Sap Flow Sensor

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Heat Pulse

Sensor types: N3D1, N3D2, N3D3

User Manual

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1. Introduction

Thank you for purchasing an Ecomatik Heat pulse sap flow (SF-HP) sensor. This is a precise sensor for continuous measurements of water flux, i.e. xylem sap flow velocity, in a plant stem or branch, under both indoor and outdoor conditions.

This manual is written to help you install and operate your SF-HP with least difficulty and for most desirable results. Please read it carefully before installing the sensor, and refer to it if you should have any difficulty with the sensor in the future.

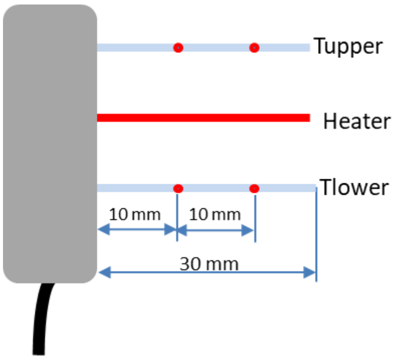
Th SF-HP is the sensor part of a measuring system. This means that the senor should be powered and connected to a data logger for continuous data recording. SF-HP is compatible with ECOMATIK Multi-Interface and data loggers from Campbell.

2. Safety Information

1. Never power the heater of the sensor with the sensor needles in air, i.e. not embedded in a tree or some other heat dissipating substance! Otherwise, the powered sensor will overheat and get damaged irreparably.
2. Always lubricate the sensor needles well before pushing them into the pre-drilled installation holes.
3. Use great care when removing the sensor. Removing the sensor with excessive force will destroy it.
4. Please open/close the plug correctly.

Damage to sensors caused by disregarding the above instructions cannot be repaired and is not covered by warranty.

3. Brief introduction to the Heat-Pulse sap flow methodology



Heat Pulse Sensor
(here N3D2 with two measurement depths)

Measuring the propagation of an applied pulse of heat in a water conducting matrix, i.e. plant xylem, is one of several techniques for continuously determining plant sap flow.

In our three-needle heat pulse sap flow probes, the heat pulse is applied between 2 vertically arranged measuring points for a short time. The characteristics of the heat-pulse propagation are assessed via temperature sensors at measuring points above and below the heater needle. Based on this data, different methods can be used to determine sap flow speed.

Various approaches are still being under scientific discussion and fine-tuning today.

Two of the most commonly used calculation approaches are the Heat ratio method (HRM) and Tmax.

HRM

The HRM is based on the work of Marshall (1958) where the sap flow velocity is determined via formula (F. 1). The formula includes a specific material constant the thermal diffusivity of sap wood (k). HRM is most precise for slow sap flow velocities. The exact velocity limits of this method depend on measurement resolution of the logging device, as well as on k. Assuming an intermediate k of 0.0025 cm2/s the HRM approach is suitable for sap flow velocities between -45 to +45 cm/h (Lopez et. al. 2021).

Tmax

Better for faster flow velocities of up to 1000 cm/h is the Tmax method, as described first by Kluitenberg et. al. 2004. Sap flow velocity is here determined via formula (F.2). The Tmax approach, however, is not precise for slow sap flow velocities.

Hence, in some approaches a combination of HRM and Tmax is employed to overcome either limitation of each respective method. In practice, however, it is not easy to establish a clear threshold of sap flow velocity at which either one or the other method should be used.

MHR

With their Maximum Heat Ratio method (MHR), Lopez et. al. (2021) present a new approach that, based on the above introduced HRM, also enables the determination of higher sap flow velocities of up to 130 cm/h. Employing MHR avoids the methodological inconsistency of switching between calculation methods.

If required, we supply all users who, in addition to sensors, also obtain data acquisition systems (data loggers and/or multi-interfaces) from Ecomatik, with measurement programs that calculate the results of all three approaches HRM, MHR and Tmax.

If not otherwise specified, we employ a default value of 0.0025 cm2/s for the thermal diffusivity k.

(F 1) $$V_{HRM} = \frac{k}{x} \ln \left(\frac{\Delta T_{60-ini\_upper}}{\Delta T_{60-ini\_lower}} \right)$$

(F 2) $$V_{MHR} = \frac{k}{x} \ln \left(\frac{\Delta T_{\max-ini\_upper}}{\Delta T_{\max-ini\_lower}} \right)$$

k = thermal diffusivity of fresh sap wood (cm2/s)

x = distance between heater needle and upper/lower measurement needles (in standard design equidistant, 6 mm)

$\Delta T_{60\text{-}80\ \mathrm{upper}}$/ $\Delta T_{60\text{-}80\ \mathrm{lower}}$ = temperature difference between initial temperature before heat pulse application at time = 0 sec and temperature a certain wait time after initiation of the heat pulse (usually measured between 60 to 80 sec after start of heat pulse).

$\Delta T_{\max\ \mathrm{upper}}$/ $\Delta T_{\max\ \mathrm{lower}}$ = temperature difference between initial temperature before heat pulse application at time = 0 sec and maximum temperature measured within a certain period after initiation of the heat pulse (usually within 50 to 60 sec).

IMPORTANT NOTE: In literature, sometimes a confounding nomenclature is used with Tu for “upstream”, i.e. assuming a upwards directed sap flow direction the lower sensor needle, and Td for “downstream” for the upper sensor needle.
For the sake of clarity we use here $\Delta T_{\mathrm{upper}}$ (upper sensor needle, far from cable) and $\Delta T_{\mathrm{lower}}$ (lower sensor needle, near sensor cable), also see F 5 and F 6.

(F 3) $$V_{Tmax} = \sqrt{\frac{4k}{t0} ln\left(1 - \frac{t0}{tm}\right) + \frac{x^2}{tm(tm-t0)}}$$

k = thermal diffusivity of sap wood (cm2/s)

x = distance between heated and no heated needles (=6 mm)

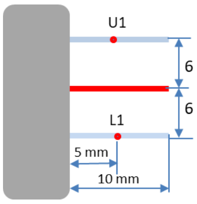
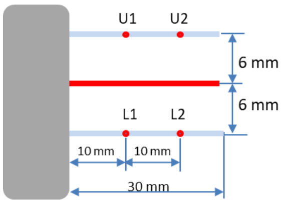
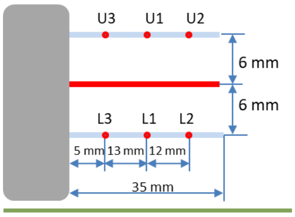
t0 = length of heat pulse (s)

tm = Duration between start of heat pulse application and occurrence of the maximum temperature on the upper sensor needle

4. Sensor design

In order to meet different requirements, ECOMATIK supplies Heat Pulse sap flow sensors in 3 different configurations: N3D1, N3D2, N3D3 as standard. Other configurations are available on request. Table 1 gives an overview of the 3 models.

Table 1 ECOMATIK Heat Pulse Sap Flow Sensors

Sensortypes	N3D1	N3D2	N3D3
			
Measuring depths (mm)	5	10-20	5-18-30
Heater Resistance (ohm)	ca. 16	ca. 37	ca. 43
Standard cable length (m)	5	5	5

5. Scope of delivery

5.1 Sensor

As shown below, the HP sensor consists of:
1x Sensor with 1 m cable and water proof connecter.
1x 4 m cable with water proof connector.
3x Reflective insulation shield of aluminum.

Heat Pulse Sap Flow Sensor

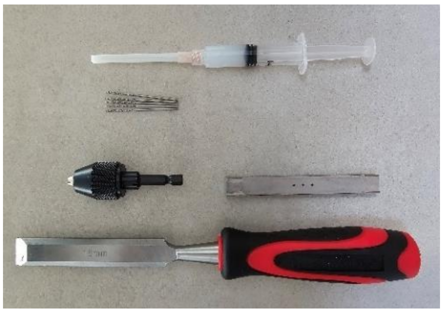
5.2 Heater control board

The heater control board is used to precisely control heat pulse power applied to up to 4 sap flow sensors. The heater control board is controlled by a digital I/O port of the employed data logger, directly switching 12V battery power to the heaters of the connected sensors.

Heater Control Board

5.3 Installation Kit

The Kit the kit includes all the tools necessary, but not available everywhere, to allow a correct installation.



Installation kit

1x Drilling Guide, the three-hole drilling guide is essential for accurate installation.
1x Mini Hex Chuck, the mini hex chuck is designed to hold small drill bits tightly.
5x Drill bits, it provides a perfect fit for the needles of a Sap Flow sensor.
1x Lubricant, to assist in easy installation, and greater possibility of removal of sensor.
1x Chisel, to remove dead bark.

6. Installation

6.1 Required tools for installation and for operation Tools

In addition to the installation kit supplied by ECOMATIK, the following components are required to correctly install and operate the HP sensor.

For installation: cordless hand drill, Cable ties, possibly cable protection tube
For Data recording: data logger, power source, tools to connect sensor to data logger
For calculating whole tree transpiration, tape measure, increment borer, magnifying glass, ruler

6.2 Choose tree

There are certainly different aspects to decide on a measuring tree. But if a representative study is important for a stand, it certainly makes sense to select a representative tree as well.
At what height on the tree the sensor is to be installed can be freely decided.
It is important that measuring location on the desired tree is free from wounds, knots or any other apparent malformations. The installation position should be protected from direct sunlight (north side), to reduce external thermal influences as much as possible.

6.3 Installation

- Carefully remove the dead bark with a chisel without damaging the living inner tissue.

- Measure remaining bark depth (worked surface until xylem). This value will also be entered in the datalogger program

- Secure the drilling guide to the tree in the desired location. It is imperative that the guide does not move during drilling!

- Insert and tighten the drill into the mini hex chuck such that the protruding length of the drill and hence the depth of the installation holes correspond exactly to the needle length of the sensor to be installed.

- Carefully drill the holes using the guide. Drill at a low rotational speed to avoid burning the inner walls of the hole. Drill the three holes in two steps, first until the tip of the chuck touches the drilling guide, second removing the guide and drill the three holes until the tip of the chuck touches the stem surface. While drilling, always pull the drill in and out again and again and free it from drilling dust. This ensures that the hole is drilled cleanly and prevents the drill bit from breaking.

- Coat the needles with sufficient lubricant and carefully insert them into the drilled installation holes. The fit will be tight. Be careful when inserting and apply force directly over and along the needles and holes in the tree. Avoid bending the sensor needles under all circumstances!
If the sensor is very difficult to insert, clean out the holes with the drill again and try again. In the case of some species, after drilling, the wood quickly swells and the drill holes narrow again. In such cases, a slightly larger drill bit can be helpful. In any case, the hole must fit exactly and there must be no gap between the inner wall and the sensor needle.

- Insulate the sensor and the area around it with the reflective insulation shield to reduce error introduced by solar radiation and changing ambient temperatures.

- Strain relief the sensor cable by fixing it onto the stem or on a peg in the ground. This can be done using a rope or cable straps. The cable between the point of fixation and the sensor should be loose and without tension.

7. Connection to data logger

The sensor cable contains up to 10 wires, their functions and connection to the logger are listed in the table.

Table 2 Sensor cables and their connection

Core		Connecting to	N3D1	N3D2	N3D3
White	Heater +	Heater board H	✓	✓	✓
Brown	Heater -	Heater board G	✓	✓	✓
Green	Common ground	Logger ground	✓	✓	✓
Yellow	Thermistor excitation +	Logger Vex + <=2.5V	✓	✓	✓
Grey	Thermistor output U1	Logger channel 1 +	✓	✓	✓
Pink	Thermistor output L1	Logger channel 2 +	✓	✓	✓
Blue	Thermistor output U2	Logger channel 3 +	×	✓	✓
Red	Thermistor output L2	Logger channel 4 +	×	✓	✓
Black	Thermistor output U3	Logger channel 5 +	×	×	✓
Purple	Thermistor output L3	Logger channel 6 +	×	×	✓

8 Measurement

8.1 Temperature measurement

If you supply the sensor with excitation voltage Vex, you get the voltage from the thermistor output in Vm. Voltage, as well as excitation time should be as low as possible in order to minimize self-heating of the temperature sensors.
The temperature T in °C at the respective measuring points is given by F. 4

x=LN(1/(Vm/Vex)-1) (F. 3)
T=-.0837*x^3+1.532*x^2-22.843*x+25.019 (F. 4)

8.2 Applying heat pulse

The heating must be switched on during each measurement in order to apply a heat pulse. The heater is supplied with 12 V DC. Switching on and off can be done either directly via the heater board or via the logger. The heating time and power consumption are shown in the table 3.

Table 3 Power supply for heater

Sensor Type	N3D1	N3D2	N3D3
Heater Resistance (Ohm)	ca. 16	ca. 37	ca. 43
Recommend heating duration (Sec)	2	6	8
Energy consumption for one measurement (W*Sec)	7.65	22.95	26.748
Power input at 12 V (W)	9	3.89	3.348

8.3 Measurement and processing sequence

The heat pulse sap flow measurement and processing sequence is as follows:

1) Determine the initial output of each thermistor: Tini_upper, Tini_lower (Temperature before turning on heating at time = 0 sec)
2) Switch on the heating for the recommended heating duration t0 (Tab. 3)
3) Measure the temperature at least once per second for at least 60 seconds. The time from second 0 to when the max. temperature occurs, is tm (s).
4) Register the maximum output of each thermistor, as well as on time = 60 seconds.
5) Calculate temperatures in °C from registered raw outputs in volts, using F 3 and F 4.
6) Calculate temperature differences
   ΔT60-ini_upper = T60_upper - Tini_upper (F 5)
   ΔT60-ini_lower = T60_lower - Tini_lower0 (F 6)
   ΔTmax-ini_upper = Tmax_upper - Tini_upper (F 7)
   ΔTmax-ini_lower = Tmax_lower - Tini_lower0 (F 8)

HRM

If you insert ΔT60-ini_upper and ΔT60-ini_lower into the F 1, the result is the sap flow velocity according to the HRM method.

MHR

Inserting ΔTmax-ini_upper and ΔTmax-ini_lower into F 2, the result is the sap flow velocity according to the MHR method.

Tmax

If you insert t0 and tm in F 3, the result is the sap flow velocity according to the Tmax method.

9 Literature

Marshall D.C. Measurement of sap flow in conifers by heat transport. Plant Physiol. 1958, 33, 385–396.

Kluitenberg G.J., Ham J.M. Improved theory for calculating sap flow with the heat pulse method. Agric. For. Meteorol. 2004, 126, 169–173.

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