SAP FLOW METER PT4.2

Instruction Manual

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CONTENT:

1. GENERAL FEATURES

Sap flow meter PT4.2 is twelve-channel battery operated system for the field measurement of sap flow in both large and small stems or branches. It covers the diameter range from 6 mm to 20 mm and than above 120 cm.

The system is designed as a closed unit containing all necessary parts for the measurement and logging the sap flow values in terms of [kg/hr].

The measurement is continuous, data are fully protected in case of power failure. Measuring points can work without reinstallation up to one year.

The installation of measuring point on large stems needs special tools that is a part of delivery. Both sensor types need a kind of protection against the rain and direct sunshine.

2. MEASURING PRINCIPLE

The heat balance of xylem through which the sap flow passes can be described by the general equation:

$$P = Q*dT*c_w + dT*z \qquad (1)$$

where P is the heat input power [W], Q is the sap flow rate [kg/sec], dT is the temperature difference in the measuring point, c_w is the specific heat of water [J/kg, deg] and "z" is the coefficient of heat losses from the measuring point [W/deg]. The amount of water in terms of mass or volume passing through the measuring point in the stem is calculated from the actual power and temperature rise of water passing through the heated space.

2.1. Large stems

The measuring principle is based on the tissue heat balance method (THB) with internal heating and sensing. Three stainless plate electrodes are used as terminals leading the A.C. electric current to xylem tissues between them. The insulated part of electrodes avoids the passing of electric current through high-conductive phloem. Consequently, the xylem volume between electrodes is heated. A part of the heating energy is lost by heat conductivity, part is carried away by passing water. The temperature of heated space along metal electrodes is quite uniform due to their high heat conductivity what makes the measurement nearly independent on the radial sap flow velocity profile. However, an approximate knowledge of that profile is always appreciated - there are three electrode lengths available (60, 70 an 80 mm) covering 25, 35 and 45 mm of sapwood depth. Supposing the sap flow density decreasing with depth, those electrodes should cover the main part of water conductive profile of most type of tree species.

The reference temperature related to non-heated part of stem is measured also along the same type of electrode as described above but inserted 100 mm bellow them. This arrangement is chosen due to symmetry of the temperature sensing.

Such an arrangement is significantly less sensitive to radial temperature gradients caused by daily changes of ambient temperature.

The measuring method uses the modification with constant power. The measuring point is heated by the A.C. electrical current passing the wet xylem tissues between three stainless plate electrodes inserted into the wood. The electronic feedback units control the heating power in measuring points at certain level (0.63 W) and the temperature difference of the heated volume is recorded for the sap flow rate calculation.

The calculation of sap-flow values derives from the equation [1], from which:

$$Q = \frac{P}{c_W * d * dT} - \frac{z}{c_W} \qquad \text{[kg/s, cm]} \qquad (2)$$

Since the measuring point catches just a part of stem cross section area, the output value have to be written in terms of unit sap flow per. Since this measuring method in nearly independent on the radial sap velocity profile, the output value is calculated per cm of circumference using the affective width of heating space ("d"), derived from the horizontal heat field pattern.

The second term of this formula represents the heat losses from the sensor. Its magnitude can be easily estimated from the data recorded under condition of actual flow approximating zero, i.e., during the zero evaporating demands as during the rain or at night before sunrise. The supporting software Mini32 has an option for easy graphic baseline subtracting.

2.2. Small size sensors ("babies")

The measuring method uses the modification with constant dT and variable power. The electronic feedback units control the heating power in gauges in order to maintenance the temperature difference in certain level.

The sap flow gauges can be easy and fast installed. At least 20 cm long part of stem or branch is needed for sensor placement, including the protection against the rain and irradiation.

Gauges are soft and flexible, thus allowing the stem or shoot to grow freely about five to ten millimeters in diameter during the sap flow measurement without reinstallation.

The calculation of sap-flow values derives from the equation [1], from which:

$$Q = \frac{P}{c_W \cdot dT} - \frac{z}{c_W} \qquad \text{[kg/s]} \qquad (3)$$

The second term of this formula represents the heat losses from the sensor. Its magnitude can be easily estimated from the data recorded under condition of actual flow approximating zero, i.e., during the zero evaporating demands as during the rain or at night before sunrise.

The measurement is continual and gives absolute values in terms of mass flow that need not to be calibrated.

3. SYSTEM DESCRIPTION

The measuring system includes the watertight box containing the electronics, sap flow gauges and connecting cables.

The electronics includes heating units and datalogger, which are working mostly independently. Nevertheless, the datalogger reads automatically the position of switches of individual channels and changes their ON/OFF setting accordingly.

The electronic circuits are designed for maximal power efficiency in order to save the energy and consequently current consumption from the batteries. The power consumption depends nearly linearly on the number of switched channels.

The sensor protection against the ambient factors in made with a special insulating weather shields. It reflects the sunshine and reduces the affecting of the heat field by ambient temperature. It also protects gauges against the rain and wind although a little wetness inside do not influence the measurement.

4. SPECIFICATION

Large stem sensors:	
No. of measuring channels	Six channels
Size of sample trees	Diameter >12 cm at the measuring point
Heating technique	Direct heating of plant tissues released by the electric current passing the xylem between the electrodes
Number of electrodes	4 pieces per measuring point
Output variable	The change in temperature of the measuring point
Sensors	Four needle thermocouples Cu-Co
Heating power	0.63 Watt
Heating current	Alternating, 1 kHz, up to 200 Volts, passing xylem
Range of xylem resistance	1000 to 25 000 Ohms
Max. increase in temperature	ca 5 deg.C
"Baby" sensors:	
Number of channels	Six channels
Range of sensor diameters	Two sizes: 8-12 mm and 12-18 mm (±2 mm allowed)
Heating technique	External soft and flexible heater
Output variable	Variable heating power
Temperature sensors	Special thermocouple
Temperature difference	4 Deg.C, controlled
Resistance of heaters	100 Ohm
Heating current	Maximum 0.125 Amp per channel
Heating power	Max. 1.6 W variable according to sap flow magnitude
Built-in datalogger:	
Accuracy	0.3% of the full scale

Internal memory	512 kByte
Memory capacity	220,000 values
Measuring interval	10 sec to 2 minutes
Storage (integrated interval)	10 sec to 1 hrs
Overall:	
Energy supply	12 V D.C. lead acid battery or DC power adapter
Consumption of current	Typically 0.5 – 2 A (sap flow rate dependent)
Working temperature	-10 up to 50 deg. C
Weight	10 kg (box only, entire delivery about 35 kg)
Device box size	43 x 33 x 20 cm

5. OPERATION

The device can work when hanged or laying everywhere. The sturdy design of P4.2 fits to harsh field conditions. Sap flow gauges are connected with the box using 50 m cables 7-pin Amphenol C16-1 and four-pin AMP Superseal connectors (large stems) or 30m cables with 7-pin Amphenol C16-1 connectors on both ends. Power supply (battery) is connected with Amphenol C16-1 4-pin connector.

Computer for datalogger setting and data downloading is connected to common 9-pin D-sub connector placed on the front panel behind the door. The device box and all connectors are waterproof (protection class IP 65).

5.1. Sensor installation

5.1.1. Large stems

Correct installation of measuring points on trees is an ultimate pre-requisite of getting correct results. Interactions between sensors and living tissues belong generally to important points of this type of measurement.

5.1.1.1. Sensor location on tree trunks

Fundamental criteria for location of measuring points at tree trunks are the homogeneity of tissues and the height above ground. The highest temperature gradient, which may interfere with the measurement, appears close to ground surface. Therefore, the measuring points should be placed at least at the height over 1 m above ground; then anywhere at the trunk but below the green crown (first living whorl). Trunk tissues should be homogenous enough, i.e., with no irregularities such as knots, mechanical or biotic injuries, etc., anything which could influence the ordinary xylem water flow pathways around trunks. All possible circumstances should be considered here. It is also necessary to calculate with enough space around the measuring point where the weather shield should be fastened.

To minimize the influence of natural variability of sap flow around trunks when requiring data valid for whole trees, it is recommendable to install two measuring points on opposite sides of tree trunks. This is important especially in stands with variable soil conditions, in trees growing on slopes, etc. Mean value of both sides is then valid for the tree. It is also possible to work with one measuring point all the time only, checking periodically the flow with the other one, too (e.g., five trees with continual record of one measuring point and periodical record of second measuring point cycling say after every two weeks).

5.1.1.2. Sensor set up

In order to measure properly the position of sensors at tree trunks it is necessary to have a certain standard level or surface. Naturally smooth bark surface is suitable for this purpose in some species, but usually it is necessary to smooth the bark artificially, so that it will be of the same thickness above the cambium layer (say 4-15 mm). This may be done with a sharp barking iron, but attention must be paid to prevent any damage to living tissues below the cork layer of bark.

When two measuring points on the opposite sides of tree trunk are proposed, their vertical level should be either nearly the same (large stems) or different for more that 20 cm. It avoids the warming of reference electrode from the opposite measuring point and also allows setting up the weather shield.

The sensor installation requires a special tool in order to insert the electrodes to exact position. The installation process needs following steps:

- bark and phloem thiskness measurement
- inserting of electrodes
- placing of thermosensors to slots in electrods
- connecting terminals to electrodes
- cable connection
- fixing of weather shield

Please refer to Appendix P for details.

The proper length of electrodes should in principle cover the most of water conductive profile. The available electrode types (60, 70 an 80 mm) cover 25, 35 and 45 mm of sapwood depth. Therefore, a general knowledge of the sapwood size and properties is necessary. On the other hand, the principle of the method is not too sensitive to the sapwood thickness and a bit longer electrodes are generally better that too short ones.

As for the weather shield, it does not protect the measuring point against stem flow completely since the wet bark surface below the shield does not influence the measuring process.

5.1.2. Small sensors ("babies")

Correct installation of measuring points on trees is an ultimate pre-requisite of getting correct results. Interactions between sensors and living tissues belong generally to important points of this type of measurement.

5.1.2.1. Sensor location on trees

Fundamental criteria for location of measuring points at tree stems or shoots are the stem/branch shape and the height above ground. The highest temperature gradient, which may interfere with the measurement, occurs close to the ground surface. That's why measuring points should be placed as high as possible above ground, but anyway below the first living whorl or foliated part of the shoot (if results should represent the whole tree or shoot). Rather straight parts of stems/shoots about 20 cm long should be selected to install the gauges. Stem or branch should be roughly cylindrical, with no irregularities such as larger knots, mechanical or biotic injuries, etc., simply anything that could influence the exact contact between the surface and the heater. It is also necessary to consider enough space above and bellow the gauge where the Mylar shield should be fastened. **See Appendix T**.

5.1.2.2. Sensor set up

Installation of the gauges is very simple but it must be done gently and very carefully. One should realize that the sensor should not affect the plant but on the other hand it should survive even a storm.

- Remove the rest of bark, needles, small knots and similar stuff which would avoid the perfect heat contact between the heater and the bark surface.
- Open both tin housings of the gauge and remove the thermocouple assembly from them.
- Fasten the plastic clip of the thermocouples at the suitable place of the stem (shoot). Fasten the cable below the measuring point with the plastic tape. Attach thermocouples at the stem surface and press the sharp tips inside the stem with your fingers **until the strait part of the needle touches the bark**. Pay attention not to damage the sensor by violent rotating of the needle in the cube when pressing the tip crooked way. Use a knife tip (carefully - watch your fingers!) to prepare a slot for the needle spike in hardwood.
- Apply the upper housing of the heater to the stem with already installed thermocouples and close it. **No direct contact of** (yellow) **heating elements with thermocouples should be assured.** The correct position of the heater along the stem is indicated by the foam insulation touching the upper edge of the cube. Then put the lower foam insulation on the stem below the cube with its upper edge just touching the lower end of the cube (see picture in appendix).
- After carefully checking the correct position of the gauge, install the weather shield. Cut its both tails according to stem diameter (the original size fits to lowest – 6 mm one) and place the shield over he sensor. Note that the lateral folds should overlap each other.
- Fix both ends with a plastic tape (at least the upper one in watertight manner). The fold of the shield must be pointed down to allow condensed water to run off.
- Connect the sensor with extension cable to the equipment.

5.2. Datalogger setting

Please read the **Mini32 software manual** first for the proper datalogger handling. Anyway, even the first setting of non-customized datalogger is quite easy –

just fill in the channel description with respect to measured trees and *by large stem channels* set the channel parameters to circumference (A) and bark+phloem thickness (B) values. If not doing that, the output sap flow values will be calculated in unit sap flow per 1 cm of stem circumference (kg/hr, cm). Refer also to chapter 5.6.1. It is good idea to initialize the datalogger (if the internal clock time should be changed) or just erase the datalogger memory in order to erase old data which do not regard to current job.

Since there is direct link between switching the hardware channels and appropriate channels of datalogger, don't worry about the channel ON/OFF setting. The datalogger channel status automatically follows the hardware setting.

5.3. Power supplying

5.3.1. Power supply voltage requirements

As the system supposes supplying from 12 Volt lead acid battery, the supply voltage higher that 12.1 Volts is necessary to start operation. Such a voltage indicates discharged battery and its next withdrawing would shorten its lifetime. When already running, the system is automatically switched off when the battery voltage drops bellow 11 Volts for the same reason. In the same time the datalogger stops logging data.

When the system is supplied with a power adapter, the minimal output voltage of 12.5 Volts is recommended.

5.3.2. Auxiliary batteries

6 x AAA alkaline batteries placed just bellow the front panel keep the datalogger running when the system is out of main power. When they are missing, the datalogger keeps data and work properly anyway; just an **abrupt** external power brake **during the measuring process** will stop logging data until midnight. In praxis, the auxiliary batteries help to overcome the main battery replacement when the system is out of power. In case of solar panel recharging system, these batteries make the system ready to log data immediately after the power resume without possible waiting on midnight reset.

5.4. Switching on

The main switch is located on the bottom of front panel inside the device box. After switching on, the flashing green light indicates the powering.

Than, the channels can be switched on with appropriated switches.

5.4.1. Large stems

Since this moment the switched units start to heat the xylem between the electrodes. The time of reaching the steady state depends basically on the sap flow magnitude. It can take minutes under the high sap flow and about one hour when there is no water movement.

Note: Do not switch off the main switch during the measuring period. It switches off the auxiliary batteries, too, and when switched off during the data logging *process, the datalogger will continue logging data as late as at midnight (unless the communication with PC will reset it earlier).*

Operation indicators

Main unit in a six channel section – green light

It indicates the power supplying of all six units. It must light up after MAINS is on. Otherwise the fuse (common for both section) is broken or the supply voltage is lower that 12.1 Volts while switching on or 11.0 Volts during operation.

Power unit operation indicators – red light

It is normally off. It lights when:

- the cable to measuring point is broken, connectors are disconnected or the terminals are not connected to electrodes. Warning - the heating voltage in such a case reaches 200 Volts. Do not touch the electrode terminals while the power unit is on!

- the unit is broken

- the xylem resistance in measuring point is above the upper limit (30 kOhms). It can happen by dead trees only.

5.4.2. Small sensors ("babies")

Since this moment the switched units start to heat until the temperature difference in each sensor reaches four degrees centigrade. The time of stabilizing depends basically on the sap flow magnitude and it could take a minute. During this time, the red LED indicating the channel status can be on indicating "full power" heating. Note that if the datalogger main operation switch is ON (by software), the channels start log data immediately when at least one channel is ON, too.

Operation indicators

Main unit in a six channel section – green light

It indicates the power supplying of all six units. It must light up after MAINS is on. Otherwise the fuse (common for both section) is broken or the supply voltage is lower that 12.1 Volts while switching on or 11.0 Volts during operation.

Power units – red light

It is normally off. It lights when:

- the steady state has been not reached yet - the unit runs in full power. Few seconds or a minute only.

- the unit has been switched off by datalogger that has found it running in full power longer than ten minutes. Perhaps due to broken cable, wrongly installed sensor or due to another failure. It will be switched on again within 50 minutes. If the problem continues, the cycle is repeated.

- the sap flow in unexpectedly high – more that 0.3 kg/hr. The available heating power is not able to maintain the demanded temperature difference. When lasting longer than ten minutes, the sensor heating will be switched off similarly as described above

- the unit is broken

5.5. Main operation indicators

5.5.1. Indicators visible from outside (closed doors).

- Flashing red LED – it collects information of all (covered by doors) units. A heating unit does not heat properly. Check measured values with computer and switch off the bad unit. Than check the cable, connectors and electrode terminals. Exchange the appropriate power unit board below the front panel.
- Green LED – system runs O.K.
- Yellow LED – indicates broken fuse
- Red LED – indicates wrong polarity of main power supply (battery)

5.5.2. Display

The information on the display depends on how the datalogger was switched off last time. Basically it should show time (usually), "OFF" (when the datalogger status is off) or simply nothing (when it was switched off during the running measurement - in such a case the time appears as late as at midnight). However, the display information is always refreshed by first communication between the datalogger and computer.

- Time **HH:MM** – normal operation (shows the time of last measurement)
- **batt** – low main power supply voltage
- **- - - -** (four dashes) – datalogger in operation (measuring, communicating with computer)
- **OFF** – datalogger operation is stopped by software setting
- **nothing** - main (HW) switch is off or there is no power available (both main power and aux. batteries are (or has been) down. In some cases after the switching the system on the display information appears as late as after next regular measurement or after communication with PC.

5.5.3. Auxiliary batteries status (green LED)

The LED must light up when pushing the check button. Replace batteries when it does not.

5.6. Data handling

All the datalogger manipulations and data handling need connected PC compatible computer running Windows© 95 or later operating system or Windows© NT, 2000, XP.

The program for datalogger controlling, Mini32, is placed on CD or two disks 3.5 inch which is a part of the delivery.

The individual options of the program assure the datalogger setting, data downloading, file processing and firmware uploading.

The options in main menu give three basic types of operations:

- the datalogger setting
- on-line data handling
- operating with data files, export to another software.

Please refer to Mini32 software manual for more information.

5.6.1. Sap flow values calculation

The sap flow values in terms of [kg/hr] are calculated from the measured electrical values according to the channel setting automatically during the conversion from downloaded *.hex file to *.dcv file format suitable for next operation.

5.6.1.1. Large stems

By default channel setting, the sap flow rate per unit of stem circumference is calculated. The parameter A is set to one, the B to zero. When the A parameter is set to stem diameter (with bark) [cm] and B to bark+phloem thickness [cm], the sap flow value extrapolated to the whole stem is calculated according to formula:

$$Q_{tree} = Q*(A - 6.28*B) \qquad [3]$$

However, in order to get the "clear" sap flow data, it is necessary to (manually) subtract the baseline representing the "fictitious flow" due to heat loses from the heated space. See 5.6.2.

5.6.1.2. Small sensors

The sap flow values in terms of [kg/hr] ara calculated automatically during conversion to *.dcv. No special activity is necessary here except of baseline subtracting.

5.6.2. Baseline subtraction

The Mini32 software is ready for graphic subtracting of the “baseline” that represents the heat loses from the measuring point (see Eq. 2). This option appears only when the system recognizes a data file coming from a sap flow system.

The time course of sap-flow values from a chosen channel is displayed on the screen. The cursor will appear together with it, which allows you to create a line connecting the points on the curve that shows the situation at 3 a.m. - zero line. In this way it is possible to prepare channels assigned for sap flow measurement and then do subtraction in all channels at the same time. The filename with character "&" at the end is offered and this is the file with the correct sap flow values expressed in [kg/hour].

When creating the zero-line, it is necessary to consider the possibility of the night flow during warm summer nights, sudden changes of heat losses and of fictive flow consequently during the changes sapwood water volume, etc. The specialist's experience on the field of plant water relations is very valuable here, though a possible mistake from the point of flow quantity is not crucial.

5.7. Switching off

Before the finishing of the measurement it is always recommendable to download the data and check them carefully. Do not forget to complete the biometric information, which might be necessary for the data interpretation. Check again the tree – sensor association to avoid future doubts. Than

- Switch of the hardware channels (recommended but not necessary)
- Switch off the main switch. Disconnect extension cables and remove sensors.

5.8. Sensor dismounting

5.8.1. Large stems

Sequence of dismounting operations:

- Remove the weather shields
- Disconnect the cable connectors
- Remove the terminals from electrodes
- Remove the thermosensors - use pliers in case when they stuck inside the slots. Do not brake any wires!
- Remove the electrodes with the special tool.
- Fill the gaps after electrodes with a natural wax.

5.8.2. Small size sensors ("babies")

Sequence of dismounting operations:

- Remove the weather shields carefully – they can be use again for similar or large diameters
- Open both tin housings of the heater and remove them from the stem
- Carefully remove tops of both needles from the plant tissue (by knife-tip inserted between the plant and needle) and dismount the sensor completely
- Dry out gauges if necessary and store them into original housing

5.9. Maintenance

Principally, the sap flow rate measuring equipment does not need any special maintenance **except of replacement of aux. batteries.** It should be done each year for sure although under normal condition (no long time switched on without main power) they should last years. Check the battery status by pressing the check button. Replace batteries when the green LED does not light up.

6. WARRANTY

The producer warrants right function of the sap flow rate measuring device for three years after it is accepted by a customer. All the faults will be removed free of charge during this time, at the measuring device itself as well as at sensors. The producer is not responsible for the faults originated by careless manipulation, incorrect operations, wrong applications or theft.

Appendix P:

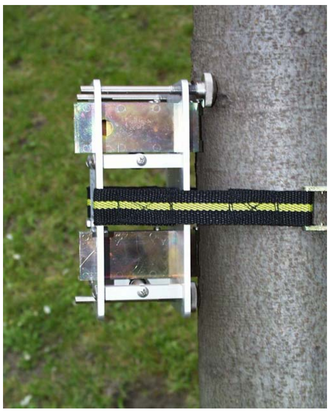
Pictorial installation guide.

The following pictures should help you to understand the process of proper installation of measuring point. Please refer to P4.2 or PT4.2 manual for more details.

The installation tool is placed in a compact box. Everything necessary for proper work is located here.

This assembly keeps the guides for proper (= parallel) inserting of electrodes.

It must be well fastened with the strap and leveled with rectification bolts.

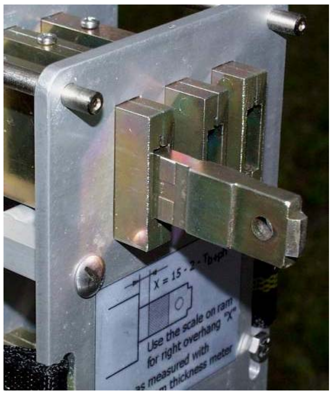


The guide frame should be parallel with the bark surface. Than, push the guides in touch with bark by finger.

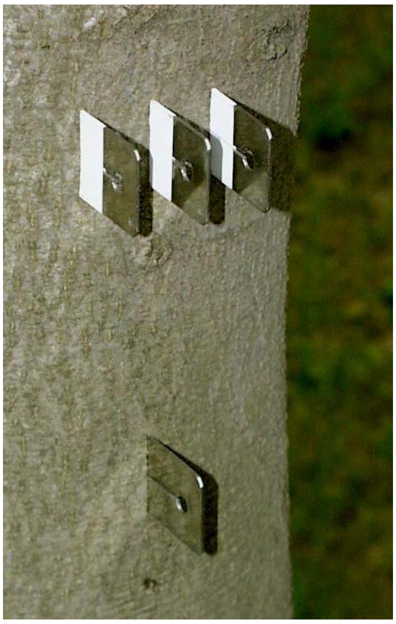
Now, the tool is ready for hammering of electrodes.

First of all, the bark+phloem thickness has to be measured. Use the longer stick with a plate on its end. Hammer it gently inside until you feel that the wood has been reached. Also the sound will change at that moment. Read the value on the scale and calculate the "overhang". See label on the tool upper plate.

Hammering of electrodes needs some basic skills is order to avoid shifting of the tool assembly. Otherwise the electrodes will not be as parallel as they should be.



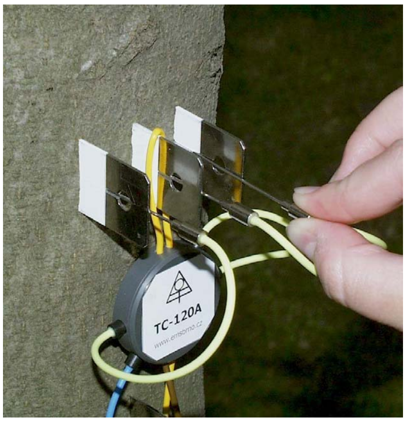
The electrodes should not be inserted completely, a part of ram should remains outside according to overhang value calculated from the formula written on the frame label. Use a rough scale on ram - the accuracy is not the most important topic here.

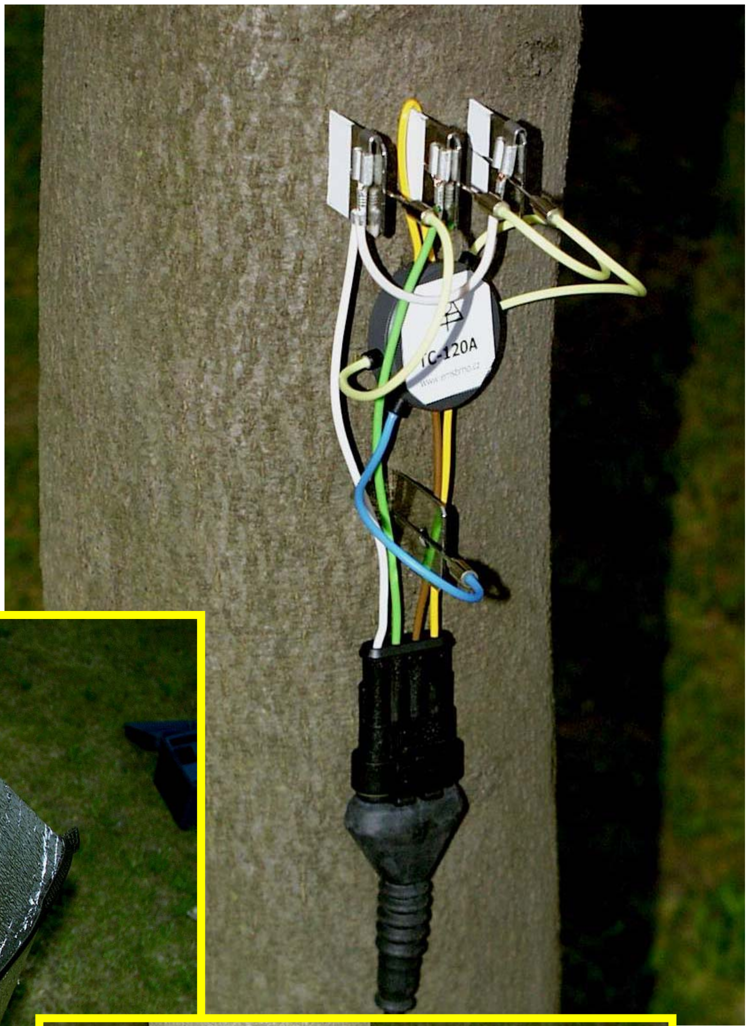


The measuring point after removing of tool looks like this. The visible length of white insulated part depends on the measured value of bark+phloem thickness.

Note that the lower (single) electrode is that non-insulated.

The thermosensors assembly with the electrode terminals should be firstly hanged on the central electrode. Than insert the needles to the slots in electrodes and finally set up the terminals. Connect the cable carefully.





Finally, the weather shield should be fastened.

APPENDIX A:

Useful images concerning the proper installation.

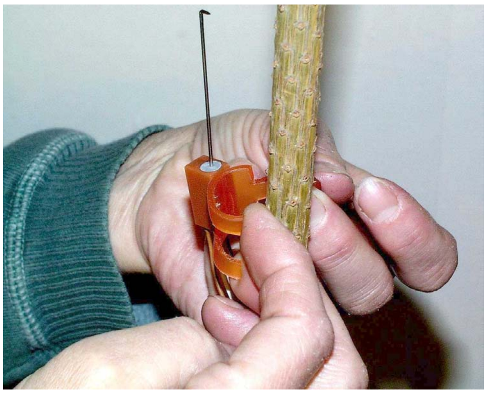
Choose the right place on the branch or stem, remove dry rests of bark from the surface (just by hand), tape the cable and place the temperature sensor assembly.

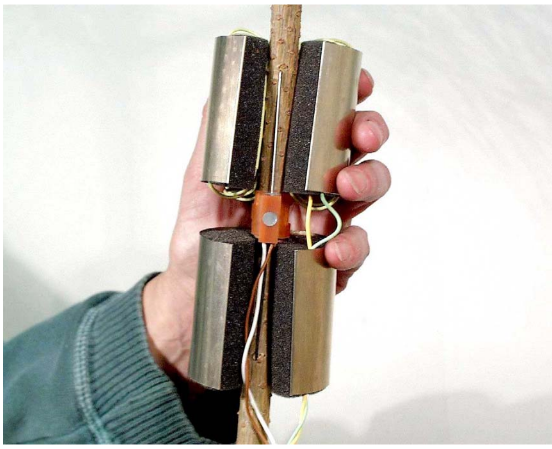
Front view:

Needles as straight as possible.

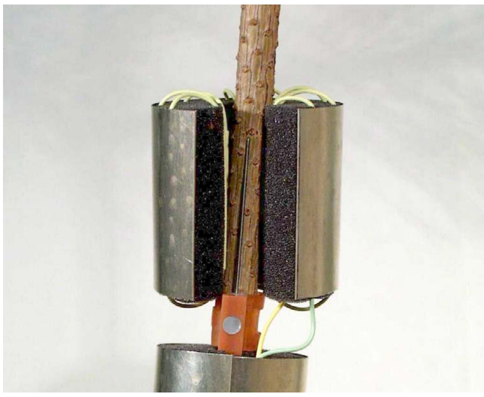
Important! Needle tips should be completely pushed in the stem. The end of straight part should be in full contact with the bark.

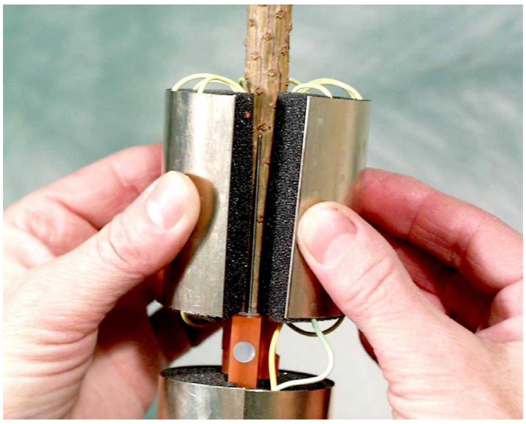
Flexible clip holds the temperature sensor in exact position and prevents strangulation.





Put the heater and compensating part over the thermosensor assembly. Watch the needle to avoid the direct contact with heating elements (yellow pipe)





and

close carefully.

As the result, the heater should look like this:

Mylar weather shield is designed to protect the sap flow gauge against the sunshine and the rain as well. Careful placement is necessary in order to prevent getting wet. Be sure the overlap is always pointing downwards. Tape the upper end against the stem flow and lower for fixing. Cut both ends to fit to thicker stems.