The heat dissipation method for sap flow measurements:

background, functioning and construction

Mätningar av savflöde med värmeavledningsmetoden:
bakgrund, funktion och uppbyggnad

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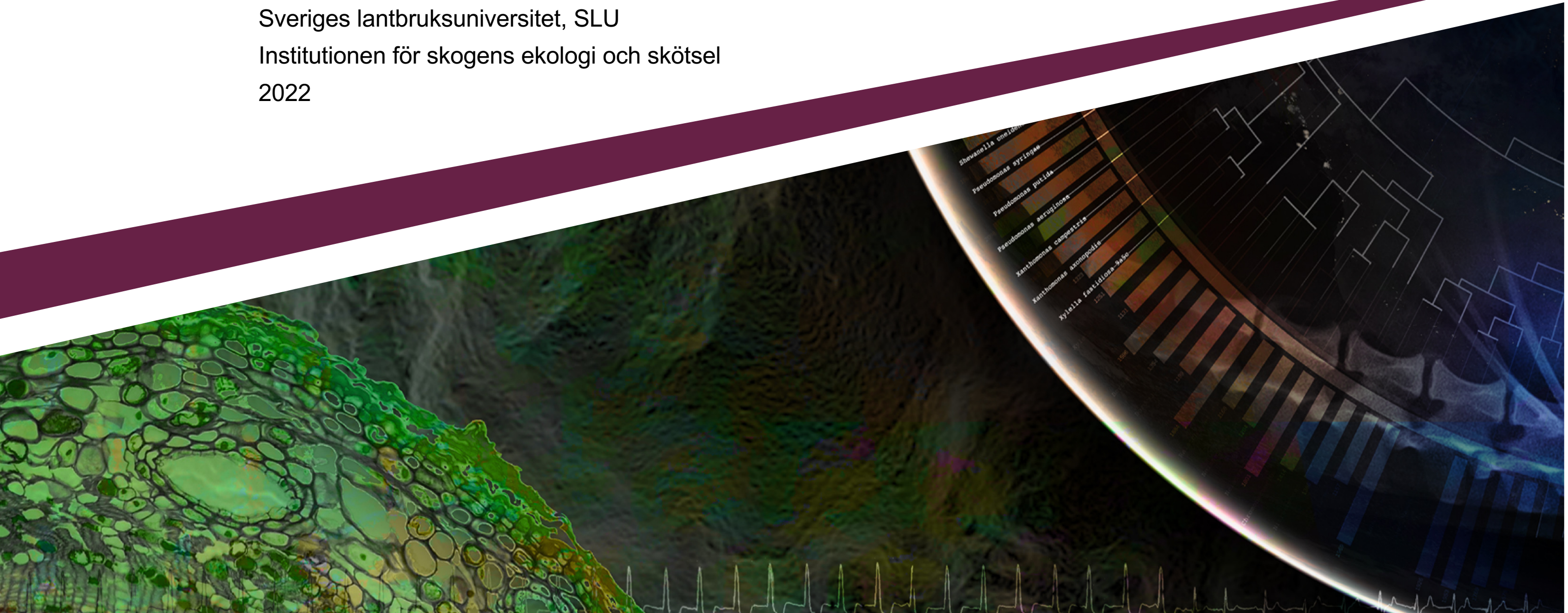

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Heat dissipation sensor, installed in a *Betula pendula* tree

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Summary

In this manual I briefly describe the working principles of the heat dissipation method to estimate sap flow. I also included a step-by-step process for the construction of these sensors, using as reference the sensor design published by André Granier in (1985). The main goal for this manual is to disseminate key information regarding this method to students, researchers, and anyone interested in it. Please consider it an introduction, there is new research on the topic being publish continuously, and details become obsolete quite fast. There are also many details I am not discussing here. Read it all, and then make the necessary adjustments to your project.

*Keyword*s: Heat dissipation, sap flow, tree transpiration

Preface

Researchers trying to incorporate sap flow methods into their studies have usually two major options; make a large economical investment on manufactured equipment, which undoubtedly makes the entire process easy, or get familiar with the technical details of the method and implement it from scratch, which in many cases might be a good long-term investment. For the second alternative, finding a common source for all the relevant technical information to successfully implement a new method might be daunting. One of the reasons is because adding all the necessary technical details in a peer review publication is impractical. Another reason for the lack of technical details is that many of them come from hands-on experience, and a common trial-and-error process over many years. The last and most important reason is the speed at which the methods evolve. Overall, this might lead to a situation where a higher percent of research funds are invested on method development and technical aspects in general, potentially hindering the ability to answer the proposed research questions.

For many of us, it is a privilege to work on all aspects of these methods, from the technical details of development, improvement, data collection, to the academic process of publication, and further, to our role as providers of key data for ecosystem management and policy development.

I believe that making openly available as many technical details as possible is a good way to help researchers, students, and land managers focus on addressing their research question, and spend less time *reinventing the wheel*. It can additionally lead to an open dialogue and critique, with the goal to properly identify pros and cons of each method, so that future users are better equipped with the necessary information before making an important decision such as adopting new methods/techniques.

-JGL

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Abbreviations & clarifications

mV = millivolts
I = current
A = amperes
mA = Milliamps
W = Watts
HST = heat shrink tubing
HDM = Heat dissipation probes
HPM = Heat pulse method
HRM = Heat ratio method
NTG's = Natural temperature gradients
HSC = heat sink compound
ga = gauge = awg = American wire gauge
F_d or Js = sap flux density (flux units)
Q = sap flow (flow units)
K = thermal conductivity
ΔTmax = maximum temperature difference
Wire = a single strand of metal
Cable = bundle of multiple strand of metal

Then, there are cables of cables, and cables of wires

Thermocouples can be made with copper and constantan wires, or with thermocouple cable (includes two bundled wires)

1 Initial comments on sap flow methods

Heat dissipation methods (HDM) or heat pulse methods (HPM)?

My personal preference are HPM, but I never push for one method over the other. My preference comes from a comparison over the years, which led me to conclude that among other things: (a) The HDM is never fully described (see Figure 1), and most of us are only familiar with its *light* version, i.e., the four-wire model (two for a heater and two for the thermocouples) with two probes. However, this leads to limited data and it is difficult to build radial profiles with it. To get three measurement points, the method needs 8 cables, and three columns of data. Now, if you also correct for NTG's, then you need another two wires for each depth you measure (that is 12 cables!). (b) HDM data is easier to get, but very tough to process. To process it, it takes more time than to process data from HPM sensors. And I am considering the entire process, from raw data to sap flow, and all associated issues with each data set. Consequently, when we compare them both, we tend to compare the light version of HDM, with a typical three-probe, three measurement points, eight-wire design of a HPM sensor.

Data sets from HDM are also simpler (often only one column per measurement point), but it is this simplicity that to me, makes them difficult to deal with. From wound-drift correction to radial profiles, HDM data seems to come with a lot more challenges than any ratio-based HPM data.

Nonetheless, if we have spoken, you know that I always insist that the best method *for you*, is the method that best fits all variables in *your project*, including what you need to monitor, access to power, human resources, physical access to the sites, budget, etc. I consider these methods just tools in my research. If you consider them tools, you know that sometimes you just need a hammer and nails to get things done, and sometimes access to a nice brushless drill with variable torque… Then if you consider that HDM is the method/tool that best fits your project, this manual will guide you in the entire process, from sensor construction to data collection. If instead you are curious about HPM sensors, check the videos I posted on YouTube on how to make those.

1.1 Why HDM in the first place?

If HDM is the only method you are familiar with, I would strongly recommend exploring other methods, if you have the time. It is not easy to have two methods running simultaneously, but it helps for some things. Again, sap flow methods are just a tool in your research project, so the more you understand the better. If you are not familiar with other methods, do not be afraid to ask.

HDM is surely one of the most constant-heat methods used, but it is one of the various methods developed so far. Some say that HDM sensors are the easiest to build, and that might be true, but it only applies to the *light* version most are familiar with. A multidepth sensor that accounts for NTG's is equally complex (or perhaps even more) than a HPM sensor of similar characteristics.

Each method has its own advantages and disadvantages, and they are usually best suited for a specific set of conditions. The overall methodology to select the sap flow measurement method should be based on equipment availability, budget, location access, but most importantly, the research questions you want to answer and how the data you will get from each method can affect that. Many years ago, we also recommended to look at the expected ranges in Js/Fd, but new research has been published on that topic, so that is no longer an issue. We do know, however, that some methods (i.e., HRM) are more sensitive to slow, medium and reverse flows (Burgess et al. 2001), and as published, do not work for fast flows. But recent publications (albeit for HPM) have shown various alternatives to address that issue (Vandegehuchte and Steppe 2012, Forster 2019, Deng et al. 2021, Gutierrez Lopez et al. 2021). There are many more, take a look at them, and select the one that best fits your project & research goals.

1.2 Comparison with other methods

Table 1 summarizes the basics, pros and cons of some of the methods developed so far. There are many more, but this is a brief reference. In it, *sap speed method* refers to the way the method solves for heat speed (if it is based on heat conduction-convection principles). *Zero flow*, the way zero flow is estimated. *Cables*, the number of cables needed for 3 measurement points inside the sapwood, which is highly recommended to properly build radial profiles. It includes additional 2 wires for the heater, but not the constantan wire, if the sensors are built with thermocouples. Note that the number of cables does not consider NTG's in HDM sensors.

2 General introduction to HDM

2.1 How it works?

The sensors that use the method called heat dissipation (HDM), based on the design by Andre Granier, consist of a pair of probes, heater (also heated probe) and reference (also reference probe) (see: Figure 1), which are inserted in the conductive tissue of any plant where we wish to monitor sap flow. Both probes are inserted anything from 10-15 cm apart, parallel to the expected direction of the flow. The reference is installed in the opposite, and the heater in the direction of the flow (or most of the expected flow). This is done because the method requires that the dissipated heat, does not interfere with the reference. A very important characteristic of the method is that the heater is commonly maintained at a fixed power (commonly 0.2 watts) which is achieved applying a fixed current to the heating element.

Inside each probe, there is a Type-T (constantan-copper) thermocouple. Both thermocouples are joined by their constantan wire, which due to the large temperature difference between them, it is possible to measure their difference in mV. We often say we measure the temperature difference, but in reality, since we do not know the real temperature, we actually measure differences in voltage, which then, (although it is not unnecessary), we can convert to temperature differences. For example, considering a Seebeck coefficient of 40 μV per ºC, a voltage difference of 0.4 mV, equals a temperature difference of ~10ºC, and a difference of 0.2 is equal to a temperature difference of 5ºC. Nonetheless, the heater is meant to be at approx. 40ºC (± 15ºC due to dissipation) all the time.

2.2 How is the data collected and why is this important?

The data is read as voltage difference in mV, between the heater and the reference, and the user can program the equipment to measure every 10-60 seconds, and store the measurements at larger time intervals between 15-60 minutes. Many studies store every 15 or 30 but it depends on the research needs and storage capabilities. Consequently, be careful on the research questions you want to answer, because the sensors might not be well suited for some of them. For example, I have seen lag time, or stem recharge studies, using heat dissipation sensors, where the data is stored as averages of 30 min spans, and the results focus on differences among species that range from 30-60 minutes. As you can see, if you store the mean of the previous 30 minutes, and you do the same on two trees, for comparison purposes the data has already a ±15-minute uncertainty. And no matter how you post-process the data, you will have a tough time convincing reviewers...

2.3 Main sources of error

The voltage differences between the heater and the reference probe depend on various factors such as:

(a) the temperature of the heater
(b) the physical and thermal properties of the monitored tissue
(c) fluctuation of natural thermal gradients (NTG's), and
(d) the heat dissipated by the sap

Then, what we measure is already a combination of various processes.

If we install a HDM sensor in an isothermal medium, with the heater off, the difference in voltages should be nearly zero, due to a nearly low temperature difference. However, because the plants we monitor are normally exposed to environmental changes in temperature, most of their tissues (e.g., stems) are anisothermal, with vertical and horizontal gradients that we often referred to as natural temperature gradients (NTG's), though there are also some artificial gradients to consider.

2.4 Natural temperature gradients (NTG's)

When the heater is off, it is primarily affected by b, c and d (see previous list). Installed in a tree, the measurements should be very close to zero, but it is never the case. In the field, the sensors pick up the NTG of the stem. If you can test a sensor in laboratory conditions, you will also notice that there is also a very small deviation from zero. This might be due to the cable, or potential issues with the sensor. Additionally, the sap flow by itself can also generate a temperature gradient inside the conductive tissue, in the direction of the flow. Because the heater and reference are between 10-15 cm apart, if this is not accounted for the data will be affected by it. The intensity and patterns of this gradient, depend on the thermal properties of the tissue, the size of the stem, branch, petiole, etc., the temperature of the sap, the temperature of the tissue, and the effect the environmental temperature has on them. For example, if the sapwood of a stem is at 20ºC at dawn, and the soil water temperature is at 15ºC, when sap flow starts, the stem will have a constant temperature gradient for a large part of the morning, until the stem reaches a temperature equilibrium. This NTG is of course caused by the cooling effect of the sap, as it moves through the stem, and can be further influenced by solar radiation. That is why we cover the trees with reflective insulation. The size of the stem also plays an important role on NTGs. It is evident that a larger stem, perfectly covered in a thick bark, will keep a stable temperature inside it. That is why, in many cases, larger stems tend to show lower NTGs compared with smaller stems. On smaller stems, sometimes it is necessary to cover the stem from the ground, all the way to the sensor, and above. The case of palm petioles, is a little more complex, but covering as much as possible the petiole gives really good data.

When the heater is on, what we are doing is simply increasing the temperature difference between the heater and the reference, in other words, we *could* say that we are adding an artificial gradient. However, because the HDM assumes that the heater does not influence the reference, then by definition, it is/should not be a gradient. Strictly speaking, we are only increasing the difference between the heater and the reference. We assume that this difference in temperature is orders of magnitude larger, compared to the NTG's, but unfortunately it is not always the case.

2.5 Solutions for NTG's

The important question is: can we address NTG's? Yes. Many years ago, there was a proposed method to account for them (Goulden and Field 1994). In summary, you have two options to implement this correction. First one is to install a new unheated sensor, as close as possible to your previous sensors, but making sure the heater does not interfere with it. This option leads to four wires per measured depth (important when you select a method based on number of cables). The second alternative, is to wire a second pair of thermocouples to your existing sensor, just as suggested by the authors, which leads to only two cables per measured depth. One caveat of the second approach, is that for it to work, you need a third metal in your series of thermocouples, usually chromel. If you use only constantan and copper (in the case of a Type-T thermocouple), you will not get the desired results. A few years back we tested the first alternative, and it gave us good results (Gutiérrez Lopez et al. 2018). The only downside, as I mentioned before, was the number of additional cables we needed.

It is also possible to reduce them to an acceptable range, covering as much as possible the tree stem, or the tissue you are monitoring. On some trees, I have added up to 1 m of double-sided insulation shield. But be careful, there are two major details you need to consider: (a) some trees *really need* their stems well ventilated, else they start growing roots/branches, (b) depending on where you are, you might get dangerous creatures moving in, and even worse, some of them might have a tendency to chew on cables. Finally, as previously mentioned, NTG's appear to be related to the mass of the tree of interest, and its thermal properties. We have observed that smaller trees and those with thin barks, are the ones most affected by them. This means that there is a small chance you might not need them in you are monitoring large trees. But run your sensors with the heater off, and see if they are there or not, and if they are proportionally high, compared to the actual measurements when the heater is on.

NOTE: Once again, removing bark is not desirable, because the tree will be more exposed to changes in ambient temperature. Try to avoid it through sensor design, or physically in the field during sensor installation

2.6 The maximum voltage differences ΔTmax

Also called the maximum temperature difference (ΔTmax), this value is often assumed to correspond to periods of time when the sap is not moving. However, because we only measure the maximum difference in voltages (temperatures), this is not a guarantee that this is because there is no sap movement. Anything that lowers the temperature of the reference, will result in a new high voltage difference. This is the reason why ΔTmax occur on rainy, cold, or windy nights. The reason why ΔTmax is so important, is because the role it plays within the method. According to the method and equations derived by Granier (1985), any value lower than this number is converted to flux density, and any value that is higher is automatically converted to zero. Finding this value on a long-term data set, is often referred to as *baselining*, and it is so difficult, that for as long as this method has and will exist, new baselining methods will be developed. Already, there is a long list of papers addressing this specific issue, and wait until the method starts dealing with wounding drift...

Understanding how this method works is very important to understand its limitations and to use it properly. For example, Lu et al (2004) recommended using a single value for baselining purposes, or to perform linear regressions between a few set of maximum voltages selected at shorter intervals. Regardless of the approach, having a clear understanding of what this value really is, and how it is influenced by NTG's, will allow you to properly process your data and avoid research questions that might be difficult to address, considering the methods limitations. For example, one might think that the perfect method for baselining is setting a threshold for any environmental variable (e.g., PAR or VPD), or a more complex approach, using as threshold an estimate of potential evapotranspiration (estimated at the same time intervals as your measurements). This is perfectly Ok, and few reviewers will disagree with it. But there are many situations where even this approach will not work, for example on extreme weathers (e.g., very cold, or very hot nights), or when the stems present large lags between environmental variables and sap flux density. In those situations, you are working withing the limitations of the method, and you need to be careful about the conclusions you draw from them.

An even more complex case when baselining that needs to be carefully considered, are radial profiles of sap flux density. Depending on the size of the tree, inner parts of the sapwood might or might not have baselines altogether. The outer parts of the sapwood can easily reach a point where sap does not move, and one can identify that it *flatlines* at some point very early in the morning. But in many scenarios such as large trees, or situations where stem refill has a strong lag, the inner parts of the stem might never truly flatline. Consequently, building radial profiles using traditional baseline methods such as those using environmental variables as thresholds, can prove to be very difficult or useless. Of course, if inner thermocouples the data clearly flatlines, then this is not a problem.

As a last comment, depending on the specific study, many of us request raw data (as it comes from the data logger) during the review process, to make sure that the data follows an expected shape, and that the processing is adequate for the research questions, and conclusions drawn from them, so be ready to provide those files when/if needed.

3 List of materials and equipment

3.1 Materials for probes

Constantan wire 40 gauge (0.12 mm)
Magnet wire 40 gauge (0.12 mm)*
Thermocouple cable
Hypodermic needles. 2.5 cm in length, 19 gauge (needles can be longer, if needed)
Aluminum tubing 3/32" 2.38 mm OD, 0.014" 0.36 mm wall thickness
Cyanoacrylate-based glue
Carpenter's glue
Heat shrink tubing (9 and 2 mm)
Loctite HP-20 epoxy resin (cartridge, mixer and gun)**
Heat sink compound (also called thermal paste, thermal compound, etc)
Low voltage computer cable[1] (for tubing and extension wires)

* Size not absolutely important. But needs to be small to fit inside the needle

**This is not necessary, but it increases sensor durability

3.2 Materials for current regulators

Breadboard (used for testing small electronics projects)
Perforated circuit board[2] (PCB) for electronics. 2.54 mm grid.
Four 2-terminal block connectors
220µF electrolytic capacitor
180Ω ±5% 0.5W, 12Ω ±5% 0.5W, 47Ω ±5% 0.5W resistances
1000 Ω trimming potentiometer. Code 102
250V 1A Fuse and fuse holder
Two 1N4001 diodes
LM317 voltage/current regulator
LM317 heat sink (TO-220)

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[1] I have chosen to use computer cable (75985K63 at www.mcmaster.com) for these sensors to reuse cable leftovers I had from other sap flow sensors. The cable tubing fits quite well the hub of the hypodermic needles.

[2] Size can vary depending on specific needs. I prefer small ones (5 x 10 cm, tinned), where I connect 6 heaters each (three per regulator). Overall, it saves a lot of space inside the equipment box.

3.3 Various tools and consumables

Weller WES51 soldering station

- Any brand works, but make sure it is a "temperature regulated" one

Solder 60/40 without rosin core, is possible

Soldering rosin. Buy pure rosin if possible. Soldering flux is "ok"

Wire cutters, wire stripper

Heat gun & Dremel rotary tool

Fluke 115 multimeter (try to buy fuses for it as well)

- Any brand with voltmeter, continuity, resistance, and ammeter works

Working table, preferably with a glass cover

Etching tools and chemicals if you decide to etch your PCB's

Epoxy resin cartridges with applicator (gun) and mixers

- If you decide to use resin

Universal support for soldering

Nozzle cleaner set

3.4 Hardware and software

Campbell Scientific CR1000X Data logger[3] or higher

Campbell Scientific AM1632B Multiplexer[4]

CRBasic program able to read differential voltage at intervals of less than a minute and average readings into intervals of 15-30 minutes

- Some codes at: github.com/joseagl/CRBasic-heat-dissipation

Weatherproof instrumentation box

12V (at least 100Ah) acid-led rechargeable battery

Solar panel and regulator (if you do not wish to physically change the battery)

Power and communication cables

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[3] Many others work, too

[4] Many others work, too

3.5 Where to buy?

I have compiled a list of potential vendors (see Table 2). Take a look at them, and please consider it a reference, because many items are not readily available in some countries. Use the list to look at the characteristics of each component and try to buy the equivalents. Remember that in case of wires, minor deviations from the suggested sizes have no major consequences. The only one that might need to be quite precise is the constantan wire, because coincidentally the Teflon cover Omega uses, seems to fit perfectly for heater construction. That being said, others should also work.

4 Sensor construction: summary

By: Christina Hackmann, 2019

1. Check that all materials are available

For each sensor are needed:

- 25 cm thermocouple wire (copper, constantan)
- 40 cm constantan wire
- 15 cm cable tube
- 4 cables of different colour (e.g. white, blue, red, yellow), 25 cm each
- 2 hypodermic needles, 24 mm length (19gauge/1.1 mm OD)
- 1 aluminum sleeve, 22 mm length*
- 1 zip tie

* It can be longer, depending on your specific design, and preferences

Additionally:

- Heat sink compound/thermal compound (e.g. ceramic paste)
- Superglue
- Teflon tape or heat shrink tubing
- Sharp blade or pliers
- Permanent marker/sharpie
- Ruler (> 40 cm)
- Soldering station, solder, epoxy resin
- File or Dremel Tool
- Multimeter

2. Prepare the thermocouple cable/wires:
    - Strip 1-2 mm at each ends of the cables and solder them
    - Dip them into carpenter's glue or superglue. Make sure there is no bulge so that it still fits into the needle

- Divide copper and constantan in the middle of the wire (using a sharp blade)
- Cut the copper (blue) wire and strip both ends
  The constantan (red) has to be uninterrupted!
- Strip about 1-2 mm of each tip of the constantan and copper wires, and solder them one copper wire to each end of the constantan wire. You do not need to twist the wires together. Remember that if you have magnet copper wire, you need to carefully strip the insulation
- Do not cut the constantan wire, needs to be uninterrupted!
- Dip the newly soldered thermocouples in carpenters glue, and make sure there are no bulges, else it will not fit inside the needle

3. Prepare the needles:
   - If not done already, cut needles to the right length (24 mm)
   - ONE needle needs a little hole 2 mm from the tip.
     Use the file or the Dremel tool to do it.
   - Make sure the inside of the needle is clean and the edges of the hole are not sharp. It can cut the constantan wire
   - Make another hole into the hub of the same needle (top to bottom), e.g., using an uncut needle

4. Constantan wire - create the heater
   - Strip both ends
   - Mark the wire at 7.5 cm and 31.5 cm
   - Insert the wire into the hole 2 mm from the tip of the needle down to the hub. Feed it until the 7.5 cm mark reaches the hole.
   - Start coiling tightly all the way down the needle, until the 31.5 cm mark is reached
   - Coil another few rounds and feed the wire through the hole in the hub

- Apply a drop of superglue where the coiling ends to keep the wire in place. Make sure there is no bulge so that the aluminum sleeve will still fit.
- Both ends of the wire should now stick few centimeters out of the needle hub. Make sure they do not have the same length so that the ends will not touch

5. Add the thermocouple wire
    - Mark one end of the wire so that you can insert it from the hub right to the middle of the heater (the needle that already has the constantan). This will be 1 cm down from the hole in the needle.
    - Fix with superglue on the inside of the hub

6. Add the cable tube
    - Cut a hole in the middle of the tube, big enough for the 4 cables
    - Feed the thermocouple wire (the one with the heater)
    - Pull the copper wire on each side of the tube

7. Add the cables
    - Strip both ends of the 4 cables
    - Choose a colour code and stick to it!

Example used here:
red & yellow – heater;
blue: heated thermocouple
white: reference thermocouple

- Feed the white cable through the hole in the tube towards the side with the reference thermocouple
- Feed all other cables through the hole to the side with the heater

8. Soldering
    - Solder the white cable to the copper wire sticking out on its side
    - Solder the red cable to one of the constantan (heater) wires, the yellow one to the other
    - Solder the blue cable to the leftover copper wire

9. Robustness: fix the tube
    - Beside the two needles that will be inserted into the tree, there should be no sensitive parts exposed to weather. Therefore, all cables and solder joints need to be covered by the cable tube.
    - First, the heater side:
      Insert the cables gently and make sure none of the solder joints are touching.
      Pull the tube over the hub of the needle
    - Then, the reference side:
      Take the second needle and insert the thermocouple wire from the hub so that its end sits right in the middle. Fix with superglue in the hub. (same way like on the other side). Let it rest until the glue is dry.
      Insert the white cable and the thermocouple wire into the tube. Pull the tube over the hub of the needle.

10. Quality control
    - In order to make sure that all joints are intact and none are touching, test with the multimeter:
    - Check for conductivity:
        - Red & yellow cable (Heater 1 & 2): conductive
        - Blue & white cable (Thermocouple 1 & 2): conductive
        - Heater – Thermocouple: not conductive
    - Check for resistance:
        - Red & yellow cable (Heater 1 & 2): ca. 15.3 Ω*

  - Blue & white cable (Thermocouple 1 & 2): > 5 Ω*

*Note that these values might change, but should be constant among sensors

- If the resistance is close to 0 or Heater and Thermocouple show conductivity, there is a connection where it is not supposed to be. Check that no joints are touching inside of the tube.
- If there is no conductivity in either the heater or the thermocouple, a solder joint might not be intact or a wire is broken.
- Either way: fix the problem, or the sensor will be useless
- To avoid having already superglued everything, also test during the previous steps!

11. Finish
    - Cover the hole in the cable tube and the area around with Teflon stripe (or heat shrink tubing) to protect it against the weather. Only the 4 cables must stick out for further connection.
    - Fix the spot right above the hole with a zip tie for additional solidity. Cut the protruding part.
    - Cover the coiled constantan wire on the needle first with a layer of heat sink compound and then slip over the aluminum sleeve.
    - Remove superfluous heat sink compound
    - Apply a drop of superglue on
      - The very tip of the needle
      - The bottom of the needle (both to fix the aluminum sleeve)
      - The connection of the zip tie
    - Let it rest

5 Sensor manufacturing

5.1 Initial general comments

Initial comments: There are two ways to build thermocouples, first buying thermocouple cable, which already has constantan and copper included, covered in an additional insulation layer. A second alternative is to buy constantan wire, and copper wire separately. I prefer to buy them separately, because then the thermocouple is thinner, fits easily inside needles, and in my opinion is easier to handle. I will try to write the description for both.

5.2 Preparation of cables and wires for thermocouples

Cut 25 cm of Type-T thermocouple cable. Pay attention to the color in your country, the most common one is red=constantan, blue=copper. If you are using constantan and copper wires separately, simply cut one 25 cm section of constantan, and two ~10 cm sections of copper.

The constantan wire (or thermocouple cable) does not need to be 25 cm long exactly. The length is just estimated so you have enough wire to work on both thermocouples. But whatever you do, remember *never* to cut the thermocouple/constantan cable/wire that joins both thermocouples. It *must* be left uninterrupted. I have seen professionally-made sensors where the constantan is cut, and resoldered later. Or worse, once I saw (also made by a professional sensor manufacturer) a sensor where the constantan between thermocouples was cut and joined with copper wire. We all have made mistakes, no problem.

There is a lot of information online on how thermocouples work, and the principle behind the Seebeck effect. One argument I have heard in favor of cutting the constantan wire that joins both thermocouples, is that the “third law of thermocouples” (also called the law of the third/intermediate metal) allows it. But it is just a misinterpretation of the third law. The law refers to a “junction” (two sides of the thermocouple), not only one side. Additionally, the entire junction needs to be at a thermal equilibrium. We have carefully tested brass connectors when we build HPM sensors that use also Type-T thermocouples, and there is no problem there.

Anyways, if your sensor has the constantan wire that joins both thermocouples cut, or interrupted, don't use it.

NOTE: Do not cute the constantan wire that connects both thermocouples. It messes up with the whole idea of a thermocouple, and with the idea of joining two thermocouples as one, in a way that can be read as voltage differences.

5.2.1 Wire for heating element

Cut a 40 cm section of constantan wire, and mark 7.5 cm and 31.5 cm (or 8.5 from the other end). With the multimeter turned to Ohms (Ω), measure the total resistance of the 40 cm section, and write it down for your records. Also, on a few of your sensors, measure the resistance between 5.5 cm and 31.5 cm mark, also write it down for your records. This is by far, the most important value you need to calculate the current needed for the heater.

5.2.2 Important details regarding heater characteristics

Why is the resistance from 5.5 to 31.5 so important? Because this is the length of the wire that is inside the tree, and the resistance we need to know, to calculate the current needed for a certain wattage. When you coil the heater, you will insert the constantan until the 7.5 mark, but this means that there will be 2 cm of extra constantan inside the tree.

Why a 40 cm wire? Well, it all goes back to sensor design and the specifications of the method:

A 2 cm coil, running at 0.2 watts

If we look at this carefully, we are expected to produce a wattage per unit of length. First, imagine that we insert the entire heater inside the 2 cm coil, and apply the right current to get 0.2 watts. Perfect, all is good now. But imagine that your dog accidentally pulls the constantan wire, and now there is only 70% of the original length inside the 2 cm coil. At this moment, your heater is no longer meeting the specifications of the method. The entire wire might be a 0.2 watts, but the 2 cm heater length that you care about, is now running at approx. 70% of that, asumming of course that the supplied current never changed. The right solution would be to use a new sensor, but to highlight the issue at hand, another way to fix it is to measure the resistance of the 70% remainder constantan wire, and apply the right current, so that you have again a 2 cm heater running at 0.2 watts. You will of course apply more current than before, but this is done to make sure you follow the specifications of the method. Applying this example to an actual sensor, we often have legs or extra wire on the heater that we leave for soldering extensions. The length of the legs can easily be 15-20% of the length of the heater, so make sure you consider *only the length of the wire inside the tree* in your current calculations *not the entire length of the constantan wire*.

NOTE: What really matters, is the constantan that will be inside the tree. We really need to know the resistance of the wire *inside* the tree. The extra wire used for soldering cable extensions should be noted, but it is not the main focus. The method calls for a 2 cm heater at 0.2 watts, and it was designed without legs and extra wire. If you use the total wire resistance in your calculations, the section of constantan wire inside the tree will not be at 0.2 watts. Don't try to force the heater to be 2 cm, focus on meeting the specifications of the method, regardless of the resistance of the 2 cm coil.

5.2.3 Tubing and sensor extensions

For the sensor design shown here, cut a 25 cm section of computer cable (also known as data cable) and remove the inner cables, mesh, Teflon, and wrapping aluminum. If you have 4 or 6 individual cables, pick four based on your color preference. Two will be used for the heater, and two for the thermocouples.
Using a sharp blade, or cutting pliers, make a perforation right at the middle of the 25 cm computer cable insulation. Make the opening just large enough to fit all four wires inside it, no larger. Try not to cut too deep, else the cable might bend. What I have noticed, is that it helps to cut the cable at a 45º angle.

5.2.4 Needles & aluminum tubing

Initial comment: Always think about the bark. The basic rule for sensor installation is to remove the least amount of bark possible. If the tree has a lot of bark, leave as much as you can (e.g., 1 cm). This means that the entire sensor design will be different. For example, the heater should start 1 cm from the tip of the needle, and all the wires and dimensions need to be modified. That being said, I will assume your trees have little to no bark, but *please do keep bark depth in mind when you design your sensors*.

5.2.4.1 Needles

Cut two needles at 2.4 cm and restore the roundness at the tip. I tend to use cutting pliers, but a Dremel (or similar tool) also works. From the tip of both needles, mark approx. 0.2 cm and starting that point measure and mark 1 and 2 cm. Using a file or a Dremel, make a small perforation at the 1 cm mark on both needles. I don't think this perforation really helps with the measurements, but it helps sealing the thermocouple inside the needle (because the glue flows by capillarity). On the second needle, make a second perforation slightly larger at the about 0.1 cm from the 2 cm mark, towards the tip of the needle.

Using a nozzle cleaner (mini files made of metal) clean all the small pieces of metal that might have fallen inside the needle. On the needle that has two perforations, try to dull the inner walls of the perforation at the tip; the constantan wire will be fed through it, and the walls of the needle should not be sharp (Figure 2).

Finally, on the needle with two perforations, use a new needle and poke a hole through the hub nearly perpendicular to the needle. This hole will eventually help to keep the heater in place.

5.3 Heat-dissipation tubing

Cut a 2.4 cm section of aluminum tubing. Avoid using any "shear" tools, most of them will squeeze the tubing and make it later difficult to insert the heater.

Sometimes, it can completely ruin the sensor. An easy way that works well for me is to roll the tubing on a surface with enough friction to make the tubing roll. Use a cutting blade and apply pressure while you do it. This should cut the tubing without squeezing it.

Does the tubing need to be exact 2.4 cm? Not really. It can be longer, but never shorter than 2 cm (for the 2 cm design, of course). In the design your see in Figure 1, the tubing can be embedded in epoxy resin, and if you do that, it is good that the tubing is long enough for that. I would advise never to pre-cut all your tubing. You might decide to build a larger sensor, and access to uncut tubing will be crucial.

5.4 Making thermocouples

5.4.1 Soldering

First, for thermocouple cable. Strip about 1-2 mm of each end of the cable. Using the right tools (I often use sharp pliers) you can strip the constantan and copper wires simultaneously. Practice a few times, using the tool that best fits you, and it will work. After this is done, split the copper and the constantan wires in the middle of your thermocouple cable at least 15 cm (more if possible). It is not easy to split thermocouple cable, and if you are not careful enough, you might damage either the constantan or the copper wires. Both situations are undesirable. *This is one of the reasons I prefer separate constantan and copper wires*.

For separate constantan and copper wires. Strip about 1-2 mm on each end of the wires. On the copper wires, it is a good idea to strip both sides now. To solder[5] the thermocouples (cable, or separate wires), make sure the two previously

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[5] Take a look at the videos available on YouTube by PACE Worldwide.
Basic soldering lessons 1-9 playlist: https://goo.gl/lohRhk

stripped cable (or wires) are touching[6]. *You do not need to twist them together*. Apply a small amount of rosin to the copper-constantan junction and proceed to solder. To solder them, grab a droplet of solder with the soldering iron, and touch the junction with it, not the other way around. Make sure there is enough solder to join both wires together, but not too much to create a bulge, as this would make consecutive steps more difficult or impossible (Figure 3 and Figure 4).

NOTE: whenever possible, use pure rosin and avoid using acid-based soldering fluxes.

The traditional soldering technique with larger pieces requires that we heat up first the junction to be solder, and then apply solder, but since these wires (copper-constantan) are so small, heat transfer to the piece to be solder is so fast, that we might accidentally oxidize the metals, and reduce their life expectancy.

Use a temperature regulated soldering station, and solder thermocouples at no more than 315ºC, to avoid unnecessary oxidation of the copper wire. The melting point of 40/60 solder is about 280ºC, however, to avoid at all costs "cold junctions[7]", solder at no less than 310ºC. Once both thermocouples have been soldered, you will end up with a constantan wire with two copper wires attached to both of its ends.

Remember to always keep the soldering station clean, particularly the soldering tip, and if you stop using it for long periods of time, turn it off. If residue builds up on the soldering tip, remove it on a damp sponge which is often included as tools. Find balance for the wetness of the sponge, a super wet sponge will create a thermal shock every time you clean it, which lowers the temperature of the tip significantly.

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[6] The literature on thermocouples is quite extensive and some indicate that twisting the wires only adds mechanical strength and no sensibility. Take a look at these introductory documents: http://www.omega.com/temperature/z/pdf/z021-032.pdf & http://www.ti.com/lit/ml/slyp161/slyp161.pdf

[7] See "cold joints" here: https://en.wikipedia.org/wiki/Soldering#Cold_joints

5.4.2 Thermocouple insulation

As mentioned earlier in the preparation of hypodermic needles, data can render useless if there is physical contact between the constantan wire used in the heater and the thermocouple. Why would this happen? Well, when you coil the heater, the constantan wire is fed through a small hole in the needle, and if you are not careful enough, the needle might pierce the insulation of the constantan wire. When the heater is on, current will flow through it, and into the needle. *If* the thermocouple is touching the needle, ten any data you collect will be useless.
You have two options to protect your thermocouples. First, using insulating tubing (e.g. polyimide[8]), and for this options both needles need to be larger, and the entire sensor design changes. We use polyimide tubing when we build HPM sensors, and it makes everything easier, but it is expensive, hard to get in small quantities, and very hard to get in some countries.

Another very simple alternative is to dip the tip of the thermocouple (only the exposed metal) in carpenter's glue[9] (Figure 5). I have noticed recently that thermocouple cable is thicker and you need to be extra careful because too much glue will create a bulge, and it will not fit inside the needle. Dip the exposed wires, and let them dry for about four hours and once the glue is completely dry to the touch, test for continuity (using the multimeter turned to the sound symbol) between any of the two copper wires and the tip of each thermocouple. There should be no continuity (multimeter will not beep).

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[8] This would require you to fill the polyimide tubing with heat sink compound to make sure the thermocouple is in direct contact with the tubing and the needle.

[9] Any other polyvinyl acetate glue should work

5.5 Heated probe

5.5.1 Initial assemblage

The heating element and the heated thermocouple are assembled at the same time. First, take one of the needles that were prepared for the heaters and insert one thermocouple from the hub of the needle. Slide the TC into the needle until it sticks out on the other side of the needle (Figure 6).

Insert a constantan wire (the ones prepared for the heating elements) in the hole opened at the tip of the needle, until it sticks out on the other side of it. Insert the constantan wire from the side where the 7.5 mark is. Carefully, feed the wire until the 7.5 cm mark, making sure that in the process, the thermocouple wires are not pushed out. *Again, this is easier with separate constantan/copper wires. But we have also done it successfully with thermocouple cable.*

Once the 7.5 cm marking reaches the hole, gently bend the constantan wire to form a 90º angle with the needle (Figure 7). This will help keep the constantan wire in place. Adjust then the thermocouple until it becomes visible through the 1 cm hole. This can be particularly tricky, especially if: (a) the needle was not properly cleaned, (b) the solder in the thermocouple is not small enough, (c) the layer of glue used to isolate the thermocouple is not thin enough or (d) you are just not having a good day.

Once both the constantan and the thermocouple are in place, apply *liquid* (gel-based does not work) cyanoacrylate-based glue (superglue) to the tip of the needle and let it fill the needle via capillarity (Figure 8). This process is easier if you apply one small drop at the time. Stop once the needle doesn't absorb any more. Keep the needle horizontally while filling it up, or the glue can accumulate on the other side of the needle (base of the hub). Let the glue harden for at least a couple of hours (it can much more) and proceed to coil the heating element.

NOTE: Perhaps I am being too optimistic, because under some conditions (cold, specially) the glue will take much longer to dry. You could use a heat gun on low heat to accelerate the process, but letting the glue cure itself over time is best.

5.5.2 Coiling the heating element

Coiling the heating element is a rather simple step, however, done the wrong way can ruin all previous work and render the probe useless. The way I would recommend coiling the heaters is by rotating the needle, rather than wrapping the wire around it. Twisting the constantan around the needle cam damage it and make it prone to rupture. Instead, coil the heater as follows: using the left hand, apply a slight pressure with the thumb and index fingers on the tip of the needle where the constantan wire is sticking out, making sure the constantan wire gently folds around the needle.

Next, rotate the needle clockwise by the hub and let the constantan wire coil downwards, all you need to do is continue rotating the needle hub. During the entire coiling process keep a constant pressure on the needle with your thumb and index fingers. Make sure the coils are tightly packed and continue coiling the wire until the 31.5 cm mark, to ensure the resistance of the heater inside the tree is fixed. Once you reach this mark, do a couple more (wider) loops to keep the coil tight and insert the other end on the hole at the tip of the hub.

Next apply a small drop of cyanoacrylate glue in the hole where the constantan wire was inserted, fold the constantan wire around the hub to keep the heater tight, and let it dry for more than two hours. *Again, depending on the environment, it might take longer.*

The final product of this step will be a hypodermic needle with a 25 cm uninterrupted constantan wire (with one thermocouple on each end) inside, and a heating element made of constantan wire coiled around it. For simplification purposes, let’s call this part the “heater-thermocouple set” (Figure 9).

5.6 Sensor assemblage

5.6.1 Heating element and extension cables[10]

The first thing we need to do is to insert the heater-thermocouple set in the gray tubing. Insert the set starting from the reference thermocouple until it sticks out on the other side of the gray tubing. Next, insert three cable extensions (the ones we removed from the gray tubing before) of your preferred color (I use red, black and green) from the center of the gray tubing in the hole opened on its back. Insert the cable extensions towards the side of the tubing where the heating element is located. Next insert another extension wire (I use white) but this time towards the end of the tubing where the unheated thermocouple is located.

At this time, strip the cable extensions from the side facing the heating element and heated thermocouples. Insert a 2 cm piece of HST on each cable and proceed to solder the extensions with their corresponding wire (i.e., red and black with the heating element, and green with the positive side of the heated thermocouple). Do not let too much heat move through the cable/wire, it can shrink the HST and you won't be able to move it. Position the HST on the recently soldered joints and apply hot air to fix it in place.

Once everything is soldered and protected with HST, pull carefully on the extension wires, only until the needle hub for the heater-thermocouple set touches the gray tubing. This is done to make sure you don't have extra wires everywhere. Next, insert the needle hub (from the heater-thermocouple set) into the grey tubing. It is best to make sure there is a tight fit, but if this is too difficult, try to loosen up the tubing first.

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[10] Remember that wires are single stranded, and cables are multi-stranded. There are cables of wires, and cables of cables. In this case, extension cables are those used to connect the constantan wires of the heating elements and the copper wires of the thermocouples. Cables are used to connect the sensors to the multiplexer and data logger. Often, wires are used as extensions due to their overall lower price.

NOTE: All these assembling steps are not easy, but if done carefully, they will protect your sensors from the environment, insects, etc., for a long time. Highly recommended.

5.6.2 Reference thermocouple

Next, on the other side, (where the reference thermocouple is sticking out), insert the thermocouple in one of the needles prepared for the reference thermocouples, until the tip becomes visible through the hole opened at 1 cm. Remember that this hole, if you decide to have it in your sensors, should be as small as possible (I personally don't like it…). Once you see the thermocouple tip through the hole, apply cyanoacrylate glue, similarly as with the other needle, and let it dry for about 4 hours.

Once the glue has dried out, strip the cable extension of the reference thermocouple (the one that should be sticking out from this end) without pulling it out of the gray tubing, and solder it to the reference thermocouple. Once everything has been soldered, coil any remainder thermocouple cable (or separate constantan/copper wires), and insert them in the gray tubing, in the same way as the heated thermocouple. If you used separate copper and constantan, also coil them and insert them in the grey tubing.

Fold all extension cables that are sticking out of the gray tubing towards the reference thermocouple. As an additional protection, use Teflon tape to cover the whole where the extension wires are sticking out. Once this is done, inset everything in a large HST (approx. 10 cm in length), apply heat, and before the HST cools down, give it a curve-like shape, it will help for the installation in the field. To further protect the sensors in the field, you can use a ZipTie (also called cable tie), and tighten all cables together.

5.6.3 Heat-distributing tubing

To increase the rigidity and durability of the sensor, the aluminum tubing will be permanently attached to the heating element and held in place by the epoxy resin[11]. Long time ago, people were advised to insert the tubing into the tree, and then insert the heating element in it. *Today, this is unnecessary and should be avoided. This, and removing the bark of the tree, are two things you should really avoid.*

Before you fasten the aluminum tubing to the heater, apply a uniform layer of heat sink compound (HSC) to the heating element. This will ensure good contact between the constantan wire (heating element), and the inner walls of the aluminum tubing. Make sure there are no areas of constantan wire without HSC.

Insert the heating element into the tubing, and level the tip of the aluminum tubing with the beginning of the heating element. You should be able to see the hole in the needle opened at the tip of the needle, from where the constantan wire sticks out and starts to coil. But do not let more than 0.1 cm of needle stick out of the aluminum tubing.

NOTE: I suggested a length for the aluminum tubing of ca. 2.4 cm. Based on your project needs, you can decide if you want the aluminum tubing to cover the entire needle of just the coiled heater. My personal suggestion, is to let the aluminum tubing cover all, even to the base of the needle.

Common question: Will longer aluminum tubing affect the measurements?
RE: Yes, longer tubing will increase the ability of the heater to dissipate heat. But if all the tubing is inside the tree, and the heater (coiled constantan wire) meets the specifications, your data will be just fine. We have a similar issue with multi-depth HPM with probes made out steel,

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[11] The epoxy resin will not bond to the aluminum, it is necessary then to either physically widen the bottom of the tubing, or to attach a piece of wire/metal to promote mechanical bonding between the aluminum tubing and the epoxy resin.

5.7 Alternative materials for aluminum tubing

Common question: Can I use another material for the tubing? I cannot find the right aluminum tubing

RE: The reason for the aluminum tubing is to dissipate heat from the heater (pardon the redundant redundancy). Then, any material will work, but the parameters use to convert the data into sap flux density were developed for a metal with a specific thermal conductivity (k). k from aluminum happens to be the highest (230 W/m K^{-1}) among the "cheap" metals. Next in line, I would recommend copper. And sure, if you have deep pockets, silver or gold would also work. Steel and bras have unfortunately very low k, so I have not tested how that would affect the parameters or the sensitivity of the measurements. But remember, the method is called "heat dissipation", so changing the dissipation properties is like using another method altogether. If anyone out there is working on a manuscript testing these specific properties of HDM sensors, please let me know, I am definitely interested in their results.

5.7.1 Epoxy resin protection

A previous version of this sensor included epoxy resin (Loctite Epoxy Resin) as protection. This step is not necessary, but if you wish to increase the durability of your sensors, follow these steps: First to seal the tip of the probe and, to add strength to the needle and the heating element as a whole. If you happen do have a mold for the epoxy resin and the sensor, that is ideal, but if not, you can use the needle lid. Cut the lid so that your sensor has 2 cm of tubing with heater. See Figure 1 for a descriptive cross-section of the finished sensor.

6 Sensor quality control

Quality control should be performed often, to avoid wasting time on a faulty sensor, or even worst, installing a bad sensor (I have done this many times, so try to avoid it).

NOTE: My basic rule for a failed sensor, or sensor component is: “put it in the garbage”. Sounds like a joke, but I have noticed that it takes more time to fix one sensor, that making a new one. Specially in the early stages. Test often, and practice “destroying” things (meaning that you should test what it takes to damage a wire, to avoid doing it). Put aside faulty sensors or components. You can fix them later if you have time.

6.1 Basic quality control tests

Consider first the following, using as reference the wiring shown in Figure 13:

A=Extension wire for upper thermocouple
B=Extension wire for lower thermocouple
C=Extension wire for heater (interchangeable with D)
D=Extension wire for heater (interchangeable with C)
E=Needle of reference thermocouple (small needle)
F=Needle for heated thermocouple (aluminum tubing)

Turn first the multimeter to continuity (often a WiFi-like symbol) and test:

1. Continuity from A or B, to E and F (Continuity = fail. No continuity = pass)[12]

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[12] This continuity is accepted, but undesired. Sensors will be fully functional, but this would create a "grounded thermocouple". Grounded thermocouples pick up more noise from their environments.

If there is no continuity, this means that the thermocouples are not touching the needles, which is a good sign. However, if you don't have a continuity test in your multimeter, you can use resistance, and if the resistance is low, but steady, it means the thermocouples are touching the needles (not desirable)

Turn the voltmeter to resistance (omega symbol) and measure:

2. Resistance from A-B (Fixed/constant resistance = pass. Else = fail)
3. Resistance from C-D (Fixed/constant resistance = pass. Else = fail)

Test all components prior to major assemblages and test all components again when sensors are soldered to extension and communication cables/wires.

7 Communication cables

Soldering communication cables is quite simple, but I would strongly recommend cutting the individual cables at different lengths, and adjust the extension cables from the sensor accordingly. This is done, to avoid having a single point where all the cables meet, which if you are not careful, it will create a bulge in the cable. Finally, don't forget to add a piece of HST to each cable before you solder them, and also to the finished cable when you are done, this means you need to add them before you start soldering. Regarding cable length, keep in mind that the sensors are run at a relatively small current, so there are a few things to consider:

- If you are using relatively thin cables (i.e., < 0.25 mm^2 in area), make sure your communication cables are no more than ~15 m in length. Else, you will start having issues with the wire resistance. If you need longer cables, try to find cables with a larger surface area (e.g., >0.3 mm^2)
- Overall, the longer the cable the greater the changes of picking up noise, and current leaks
- Make sure all your cables are the same length. This might be wasteful, but it is a way to control all sources of error
- For longer cables, you *could* run the sensors at 0.3 watts, and that might reduce the noise/signal ratio, but make sure your trees can handle it

If the power source could be right at the sensor/tree base, then of course, the cable could be larger.

8 Current regulators

Initial comments: I have received many questions regarding the circuit, components, replacements, etc. My answer is always the same: "this is the only step you can skip *relatively easily*" The truth is that you really do not need to build your own regulators, and consequently, you do not need to know much about electronics.

8.1 Buying current regulators

So, what can you do? The easiest is to buy a pre-made regulator. Today, you can buy the same circuit for under $20 USD (of course, 5 times that amount if the regulator has a metal case, screen, nice brand, etc..). Brand, screen or no screen, color, box or no box, etc... those details are not the priority. The important details that you need to look for are:

1. A step-down (also called a buck) regulator
2. A regulator for amperes and volts (amperes are the important)
3. A regulator capable or regulating between 0.050 and 0.200 Amperes
4. A regulator with a precision of 5 milliamps

The last one, refers to how easily it is to adjust small amounts of current. On the circuit design included here (Figure 10), the trimpot has 25 turns, which gives you're the ability to fine tune current. There are other potentiometers with only one turn, but adjusting them would be quite difficult. With the 25-turn trimpot, is possible to easily regulate 1mA increments. So if you need 0.113 vs. 0.115, it is actually quite easy. Don't forget to pay attention to all the small details, particularly the ones I mentioned above. Many fancy brands include a single-turn potentiometer, this means that fine-tunning current will be quite tricky.

Here is one example:

You find online a regulator that says:
"DC DC buck boost converter adjustable voltage 0.5-32V to 1.5-32V 4A"

This means that it works between DC (direct current, or a battery). "Buck boost" means it can lower or increase the source current. 0.5-32V to 1.5-32 means its input range is 0.5 to 32 Volts, and the output can be 1.5 to 32 V. 4A *might* mean that it works at 4A, or that 4A is the maximum current at which it can run (see the description before you buy).

In theory something like this would work, but make sure it says that you can regulate current. Some vendors might skip the details, but they clearly show some screen where milliamps are measured. Also, you might see that their design includes two trimpots (google "top adjust multiturn trimpot"). This means that you should be able to regulate current.

If you read things like "Variable voltage 5V, 6V, 9V, 12V", it might mean it only switches between those voltages. In that case, read all the description, to really decide if it works or not. If it works with AC (alternating current), then it will not work.

What would *not* work?

1. Only a step-up or boost regulator
2. Regulator that cannot "regulate" between 0.050 and 0.2 amperes
3. Regulator that cannot regulate under 7V

Final note on this: there are many options for current regulators, however, whatever you buy, please test it first and make sure works as expected (see my *What you need to look for* list).

8.2 Building current regulators

Initial comments: Building your own current regulator might be the only choice if you are unable to buy pre-made regulators in your country. Make sure to add time in your schedule for this step. Assembling a single regulator can take you anything from hours to a couple of days. Once you assemble one, test it fully with a power source and load to make sure it works, before reproducing it. Make also sure to test all the regulators you build, and if you forgot already, take a look again at the "cold-joint" concept I mentioned before, and avoid it when you solder. If there is one step where cold-joints can appear is here. In general, if you are not familiar with soldering, practice and review the videos I suggested above.

I revised the current regulator circuit (Figure 10), to hopefully make it easier to read. It is nearly identical to one we published a few years ago (Gutiérrez Lopez et al. 2018). Note that the design is meant to show you where the components should be laid out in your PCB. The nice thing about analog circuits, is that if built properly, they can last forever (I built some in ca. 2013, and they still work perfectly fine).

Another couple of additions, are: a version that includes a relay (Figure 16), in case you want to program your equipment to turn off the heaters when the battery is below a threshold, to avoid permanent battery damage. The final addition is the simulation of how voltage and current are regulated (Figure 12), which would give you an idea of the wattage range you can achieve

Now, if you decide to build your own regulators, which can be actually easier than you think, continue reading….

8.2.1 The basics

Current regulators[13] are extremely important. Since I am already providing a working circuit for a "Linear current regulator", the overall process for their

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[13] The main function of this component is to regulate the current flowing through the constantan wire, known as the heating element.

construction is: (a) circuit assembling and testing, (b), component soldering, (c) physically inspection and quality control, (d) final test with heaters.

8.2.2 Description of main components and their main function:

220μF capacitor
Electrolytic capacitors can serve as buffers or to filter noise
180Ω ±5% 0.5W, 12Ω ±5% 0.5W and 47Ω ±5% 0.5W resistances
Limit current flow (fixed)
1000 Ω Trimming potentiometer
Limit current flow (adjustable & linear)
1A Fuse
Cut current flow if it exceeds 1A (notice we don't need more than 1 ampere)
LN4007 diode
Forces current flow in one direction, and it is used to protect against inverse current i.e., when you connect the battery backwards
LM317 current regulator integrated circuit
Adjustable regulator of I and V, thermal overload protection (i.e. if it gets too hot, it should turn itself off

The current regulator circuit described here, as all circuits, is a closed loop where current flows from a higher to a lower potential, in this case that loop starts and ends in the battery. This circuit allows connecting three heating elements in series (meaning they need to share a common current source), and regulating the current flowing through them to meet a desired wattage. As current flows through the circuit (and the heating elements), the constantan wire in the heating elements heats up due to constantan's higher resistance[14] (relative to copper). I have included

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[14] Constantan is a metal alloy of 55% copper and 45% nickel. The main characteristic of constantan is that it has a fixed resistance over a wide range of temperatures. Copper on the other hand, increases resistance with temperature.

in the diagram a slide switch that deviates current to a block connector to facilitate current regulation without interruptions, or to turn if off without having to remove the fuse.

If you are not familiar with volts, current, amperes, resistance, direct & alternate current, getting yourself familiar with them is important to understand the function of current regulators and to avoid unwanted errors using HDM as a tool to estimate sap flow.

8.2.3 Brief background

Voltage (V) is the potential of energy, current (I) is the flow of that energy, amperes (A) is the measure of the flow of energy, resistance (Ω) is limitation of current flow, direct current (DC) is an uninterrupted flow of current, alternate current (AC) is current that oscillates between a positive and a negative value.

Using the water tank analogy[15], it can be seeing also as:

Voltage (V) the total water stored in the tank, current (I) the water flowing from a pipe connected to the tank, amperes (A) the measure of the water flow, resistance (Ω) limitation of water flow (i.e., water valve), direct current (DC) uninterrupted flow of water.

8.2.4 Circuit design and initial testing

The first step is to mount all components according to Figure 10 on a breadboard. Once all components have been mounted and connected, feed the circuit with a 12V battery and make sure the voltage changes across the current-regulated positive and the negative ends (NEG, REG-POS in Figure 10). Spot and

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[15] I personally dislike the water tank analogy, because it fails to explain to a greater detail pretty much everything: what happens to voltage and current when connected in series or parallel (the case of batteries), what is the principle behind alternate current.

replace faulty components, if you wish to, you can test components in series with the same circuit (i.e., remove the trimpot only, install a new one, test the circuit, etc.). To test current regulation, you will need to connect three heating elements, or three resistances of similar value to your heating elements, and connect the ammeter in series.

NOTE: Be very careful never to read volts when your multimeter is in amperes mode. Most multimeters have a fuse, which will likely burn if you try to read voltages when it is in amperes mode. *So please be careful!*

8.2.5 Solder components

Once you feel comfortable with the circuit and had made sure all components to be used work properly, proceed to mount and solder all components on a PCB board[16] of your preference. Follow standard soldering techniques (e.g., avoid overheating components, clean all rosin remainders, etc.). Literature is extensive[17] on soldering techniques, and once again, I would strongly suggest to practice first if you are not familiar with soldering. Use rosin only and avoid using acid-based soldering flux.

8.2.6 Physical inspection and quality control

The next step is to physically inspect soldering joints and make sure there are no loose components, cold joints[18], or any other common soldering problems. If you find any, make sure all are properly addressed. Once everything is soldered, components legs have been cut to proper length, apply at least three layers of circuit protector lacquer to avoid premature oxidation of components.

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[16] You can always design, perforate and etch the circuit board that fits your needs. The downside of fixed circuit boards with custom-made perforations is that it reduces your ability to make additions/improvements to an old design.

[17] Take a look at the videos available on YouTube by PACE Worldwide.
Basic soldering lessons 1-9 playlist: https://goo.gl/lohRhk

[18] Cold joints and other common soldering problems are covered in the PACE videos.

9 How to regulate current

The basic formula to regulate current is:

$$I = \sqrt{\frac{watts}{resistance}}$$

In this case, the desired wattage is 0.2 as indicated in (Granier 1985), and considering the estimated resistance for the heating element (only constantan inside tree) we have:

$$I = \sqrt{\frac{0.2\ W}{11.5\ \Omega}}$$

$$I = 0.1318\ A$$

$$\text{or} \sim 132\text{mA}$$

Regulate current using the multimeter turned to amperes. Most multimeters work in a similar way, but for the Fluke 115, turn the knob to A-DC (Amperes in direct current mode), remove the red lead from the right side (volts and resistance) and insert it into the left side (Amperes). Connect the leads in the block connector installed to measure current, slide the switch to the current-measuring position and proceed to adjust the trimming potentiometer (trimpot) until you see the desired amperage. When you are done adjusting the current, slide back the switch to divert current back to the fuse, and remove the multimeter leads.

NOTE: Current *must* be measured in series. This means that at some point in the circuit, the current needs to flow through the multimeter. As you can see in Figure 10 and Figure 11, there is a switch that deviate the current, so that you can measure it, without interrupting the current flow. If you don't add this switch, you can measure current across the fuse holder, of course, you need to remove it first.

The original work by Andre Granier in 1985, suggested 0.2 W. Due to various technical or human errors, sensors might not be running at exactly 0.2 watts. To address this issue, some years ago we tested how changing wattage influences sap flow measurements and fund no significant difference within a range of 0.1 to 0.25 watts (Gutiérrez Lopez et al. 2018). That being said, the parameters published by Granier, 1985, were developed for 0.2 W. What we did observed, as expected, was that ΔTmax tends to be more susceptible to fluctuations due to ambient temperature at low wattages. If you modify your sensors and run them at less than 0.1 watts, expect reviewers to request gravimetric validations and raw data.

10 Battery life

The HDM is known for its large battery use, and many consider that to be its Achilles's Heel[19]. Unless you have access to power in your sites, to deal with battery issues, you have primarily three options: (a) use large batteries, and replace them at regular time intervals, (b) use solar panels, (c) reduce the power consumption of the sensors (e.g., from 0.2 to 0.1 watts). Regardless of the solution you adopt, there is always a major question that it is very tough to answer:

How long will my battery last?

The short honest answer is: "a rough estimate ±2 days". That is the best you will ever get, and the reason is that there are many factors that influence battery capacity that are not so easy to predict. For example, the ambient temperature, and how that influences battery internal temperature, which in turn affects the battery resistance, and the amount of current you can draw from it. This is a very complex field, and people write PhD thesis on the subject. I will limit myself to tell you what the common mistakes we make when estimating battery capacity:

1. Rely on battery capacity provided by the vendor
2. Assume you have access to all battery capacity
3. Assume battery discharge is linear
4. Reduce battery life expectancy during recharge

First, (1) the capacity battery provided by most vendors is a rough estimate, and as David Jones (from EEVBlog) says "it is borderline *incorrect*". If your battery is 100Ah, then use it with reserve, and not as an absolute value. Next, (2) if your battery is 12V 100Ah, you *do not* have access to 100 hours at 1 ampere, as the capacity might indicate, so the battery life estimates you can get from that value, should also be used carefully. Remember that Campbell Scientific data loggers (and also many others) will turn themselves off when the voltage drops below 9V, but to

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[19] Though, the real Achile's heel of HDM sensors is the way they deal with radial profiles, specially if you have only a couple of measurement points.

avoid reducing the life expectancy of your battery, make sure the discharge depths (the amount of charge you take out at one time) are as small as reasonable possible. For example, a 12V 100Ah battery can be replace when it is at 10V, which is already on the low range. Additionally, (3) the "discharge curve characteristic" in a battery, which shows how much the battery has left after a given time, at a fixed current withdraw, is not linear. Google "discharge curve characteristic 12V 100Ah", and you will see the discharge curves get dangerously steeper as the battery discharges. To increase battery life expectancy, try to stay away from the steep part of the curve, you can nearly triple the battery life, if you keep your discharge depths at less than 20% (in super simple words, change it if it is already ~11V). And finally, (4) the way you charge the battery, significantly affects its life expectancy. Once again, this is a complex topic far beyond my understanding, but in simple terms, the amount of current you use to charge a battery, should be proportional to the battery capacity. We often find a simple rule: "charge at 10% the battery capacity". This means that our 12V 100Ah battery, should be charged with 10Amps. However, if you Googled the "discharge curve characteristic", you might infer that the charge characteristic is somewhat the same. Charging at a constant current for me, seems excessive. Consequently, many smart chargers, include charging cycles, where the current applied to the battery, is proportional to the actual voltage, in various cycles of often decreasing current intensity, which is good for the battery life expectancy.

Finally, in case the information is relevant. I have used a 12V lead acid battery of 110Ah in extreme environmental conditions, and it tends to last 6 days, running 12 HDM sensors running at 0.2 watts. And on the same battery I have had the same amount of HPM sensors running simultaneously.

11 Basic wiring using a CR1000 and a AM1632

This report assumes that you are using Campbell Scientific equipment, specifically a CR1000X or higher, and a AM16/32B multiplexer. If you use open-source data loggers, make sure your equipment is sensible enough to store differences of a few mV, else it might not work.

The basic instruction calls for a voltage difference between the heater and the reference (Figure 1), and this is commonly wired in a differential channel in a AM1632 multiplexor (High=heater, Low=reference). If you choose to install an additional unheated sensor to address NTG's, it needs to be wired in a similar way, as shown in Figure 13. Additionally, note that on both sensor and NTG sensor, I left the cable ground, and connected it to the multiplexor ground. This will avoid turning your cables into antennas accidentally.

NOTE: It is best to connect your current regulator circuit directly to the battery.

12 Final thoughts

If you are new to sap flow, the most basic advice I would give you is: be patience, and always make more of what you need. Things tend to fail, and you need to be ready for when that happens. I hope you read this manual and tested a few sensors before deploying your own. It is really difficult to get all things right the first time around. Identify and address all the common issues. And as I said before, there isn't much you can do if a bear or cows destroy your sap flow station, or if lightning fries your equipment, but covering all the basics can help you overcome 90%[20] of the challenges associated with sap flow.

Here are some of my personal suggestions:

- Depending on your level of interest, sap flow can be a very steep curve. Identify the areas you feel comfortable with, and reach out for help in areas you don't
- Sap flow sensors have been around for a long time. It is very likely that someone has already found a solution for your problem
- There is no such thing as a "one method fits all". Every method has its pros and cons. Get yourself familiar and comfortable with both
- HDM sensors need a reference set of sensors to correct for NTG's (ask about that if you don't know)
- Sap flow stations require constant maintenance and monitoring
- Only the combination of a good installation and proper maintenance will guarantee good data collection
- Keep a low impact approach in your sites, and clean the area when you are done
- Do all within your power to make sure your work (sensors, installation, wiring, cables, etc.) look neat and professional
- Have fun!

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[20] In my experience, it is foolish to think you can control everything. A tree can fall on your station, chipmunks can chew on your cables, deer and/or bears can rip off your cables, equipment can "disappear", lightning can strike, data loggers or multiplexors can fail, or maybe the spirit of the forest, just does not likes you, oh well, you get the idea. If you are able to handle 80-90%, you are all set.

13 Figures & diagrams

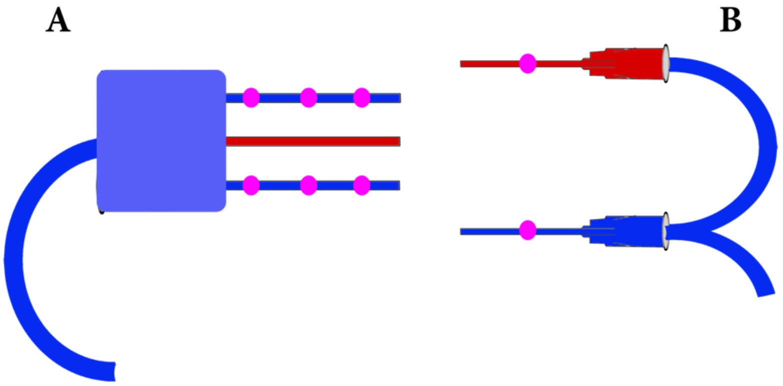

Figure 1 Basic diagram of a heat pulse sensor (a), and a heat dissipation sensor (b).

In this design, I compare the measurement points of a common three-probe, three depth HPM sensor (a), vs. a two-probe, one measurement point HDM sensor. This is the common versions of each method that are often compared, that lead to a conclusion that HDM is an easier to use sensor, despite being a very limited version. However, is that in some cases, especially when the sapwood depth is very thin, a single measurement point should be enough, so not always more measurement depths increase data quality. Note that no heater is shown in b.

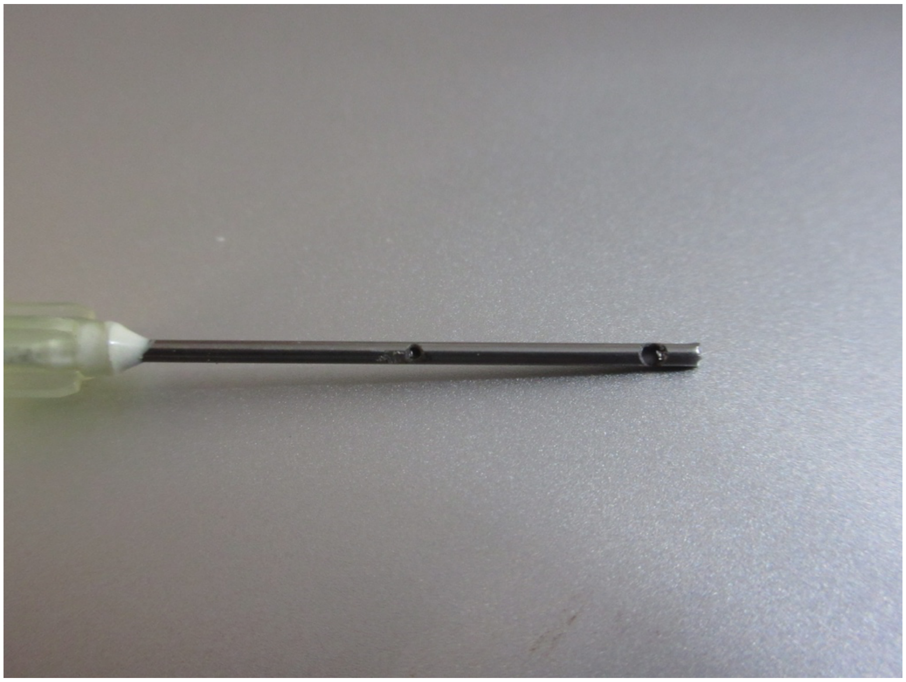

Figure 2 Hypodermic needle for heated probe.

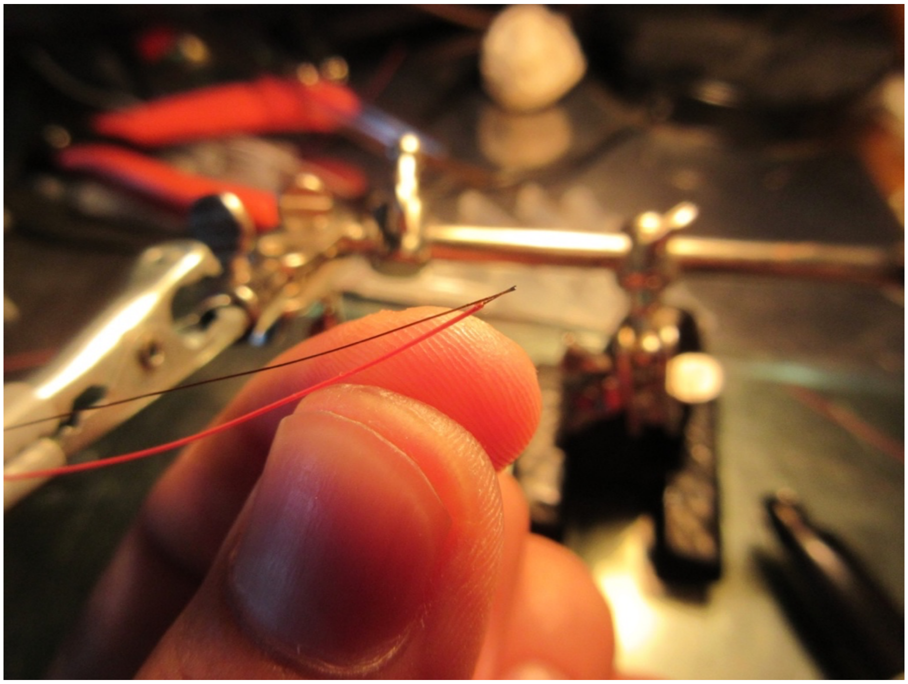

Figure 3 Type-t thermocouple with constantan and magnet wire

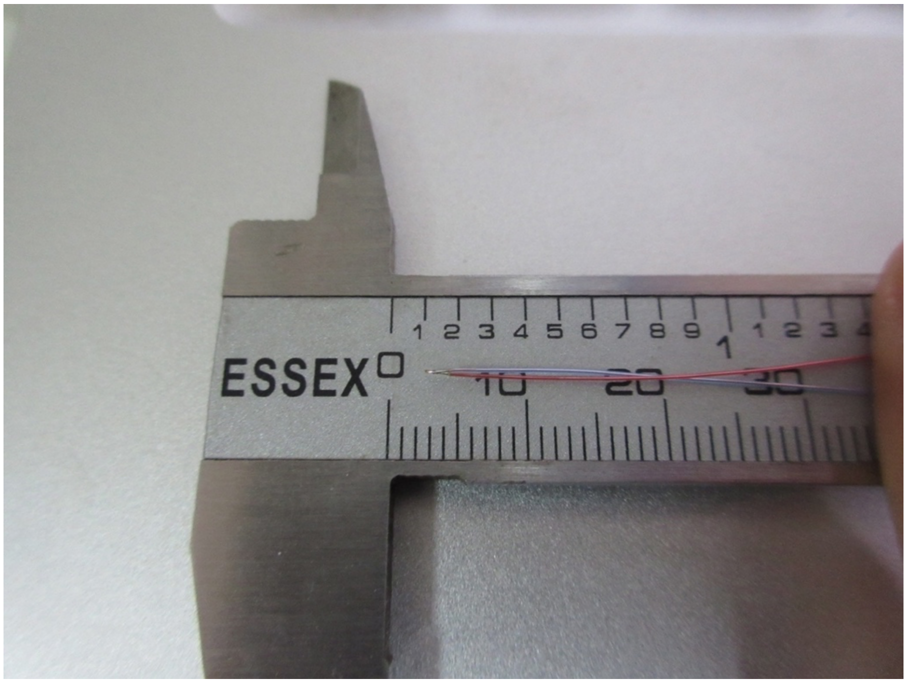

Figure 4 Type-T thermocouple with constantan and insulated copper wire

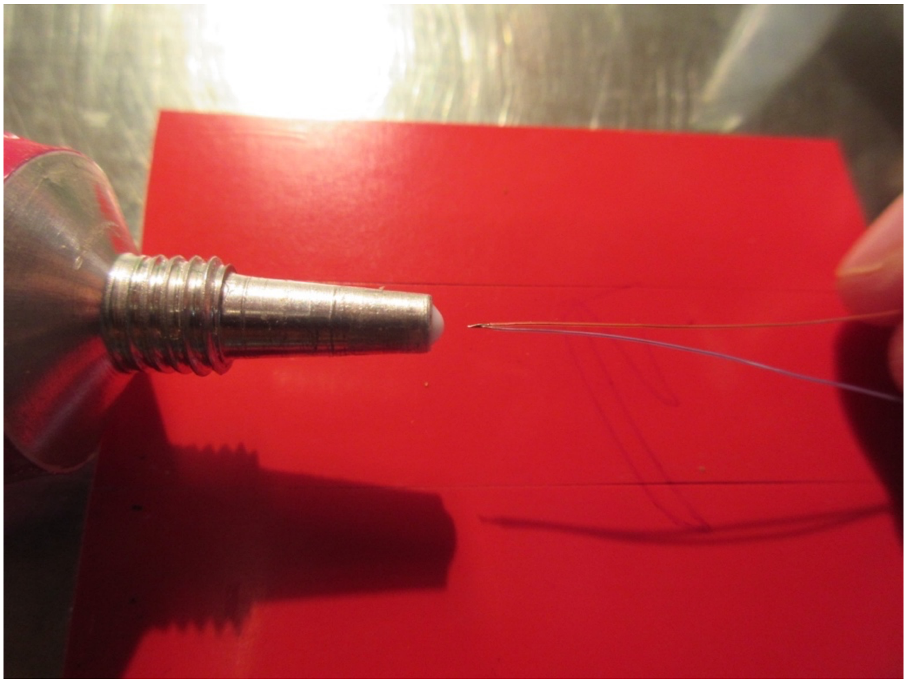

Figure 5 Inserting thermocouple in acrylic glue for electric isolation

Figure 6 Hypodermic needle with thermocouple during initial assemblage

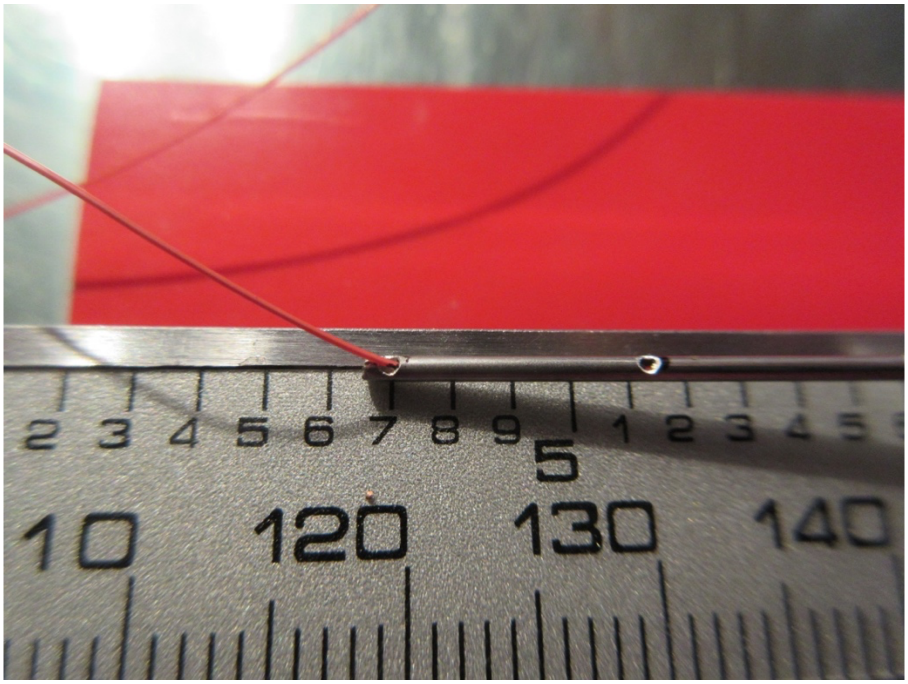

Figure 7 Hypodermic needle with constantan wire inserted from the perforation in the tip of the needle

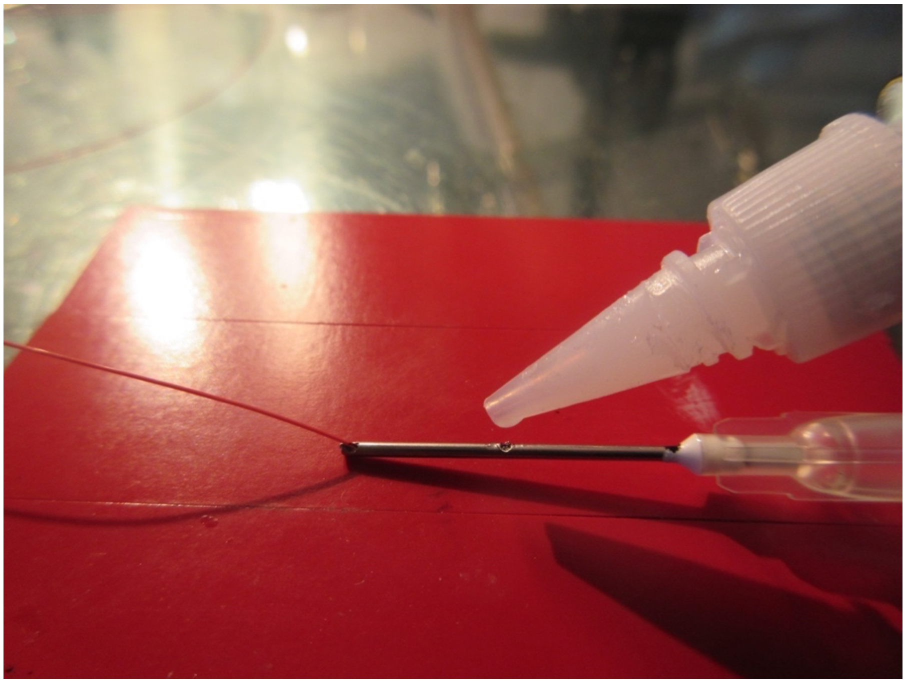

Figure 8 Cyanoacrylate glue applied to the needle to hold wires in place.

Results are better if you apply the glue from the tip of the needle

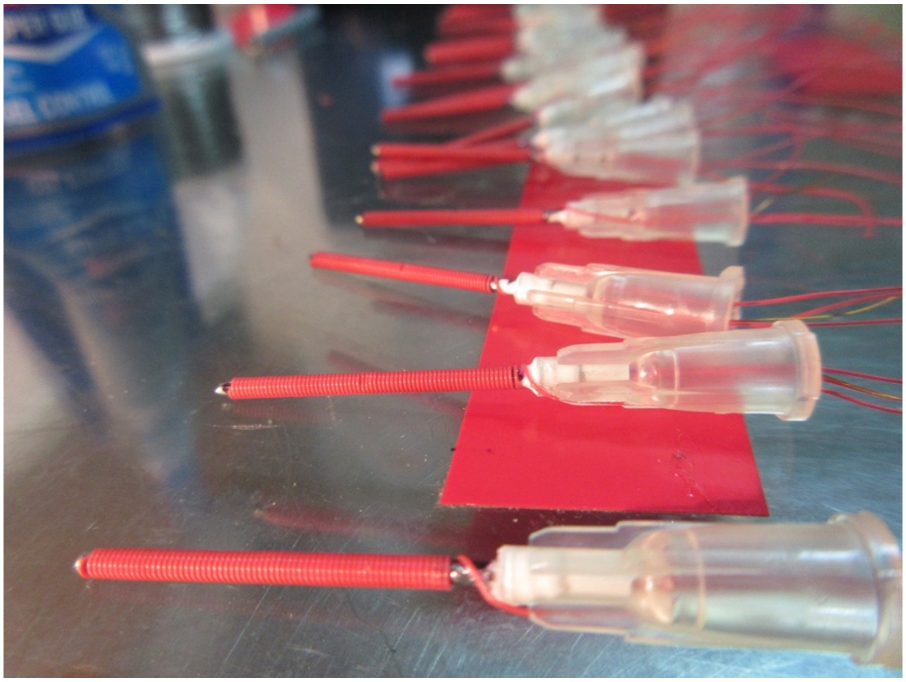

Figure 9 Heater-thermocouple set

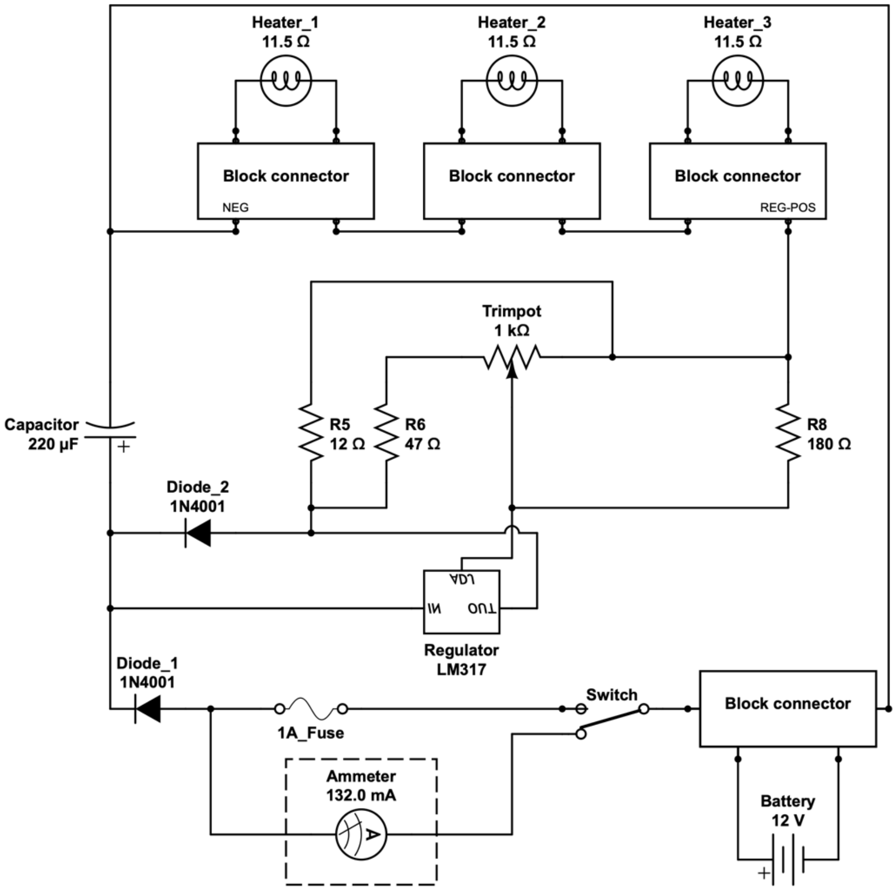

Figure 10 Diagram of current regulator.

This diagram describes the basic circuitry of a current regulator. The circuit is fed using a 12V 105Ah Lead-Acid battery, connected to the PCB via a block connector. A slide switch facilitates amperage measurement by redirecting the current flow to an open bridge (e.g., block connector) where the leads of the multimeter can be attached in series to measure without having to interrupt current flow

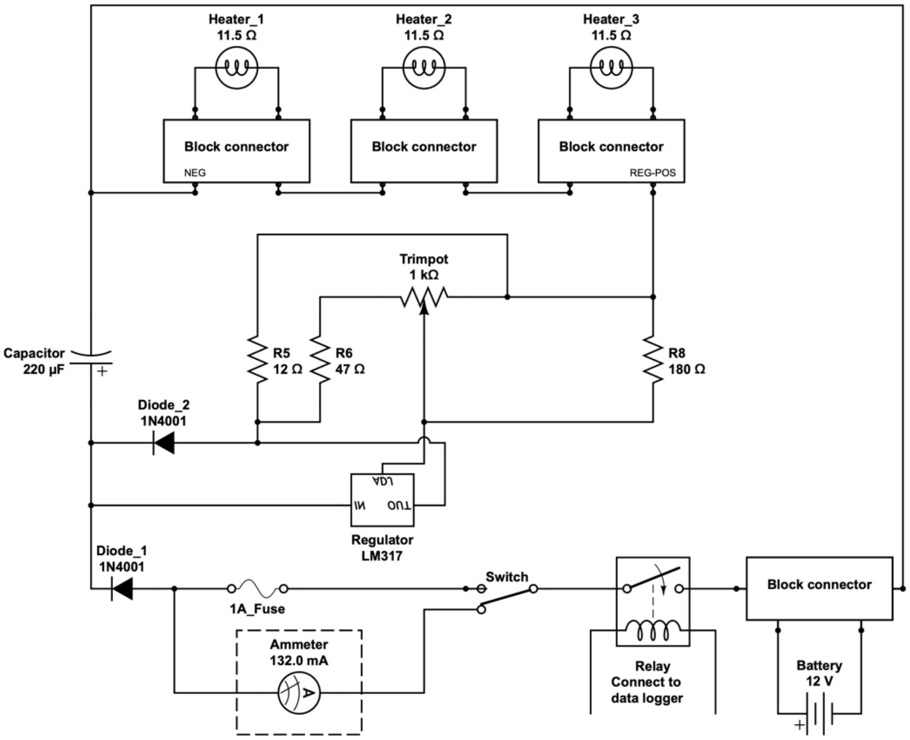

Figure 11 Current-regulator diagram with relay for intermittent use

This diagram, similar in function to the previous one, includes a relay to turn off the circuit when desired conditions are met (i.e., when battery drops below a threshold, at night to reduce power consumption, etc.). If your battery drops below the minimum required by the data logger, it will shut off and, if the internal data logger battery is low, you might lose your data. For this particular circuit, I suggest using solid-state relays, but any relay with at least 1A will work. You can also buy a pre-made relay circuit if you don't want to make your own.

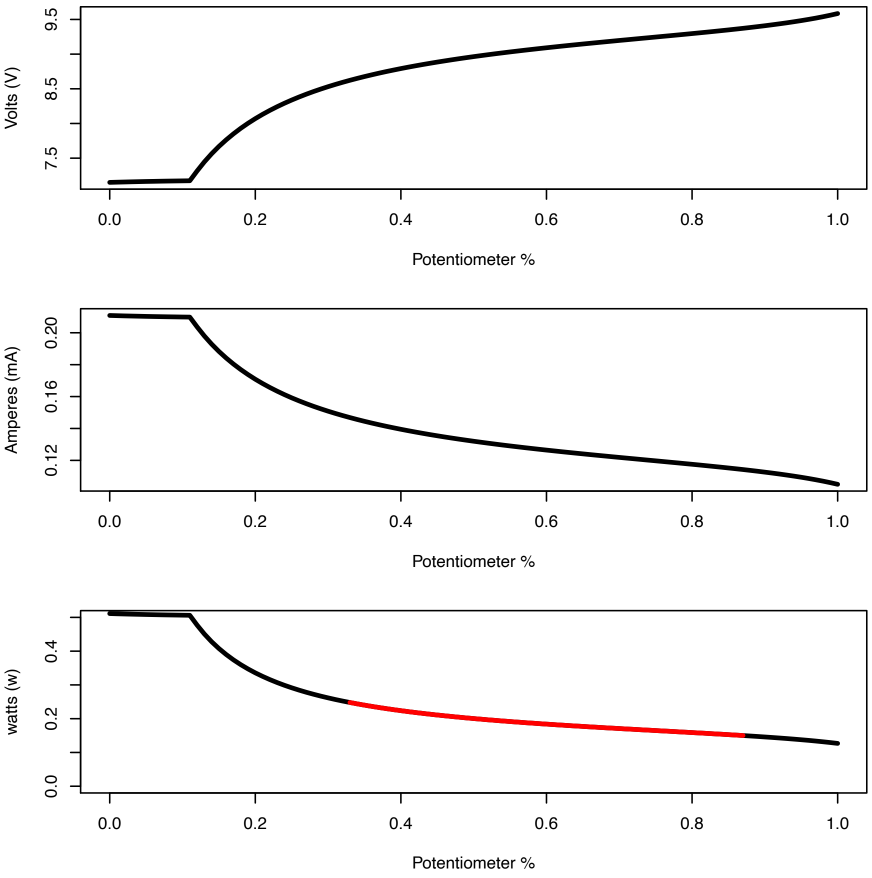

Figure 12 Simulation of voltage and current regulation

This diagram shows the expected current, voltage and expected wattage. For the simulation, I used a 1K Ohm trimming potentiometer (trimpot), and the simulation was run from 0 to 100% of the trimpot resistance. It is a way to simulate what would happen in the circuit, if you turn the trimpot. In the third panel, the red section of the line, is what I have tested as a good range for the wattage that HDM sensors can be run at (for more details, see: Gutiérrez Lopez et al. 2018). Important detail: This simulation should be used *only* for reference purposes. Remember that we are not including cable resistance, and the simulation was run with 11.5 Ω as heater resistance, not including the heater legs. Including the heater legs in the simulation, results in a range ~0.1-0.3 Amps

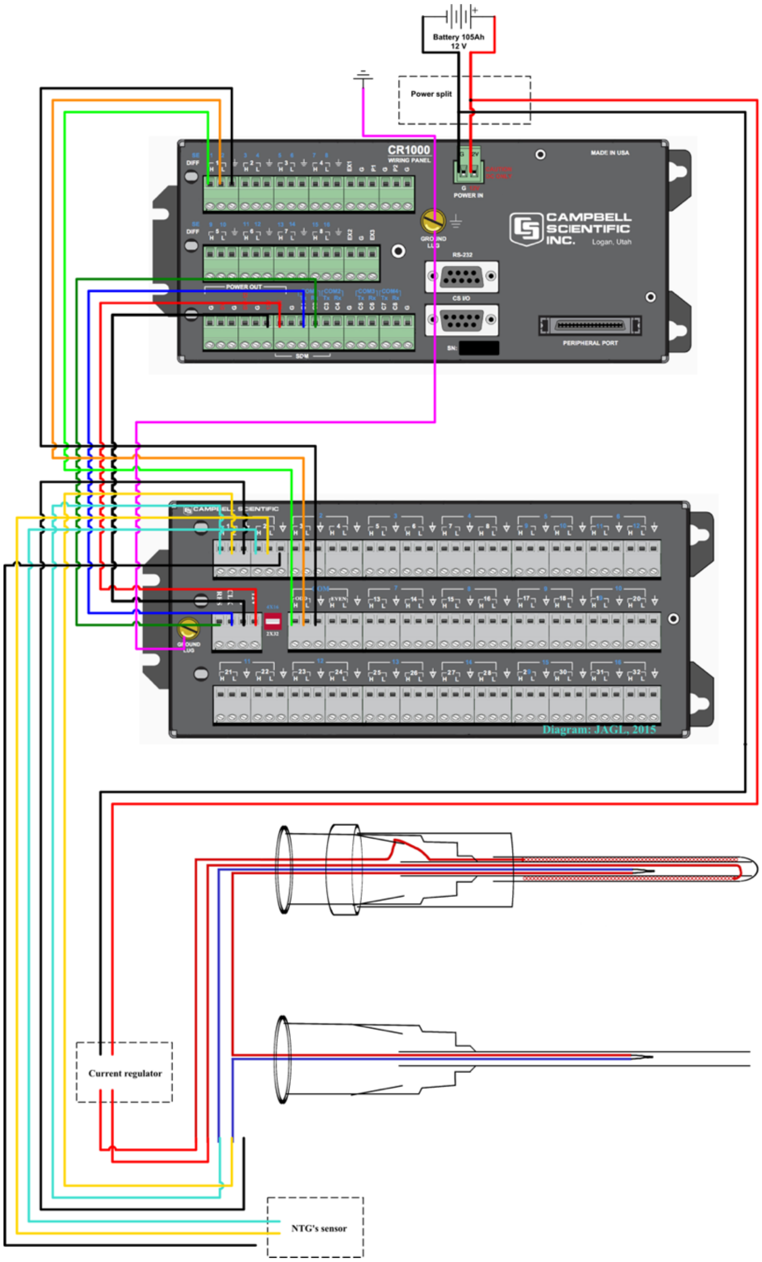

Figure 13 Basic diagram of sap flow station using the HDM and a reference sensor for NTG's

This diagram describes the basic wiring for one HDM sensor, and its reference for NTG's, using a CR1000 data logger and an AM1632 Multiplexor in 2X32 (differential) mode. This configuration allows connecting 16 sensors per multiplexor, and several multiplexors can be connected to the same data logger if needed.

TABLES

Table 1 Comparison of various heat pulse and heat dissipation methods

Method	Heat source	Sap speed method	Range	Zero flow	NTG	Wound correction	Cables
Heat dissipation	Continuous	Empirical	Slow, medium and fast	Determined empirically	Strong	Not developed	8
Heat field	Continuous	Empirical	Reverse, slow, medium and fast	Determined empirically	Strong	Not developed	8
Compensated heat pulse	Pulse	Temperature balance	Medium and fast	Determined empirically	Moderate	Developed	8
Tmax	Pulse	Tmax	Medium and fast	Determined visually	Minimal	Developed	5
Heat ratio	Pulse	Ratio-based	Reverse, slow and medium	Ratio of temperatures around heater source	Minimal	Developed	8
Sapflow+	Pulse	Derived from raw data	Reverse, slow and fast	Based on estimates	Minimal	Developed	8
DMA	Pulse	Ratio based, and Tmax	Reverse, slow, medium and fast	Ratio of temperatures around heater source	Minimal	Developed	8
DHR	Pulse	Ratio based	Reverse, slow, medium and fast	Ratio of temperatures around heater source	Minimal	Developed	8
MHR	Pulse	Derived from raw data, and ratio based	Reverse, slow, medium and fast	Ratio of temperatures around heater source and derived from estimates	Minimal	Developed	8

Table 2 List of materials for current regulator and potential vendors

Item	Vendor code	Webpage	Last time checked MM-YY
PCB and breadboards	Various	www.digikey.com, www.amazon.com	May-22
Constantan wire 0.005”, 0.12 mm	TFCC -005-100	www.omega.com	May-22
Magnet wire 36 AWG (0.127 mm)	RW36HTAIHUR	www.amazon.com, www.eis-inc.com	May-22
Hypodermic needles 19ga 2.5 cm	901-19-100	www.cmlsupply.com	May-22
Aluminum tubing	48KU89. 7237K23	www.grainger.com, www.mcmaster.com	May-22
Low voltage computer cable	75985K63	www.mcmaster.com	May-22
Loctite epoxy cartridge, mixer & gun	4UK09, 4UK16, 3NVL4	www.grainger.com	May-22
Heat sink compound	Various	www.amazon.com, www.grainger.com	May-22
Terminal block connectors	2094506	www.jameco.com	May-22
220μF capacitor	158263	www.jameco.com	May-22
Resistances	661327, 659833, 661183	www.jameco.com	May-22
1000 Ω trimming potentiometer	853556	www.jameco.com	May-22
250V 1A Fuse and fuse holder	197465, 2329743	www.jameco.com	May-22
1N4001 diode	35975	www.jameco.com	May-22
LM317 V/I regulator	898800	www.jameco.com	May-22
LM317 heat sink	294-1043-ND, 2155348	www.digikey.com, www.jameco.com	May-22

14 How to cite

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16 References

Burgess, S. S. O., M. Adams, N. C. Turner, C. R. Beverly, C. K. Ong, A. A. H. Khan, and T. M. Bleby. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants (vol 21, pg 589, 2001). Tree Physiology **21**:1157-1157.

Deng, Z., H. K. Vice, M. E. Gilbert, M. A. Adams, and T. N. Buckley. 2021. A double-ratio method to measure fast, slow and reverse sap flows. Tree Physiology **41**:2438-2453.

Forster, M. A. 2019. The Dual Method Approach (DMA) Resolves Measurement Range Limitations of Heat Pulse Velocity Sap Flow Sensors. Forests **10**:46.

Goulden, M. L., and C. B. Field. 1994. 3 Methods for Monitoring the Gas-Exchange of Individual Tree Canopies - Ventilated-Chamber, Sap-Flow and Penman-Monteith Measurements on Evergreen Oaks. Functional Ecology **8**:125-135.

Granier, A. 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Annals of Forest Science **42**:193-200.

Gutierrez Lopez, J., T. Pypker, J. Licata, S. S. O. Burgess, and H. Asbjornsen. 2021. Maximum heat ratio: bi-directional method for fast and slow sap flow measurements. Plant and Soil **469**:503-523.

Gutiérrez Lopez, J. A., J. Licata, T. Pypker, and H. Asbjomsen. 2018. Analysis of changes in the current supplied to heat dissipation sensors using an improved tree-cut experiment on young Eucalyptus grandis trees. Tree Physiology.

Vandegehuchte, M. W., and K. Steppe. 2012. Sapflow+: a four-needle heat-pulse sap flow sensor enabling nonempirical sap flux density and water content measurements. New Phytologist **196**:306-317.