6 Heat Ratio Method Theory

The Heat Ratio Method (HRM) can measure both sap velocity (V_s) and volumetric water flow in xylem tissue using a short pulse of heat as a tracer. It is a modification of the Compensation Heat Pulse Method. By measuring the ratio of heat transported between two symmetrically placed temperature sensors, the magnitude and direction of water flux can be calculated.

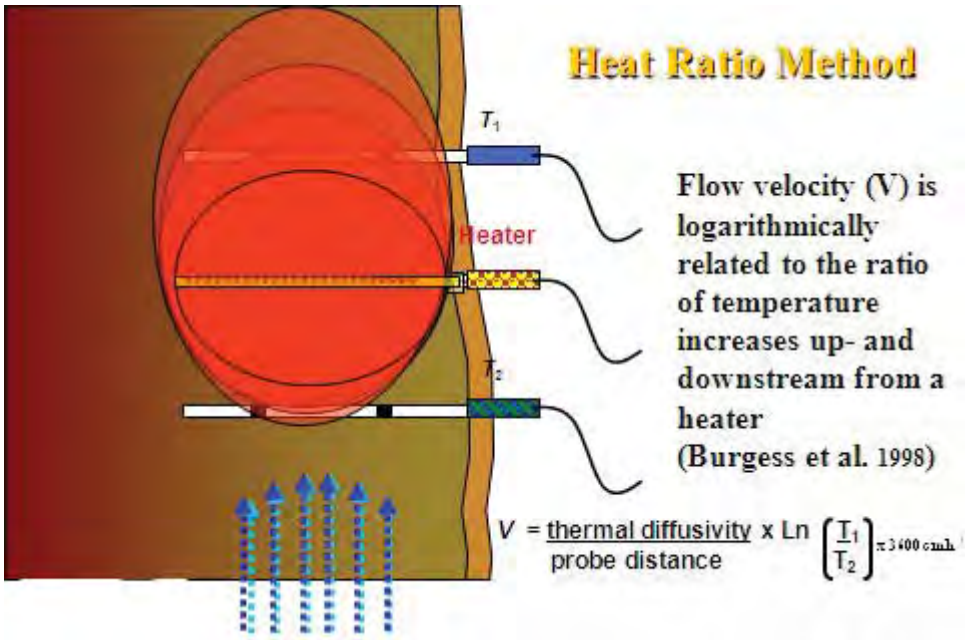

Figure 2: Heat Ratio Method principle.

This method was developed by the University of Western Australia and partner organisations ICRAF and CSIRO. The SFM1 Sap Flow Meter has been validated against gravimetric measurements of transpiration and used in sap flow research since 1996. (Burgess et al. 2001). It is the only truly digital Sap Flow Meter as it incorporates a microprocessor in the instrument design. The SFM1 can be used on lignified or woody stems greater than 10mm in diameter without any maximum diameter limit. It can also be successfully used on hollow stemmed plants such as bamboo. Because of the invasive nature of this method, HRM is not suited for use on herbaceous crop plants (although trials with Sugar Cane and Maize have demonstrated very good results). The operator can choose to report data output in raw temperature mode; Heat Pulse Velocity; fully processed Sap Velocities; or Sap Flow. The last two options eliminate the need to post process data. SFM1 is capable of measuring accurately between 100 to -100 cm hr^{-1} covering a very wide range of plant species and environmental conditions that produce high, low, zero and reverse rates of sap flow.

NOTE 11: The expected heat pulse velocities of the majority of plant species in most environments will be in the range of < 60 cm hr^{-1} for conventional or acropetal flow and no greater than -5 to -10 cm hr^{-1} reverse or basipetal flow.

The following extract of the Heat Ratio Method theory has been published in Tree Physiology 21, 589-598 © 2001 Heron Publishing – Victoria, Canada

"AN IMPROVED HEAT PULSE METHOD TO MEASURE LOW AND REVERSE RATES OF SAP FLOW IN WOODY PLANTS"

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6.1 Measurement and calculation of heat pulse velocity

6.1.1 CHPM (Compensation Heat Pulse Method)

For the CHPM, two probes containing temperature sensors are aligned with the axis of a plant stem or root and inserted radially to equal depths in the xylem. A heater element is similarly inserted at a fixed distance upstream from the midpoint between the temperature probes. A common configuration locates the heater 0.5 cm from the upstream temperature probe and 1.0 cm from the downstream probe (here denoted as a –0.5, 0, 1.0 cm configuration). During measurement, wood and sap are heated in pulses and convection through the flowing sap stream carries the heat toward the midpoint between the temperature probes. When both temperature probes have warmed to the same degree, the heat pulse has moved the 0.25 cm from the heater, i.e., to the midpoint between the probes. The time taken for the heat pulse to move this distance is used to calculate heat pulse velocity (V_h):

$$V_h = \frac{x_1 + x_2}{2t_0}\ 3600 \qquad \textbf{Equation 1}$$

where: t_0 is time to thermal equilibration of the downstream and upstream probes after release of the heat pulse, and x_1 and x_2 denote distances (cm) between the heater and the downstream and upstream temperature probes, respectively (we use these terms as they apply in the case when water flows from soil to leaves). A negative value is assigned to x_2 because it is located on the opposite side of the heater to x_1.

6.1.2 HRM (Heat Ratio Method)

The HRM measures the ratio of the increase in temperature, following the release of a pulse of heat, at points *equidistant* downstream and upstream from a line heater. Heat pulse velocity is calculated as (Marshall 1958):

$$V_h = \frac{k}{x}\ ln(v_1/v_2)\ 3600 \qquad \textbf{Equation 2}$$

where: k is thermal diffusivity of green (fresh) wood, x is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater. The probe positions relative to the heater used with the HRM are –0.6 and 0.6 cm, hence x = 0.6 cm. Thermal diffusivity (k) is assigned a nominal value of 2.5×10^{-3} cm^2 s^{-1} (Marshall 1958) and this value is further resolved once sapwood properties have been measured (see below).

6.2 Influence of measurement time

Marshall (1958) stated that the v_1/v_2 ratio remains constant with time, rendering the time of measurement unimportant; however, Marshall's (1958) description did not account for departures from the ideal state that can arise from two sources. **First**, patterns of heat transfer are altered by blocking of, and damage to, xylem vessels caused by insertion of probes. Additional disruption of heat transfer occurs because the thermal properties of the sensor material (e.g., stainless steel) differ from those of xylem. **Second**, even with careful probe placement, it is likely that probe spacing will be at least slightly asymmetrical. Both of these departures from the ideal cause v_1/v_2 to change with time with the result that measurement time affects results. Ratios of v_1/v_2 will approach an ideal value asymptotically, with the rate of change decaying exponentially with time following the heat pulse (Figure 1).

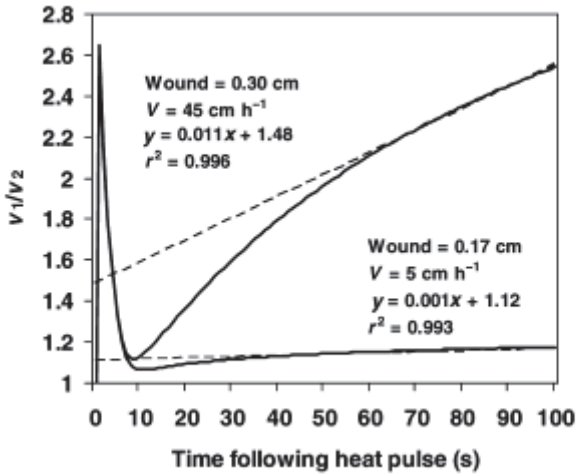

Figure 3: Modelled changes in v_1/v_2 ratios with time for a small wound width (0.17 cm) and low sap velocity (5 cm h^{-1}) compared with a large wound width (0.30 cm) and high sap velocity (45 cm h^{-1}). Note that, with both mild and extreme departures from the ideal caused by sensor implantation, v_1/v_2 is essentially linear between 60 and 100 s as indicated by the r^2 values for the linear regressions fit over the data for this period.

However, even in the most extreme cases, the rate of change in v_1/v_2 after 60 s becomes extremely small and ratios will be effectively linear and have a slope of less than 0.01 (Figure 1). This finding has two important implications. First, measurements should be made at least 60 s after the heat pulse has been released. Second, multiple sampling of v_1/v_2 is possible. For example, because our multiplexer cycle speed was 2.8 s, we logged and averaged 14 measurements of v_1/v_2 over the period 60–100 s to minimize the contribution of any random signal noise to measurements. Because v_1/v_2 is effectively linear between 60 and 100s, the value of these averaged ratios will differ from an "ideal" value measured at the median time of 80s by < 0.4% for extreme cases, although generally this difference will be negligible. Because random variation in v_1/v_2 arising from thermal and electronic interference can contribute an error an order of magnitude greater, multiple sampling of v_1/v_2 is desirable.

6.3 Correction for probe misalignment

All heat pulse velocity techniques are highly sensitive to errors arising from inaccurate probe spacing. For example, when the CHPM is configured as described earlier, a 1mm error in spacing for either probe will introduce a 20% error in calculations of V_h. With the CHPM, probe misplacement is assessed by placing over-length probes in drill holes and measuring the spacing and angle of the protruding probes (Hatton et al.1995). With the HRM, probe placement is measured *in situ*, which takes into account thermal as well as physical symmetry (e.g., whether thermocouples or thermistors lie symmetrically within the probe housing (Becker 1998)). At V_h = 0 (which can be imposed by severing the root or stem), probe spacing is calculated as:

$$x_2 = \sqrt{(4kt\ ln\ (v_1/v_2) + {x_1}^2)} \qquad \textbf{Equation 3}$$

Where: x_2 denotes the incorrectly spaced probe, x_1 is assumed to be correctly spaced at 0.6 cm and t is measurement time (Equation 1). Because time has an essentially linear effect on Equation 3 over 60–100s, it can be solved by using the median measurement time (80s) or by averaging solutions calculated for each t value used in the measurement series. Results of the two approaches differ by < 1% in extreme cases. Once calculated, x_1 and x_2 values can be derived with Equation 3, and corrected V_h calculated as (adapted from Marshall 1958):

$$V_h = \frac{4kt\ ln(v_1/v_2) - ({x_2}^2) + ({x_1}^2)}{2t(x_1 - x_2)}\ 3600 \qquad \textbf{Equation 4}$$

By correcting a small sample of data and comparing uncorrected values with corrected values, a simple linear relationship can be derived that can be used to correct the remaining data.

Because it is not known which probe is incorrectly positioned, our approach was to also solve Equations 3 and 4 assuming x_1 is incorrectly positioned and then average the two solutions to yield an intermediate solution (Burgess et al. 1998). Use of this intermediate solution prevents biasing corrections of sap flow in either direction. Results for the two extreme scenarios differ from the intermediate solution by ± 4 to 22% for moderate (0.05 cm) to extreme (0.3 cm) positioning errors, respectively (see Figure 2B), indicating that large errors in probe placement cannot be corrected with sufficient certainty and these cases should probably be abandoned. Examples of the effects of a large spacing error on measurements, the correction procedure and its results are shown in Figures 2A and 2B.

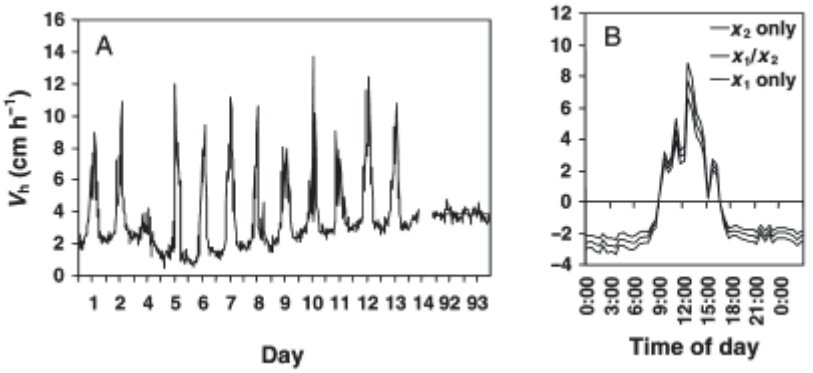

Figure 4: (A) Example of an episode of reverse flow (hourly means) in a lateral root of *Eucalyptus camaldulensis* Dehnh, erroneously measured by probes with a large spacing error (~0.2 cm). Data on Days 92 and 93 were collected after the root was severed to stop flow and indicate the potential for ambient temperature fluctuations to disturb measurements in un-insulated sensors. The straight line shows the mean erroneous velocity arising from a probe spacing error. (B) Example of corrected data (corresponding to Day 7 in Figure 2A) derived with the protocols described in the text. The middle series is the intermediate solution, which assumes both downstream and upstream probes contributed to the spacing error, whereas the other two series assume that only probe x_1 or x_2 was incorrectly spaced.

6.4 Correction for wounding

Installing sensors in xylem tissue causes substantial mechanical damage. In addition to the interruption of flow pathways by the insertion of the probes, intact vessels may become occluded as the plant responds to wounding by forming tyloses (Barrett et al. 1995). The resulting region of non-conducting wood around the site of probe insertion affects measurement of V_h by decreasing v_1/v_2. Swanson and Whitfield (1981) used a finite-difference numerical model to produce a simple algebraic equation for wound correction. The model calculates three coefficients (*a*, *b* and *c*, for varying wound widths) to calculate corrected heat pulse velocity (V_c) measured with the CHPM according to:

$$V_c = a + bV_h + cV_h^2 \qquad \textbf{Equation 5}$$

Swanson (1983) also generated a limited number of coefficients for symmetric probe configurations such as the HRM. Unfortunately, as with the coefficients for the CHPM, Swanson's (1983) solutions do not pass through the origin and the resulting corrections yield a poor approximation of low, zero and reverse rates of sap flow. We therefore developed a new numerical model to supply appropriate wound correction coefficients. To correct heat pulse velocity measured with the HRM, three coefficients; *b*, *c* and *d* are used in Equation 6:

$$V_c = bV_h + cV_h^2 + dV_h^3 \qquad \textbf{Equation 6}$$

6.5 Determining sap velocity

Only a portion of xylem tissue (the xylem lumen) contains moving sap. Heat pulse probes effectively measure a weighted average of the velocities of moving sap and "stationary" wood (Marshall 1958). Sap velocity can be determined on a real basis by measuring the fractions of sap and wood in xylem and accounting for their differing densities and specific heat capacities. Barrett et al. (1995) modified Marshall's (1958) equation relating V_c to sap velocity (V_s) as:

$$V_S = \frac{V_c \rho_b (c_w + m_c c_s)}{\rho_s c_s}, \qquad \textbf{Equation 7}$$

Where: ρ_b is the basic density of wood (dry weight/green volume), c_w and c_s are specific heat capacity of the wood matrix (1200J kg^{-1} $°C^{-1}$ at 20°C (Becker and Edwards 1999)) and sap (water, 4182J kg^{-1} $°C^{-1}$ at 20°C (Lide 1992)), respectively, m_c is water content of sapwood and ρ_s is the density of water.

6.6 Converting sap velocity to sap flow

Volumetric flow can readily be derived as the product of sap velocity (V_s) and cross-sectional area of conducting sapwood. Gross wood cross-sectional area is calculated from its under-bark radius. Heartwood area is discounted by staining the sapwood (Goldstein et al. 1998) or by observing the dark colour often associated with heartwood. Where sap velocity (V_s) is estimated at several radial depths, total sapwood area is divided into concentric annuli delimited by the midpoints between measurement depths. In this way, point estimates of sap velocity (V_s) are weighted according to the amount of conducting sapwood in the annulus they sample.