must be inserted among the tracheids to meter the flow through them. While it might be possible to sharpen the probes to such an extent that they could be inserted without severing any tracheids, the usual procedure is to drill holes and insert fairly blunt probes to the desired depth. Drilling does disturb a considerable number of tracheids. This results in a drying of the water conducting elements immediately above and below the measurement plane. Figure 5 shows how such drying appears in dye staining patterns on instrumented cross sections. The dye pattern separated 2 to 3 cm below the lowest probe and stayed separated for about 3 cm above the highest probe. The width of the dried area is greater than the diameter of the largest probe. In figure 5, all probes are 1 mm diameter, the dry area about 2 mm wide.

Figure 6 shows the area of wood about the probes that receives influence from the heat pulse. The most influenced area is immediately adjacent to the vertical (Y-Z) plane of the heat source. Relative influence decreases rapidly both directions perpendicular to the heat source plane.

The response curve of figure 6 is not symmetrical. This is because the thermistor probes used to obtain this data were mounted in hypodermic needles and were influenced more by heat travelling along the butt toward the tip than by heat travelling through wood to the tip. Less conductive probes result in better symmetry. Regardless of symmetry, if we accept 5% relative response as being the minimum detectable with the indicating instrumentation, then the "sensed" area is roughly a rectangle, extending 0.75 cm to each side of the heat source.

Figure 5 shows that an area 2 mm wide immediately adjacent to a probe set is not functioning in conducting water through the metered section. This information compared to that of figure 6, suggests that the most responsive portion of the sensitive area is not functioning. The area remaining after the 2 mm wide band is removed is 1.3 cm wide, or approximately 87% of the sensitive area is responsible for the heat pulse velocity measured. An assumption that the dried area is always twice the size of the largest probe helps explain the underestimate of figure 4. The thermistor probes for that study were 2.28 mm diameter: if an area 4.56 mm wide was not functioning, then only 1.044/1.500 or 69% of the area was causing the heat pulse velocity readings. Thus, the 75% and 65% of actual flow calculated with (HPV) X (A) or (SF) X (A) are not out of line if a probe size correction based on twice the diameter, is applied to those readings.

3. Other potential error sources.

A complete discussion of the evidence for assuming a parabolic heat pulse velocity-depth distribution is included elsewhere in this proceedings.[2] It will suffice to say here that this assumption is reasonable in light of the experimental evidence to date. More important are the sampling problems in obtaining heat pulse velocities at 1.0 and 2.0 cm deep. The interior of a tree is not homogenous. As a tree grows, old knots, wounds, et cetera, are grown over and often not visible on the surface. The more limbs a tree species has, the greater the chance of encountering one of these imperfections. Their effect is similar to that of severing several tracheids. Flow divides around the knot or wound area, leaving a non-conducting void immediately above and below.

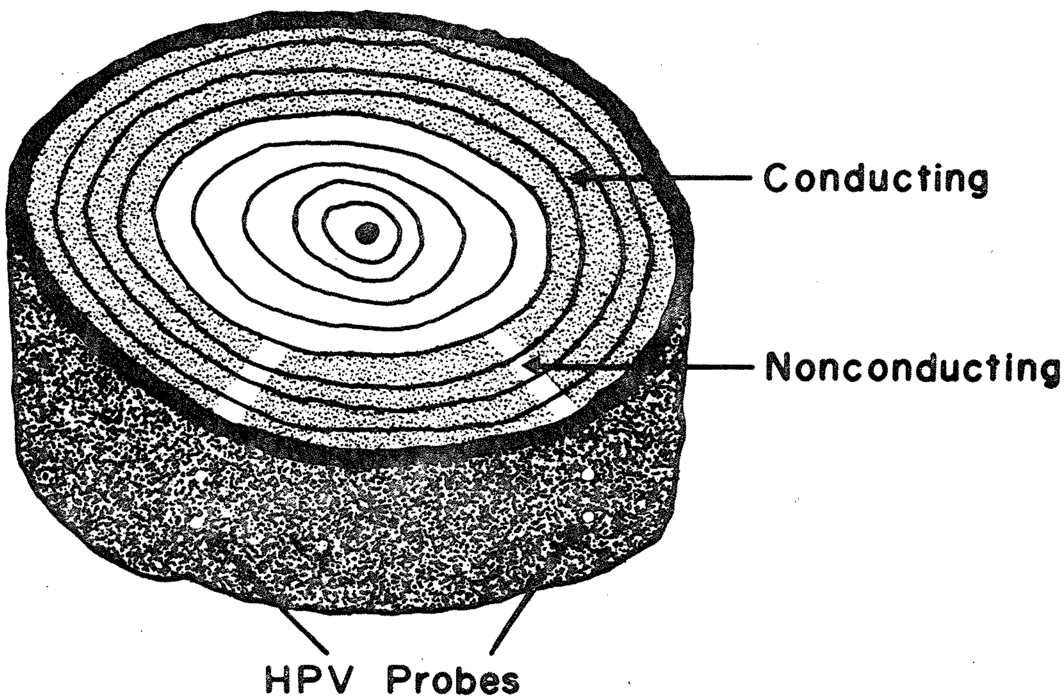
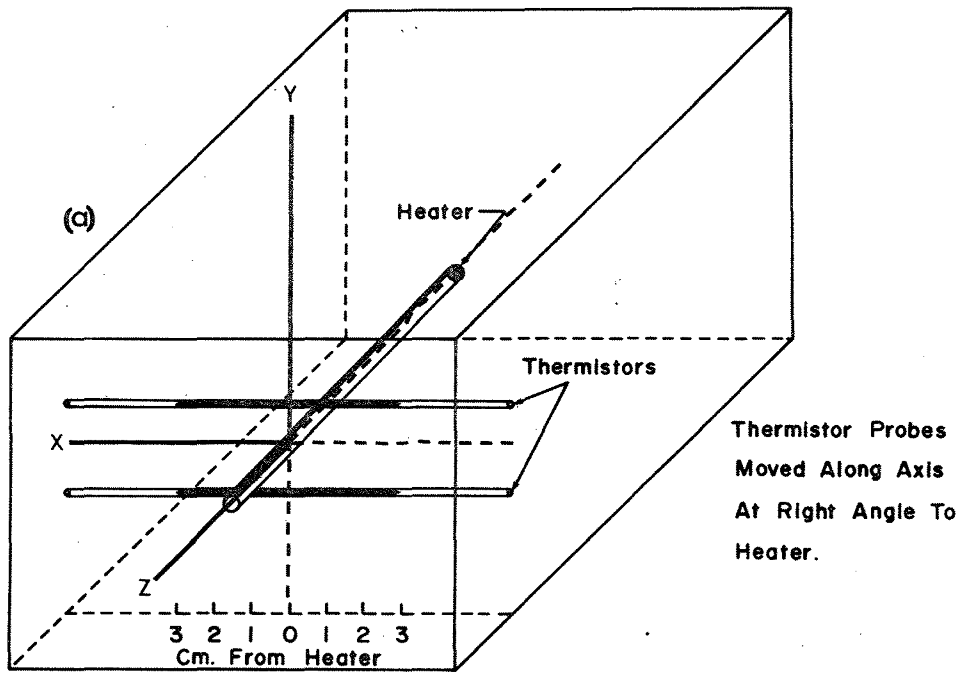


Figure 5. Dye staining pattern within a cross section instrumented with heat pulse velocity measuring probes.



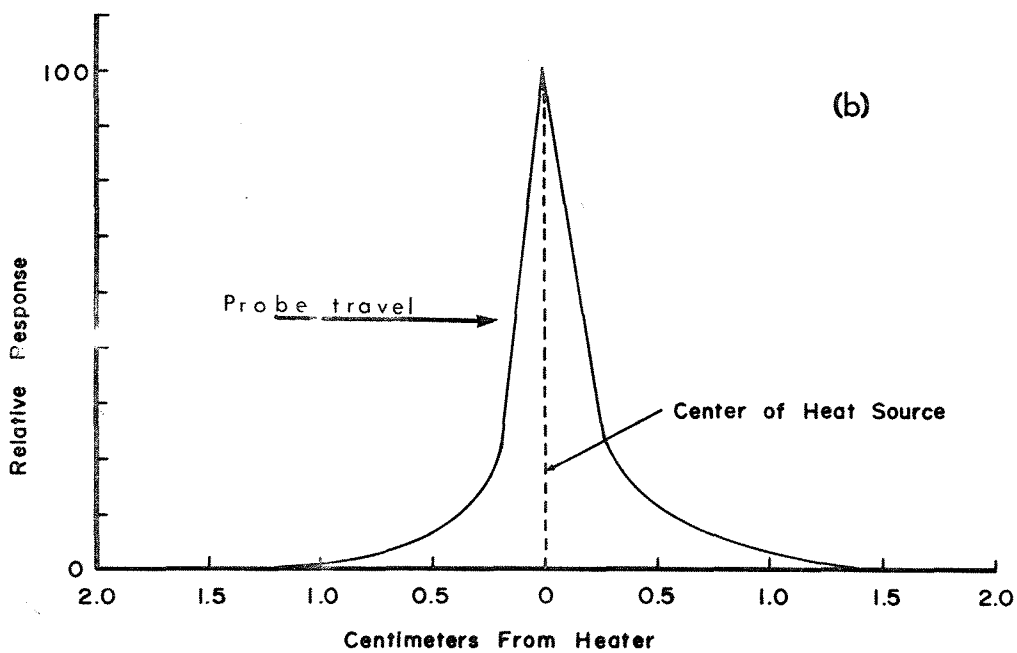


Figure 6. Area in the y - z plane influenced by a heat source on the x axis.
(a) Diagramatic sketch of measurement scheme.
(b) Graphical result.

In general, it is not possible to avoid such areas. Careful attention to probe placement to avoid visible defects is mandatory. However, a random sampling program and careful analysis of the collected data to detect obviously erroneous readings are the only way to insure representative data, free of bias.

What are "obviously erroneous readings"? Certainly, those which when analyzed by equations (4), (5) and (6), produce a Dp much greater than one-fourth the total diameter of the tree. Only in very juvenile trees without developed heartwood would there be appreciable sap movement throughout the entire cross section. Also, readings that produce an "a" greater than zero indicate an inverted velocity distribution: improbable and likely impossible.

Less obvious errors are those caused by careless probe installation. Distances x, x' are usually 1.0 and 0.5 cm respectively. Small errors in the placement of either of these produces large errors in indicated heat pulse velocity. For example, if x were 0.9 and x' 0.6 cm, equation (3) becomes $480/t_o$ rather than $900/t_o$. A ten and 20 percent error in spacing result in a 47 percent error in heat pulse velocity. The best technique, even with careful probe placement, is to measure x, x' in the tree and prepare a separate equation (3) for each measurement locus.

Heat loss from the measurement section is an important but not obvious source of error. Fortunately, the effect of heat loss is more noticeable at low heat pulse velocities, than at high ones. Therefore the percent error is small. A series of tests to determine how long it takes for a 10-watt second heat pulse to dissipate to undetectability showed that the minimum time was 300 seconds, the maximum well over 1800. My field practice has been to stop all readings at 300 seconds. The lowest acceptable HPV with a probe spacing of x = 1.00 cm, x' = 0.50 cm., is

$$HPV = 900/300 = 3.0 \text{ cm/hour} \qquad (11)$$

Experience in using the instrumentation with a particular set of probes will allow longer t_o's.

CONCLUSIONS

A thermal flow meter for measuring heat pulse velocity consists of a heat source, temperature sensing probes, an indicator of temperature difference and a one-second timer. Practical field instrumentation can be built with readily available electronic parts.

Heat pulse velocity through a tree stem is indicative of evaporation rates at the leaf surfaces of trees. The flow magnitude indicated by HPV measurements is less than the magnitude of the actual flow. Indicated magnitude is influenced by the size of probes placed in the stem. Larger probes apparently indicate less flow than smaller ones. There appears to be a consistent and predictable relationship between probe size and error percent but more absolute flow measurements are needed to confirm and define the relationship.

ACKNOWLEDGEMENT

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LITERATURE CITED

1. D.C. MARSHALL, Plant Physiology 33: (6) 385-396. 1958.

2. R.H. SWANSON, Theme 4, this proceedings.