Direct method of transpiration control in plant production processes

Alexander Grishin*, *Andrey* Grishin, *Vladimir* Grishin, and *Elena* Pavlova

Federal Scientific Agroengineering Center VIM, Laboratory of Intelligent Robotic Tools and Climate Equipment for Closed Ecosystems, 5, 1st Institutsky pas., Moscow, 109428, Russian Federation

Abstract. A brief review of devices and methods of functioning of sensors for direct control of transpiration phenomena, their advantages and disadvantages are given. The task of the research is to experimentally confirm the selected calculation dependence for determining the values of xylem flow, i.e. to obtain a formula for determining the rate of xylem mass movement depending on the temperature gradient on the stem surface, which is measured by sensors and given to the system of digital control of production processes based on thermoregulation. And the higher the flow velocity, the faster the temperature front will reach the remote sensor and will cool down by a smaller value than at lower flow velocity and the temperature difference will have a smaller value. The dependence of xylem flow velocity (sap flow) q (g/s) on the temperature difference Δt of the coolant at the inlet of the stem system (heater) and at its outlet (remote sensor-thermocouple) was experimentally obtained. The obtained dependence agrees well with the hyperbolic function $q = 0.15 / \Delta t$, obtained by computational method, which confirms the possibility of its application in the processor of digital control of the system of productivity processes in plant systems.

1 Introduction

Measuring crop transpiration in the field and throughout the growing season is a difficult task. Nevertheless, measuring transpiration is important to ensure efficient productivity of plant systems, which is achieved by the self-organizing process of evaporative cooling and its application to control the growth of these systems. This process underlies the thermoregulatory function of these systems, which in turn results in the maximum rate of the chemical reaction of photosynthesis and creates the conditions for the greatest provision of mineral nutrition to the plant systems.

Stem flow meters for measuring plant transpiration are based on the stem heat balance method, which utilizes the effect of conservation of energy and mass. The original design is based on measuring temperature changes using thermocouples separated by a known distance obtained by wrapping a heater around the plant stem.

* Corresponding author: 5145411@mail.ru

The sensor actually measures the amount of heat carried by the plant's sap, which is then converted directly into flow units - grams or kilograms per second. The sensor is safe for plants, as typical heat is between 1 and 5 degrees.

Leaf temperature and sap flow can reflect not only physiological and energetic changes in plants, but also serve as an indicator of plant health.

Another method is based on infrared measurement of leaf temperature and associated transpiration phenomena. However, facts affecting accurate measurement such as ambient temperature, sunlight, rainfall, wind speed should be taken into account.

In this regard, the development of new compact combined sensors of sap movement and xylem flow is a prerequisite for the assessment of productivity processes in order to increase plant productivity and its further application in the algorithm of digital control.

It is noted in [1] that the main approaches in the study of transpiration of an individual plant are measurements of water exchange parameters of an individual leaf and xylem flow rate at the level of the plant as a whole. Although the first approach is characterized by high accuracy in measuring water exchange parameters, the transition from individual leaf transpiration to whole plant transpiration is a very difficult task. However, determination of the transpiration rate of an individual plant, estimation of its daily and seasonal dynamics is the most important task of ecophysiology. Let us consider methods and technical solutions to this task.

1.1 Method of compensatory measurement

The approach based on the determination of heat pulse velocity (HPV) is realized.

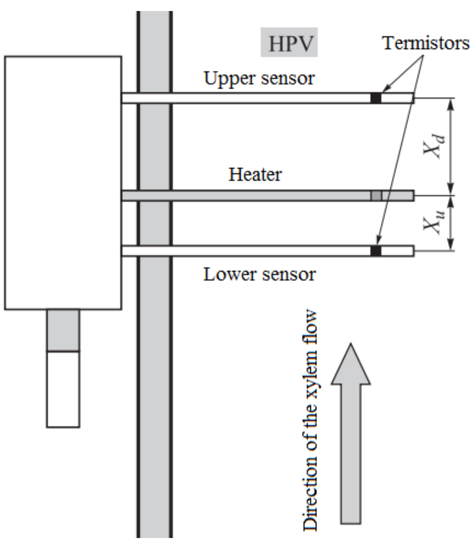

Fig. 1. Schematic diagram of the sensor module of the measuring complex for recording the xylem flow velocity using the Heat Pulse Velocity (HPV) method [2].

The sensor module of this complex (see Figure 1) consists of two measuring needles, with a thermistor placed in each needle at a distance of 5 mm from the end. A heating element is placed between the temperature sensors.

The main disadvantage of the whole group of methods based on the measurement of the heat pulse propagation velocity is the need for additional manipulations that violate the integrity of the plant in order to experimentally determine the parameters - masses of the raw and dry elements of the sample.

1.2 Thermal dissipation estimation method - Granier method

The Granier method [3, 4] is used to measure xylem flow density in trees with a trunk diameter exceeding 4 cm. The sensor unit of this device consists of two steel needles 30 mm long and 1.2 mm in diameter, which are installed in the trunk one above the other at a distance of 40 mm (Figure 2).

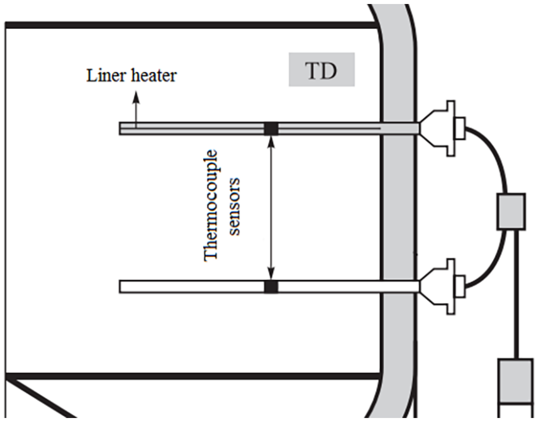

Fig. 2. Schematic of the sensor module of the measuring complex for recording xylem flow velocity by the method of thermal dissipation estimation (Granier's method) [3, 4].

The two main disadvantages of the described technique are the uncertainty of the fact of zero flux, the estimation of which is extremely necessary for accurate interpretation of the measured curves, and the lack of theoretical physical justification of the applicability of the found constants to work with different plant species

1.3 Heat field deformation estimation method

This approach (see Figure 3) is unfortunately also very sensitive to the accuracy of registration of heat field parameters at the moment of zero xylem flow velocity. The authors of the method propose an original approach to approximate the missing zero-flow data when working in the field [5]. However, such a solution is also empirical and probably needs to be verified under the conditions of a specific study.

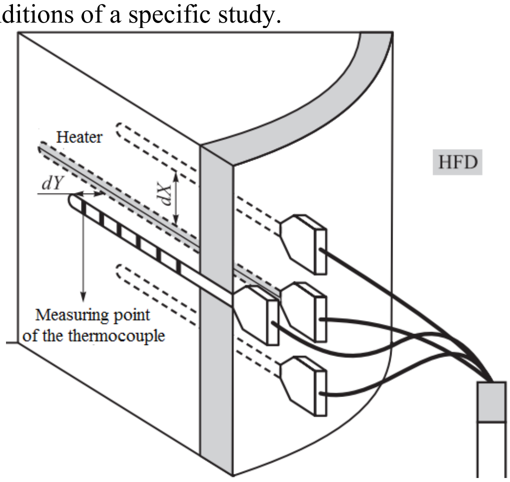

Fig. 3. Schematic diagram of the sensor module of the measuring complex for recording the xylem flow velocity using the Heat Field Deformation (HFD) estimation method.

1.4 Hybrid method of measurement using the counter heat pulse technique

The basis for using a hybrid measurement scheme is the assumption that by combining the thermodissipation and HPV techniques, there is a theoretical possibility of leveling some disadvantages and limitations inherent in each of these techniques separately. If the HPV-method and the corresponding set of sensors are used as a basic mode, it allows to reduce significantly the power consumption of the measuring unit in comparison with the Granier method and to link the obtained data to a well-developed physical model.

However, there are other methods for determining the velocity and mass of the transpired fluid. One of them has been developed in the Laboratory of Intelligent Robotic Tools and Climate Equipment for Closed Ecosystems at Federal Scientific Agroengineering Center VIM.

1.5 Theoretical prerequisites for the choice of technical solutions of the sap movement sensor

The sap movement sensor is designed to determine the rate of xylem mass movement in the stem of a vegetable crop, which has an insignificant diameter and a structure easily susceptible to deformation [5-6].

Therefore, the task of the present research is to derive a formula for determining the rate of xylem flow mass movement depending on the temperature gradient on the stem surface, which is measured by sensors and fed into the system of digital control of production processes based on thermoregulation.

2 Materials and methods

In the presence of xylem flow, its velocity is determined by recording the difference in the velocity of the heat front from the heater H2 to the thermocouple T3 (see Figure 4).

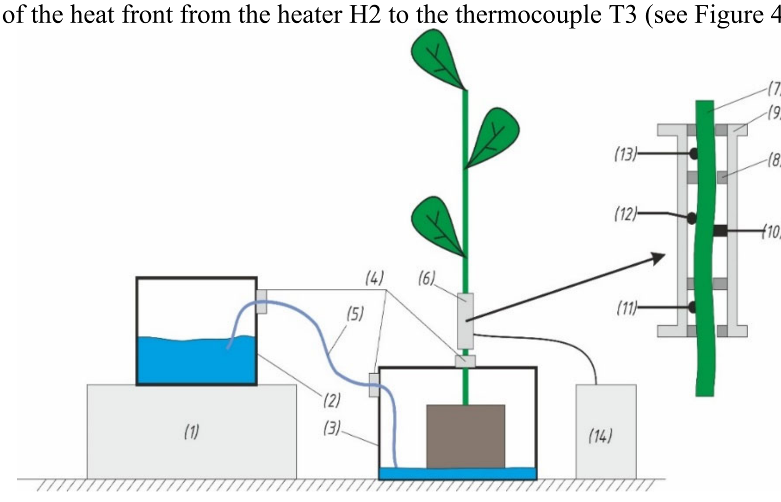

Fig. 4. Scheme of the experiment. (1) - scales OHAUS Compass CX2200; (2) - sealed box with nutrient solution; (3) - sealed box with plant; (4) - seal lead; (5) - flexible drip water line; (6) - sap flow sensor; (7) - plant stem; (8) - heat insulator; (9) - body of sap flow sensor; (10) - heating element H1; (11) - temperature sensor T1 (thermocouple); (12) - temperature sensor T2 (thermocouple); (13) - temperature sensor T3 (thermocouple); (14) - control unit.

In this case, the heated flow region moves to the upper sensor, losing heat and decreasing its temperature. That is, as the xylem flow rate increases, the temperature difference between the heated area of heater H2 and sensor T3 will decrease. Such a pattern will correspond to the ratio of the coolant flow rate q (g/s) in the system from the temperature difference T2 - T3 of the form [7]:

$$q = \frac{Q}{c\Delta t} \quad (1)$$

where c is the specific heat capacity of salt solution in water (sap), taken equal to 3.6 kJ/ (g ºC); Δt is the temperature difference. °C, of the coolant at the inlet to the system and at its outlet; Q - heat capacity of the system, W.

As already mentioned, the research task is to experimentally confirm the selected calculated dependence (1) to determine the values of xylem flow in plant systems and use in digital control systems.

To compare the experimentally obtained function of the coolant flow rate from the temperature difference with the calculated one according to (1), we set the values of the heater heat power H2 equal to 0.54 W (to exclude damage to the stem by dangerous heating) and a number of temperature differences of 0.5...4 ºC. The values of the calculated dependence are given in Table 1.

Table 1. The values of the calculated dependence.

Δt	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**
q (g/s)	0.5	1.0	0.1	0.08	0.06	0.05	0.04	0.04	0.03

Experimental values will be obtained experimentally on the bench (Figure 5).

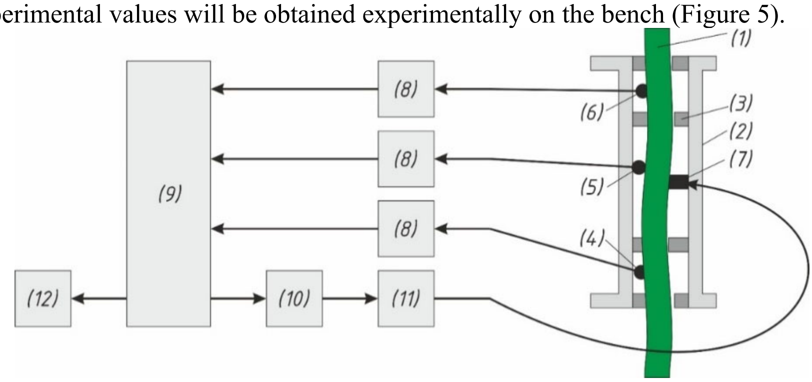

Fig. 5. Scheme of sap flow sensor. (1) - plant stem; (2) - sensor housing; (3) - thermal insulator; (4) - temperature sensor T1 (thermocouple); (5) - temperature sensor T2 (thermocouple); (6) - temperature sensor T3 (thermocouple); (7) - heating element H1 (40W, 12V); (8) - thermocouple signal converter MAX6675; (9) - central processor AMG2265; (10) - voltage converter 0... 5V; (11) - relay; (12) - display.

The work of the sensor is tested on the experimental stand in the composition of the studied plants tomato variety "Alice" and "Cameo", placed at different times in a sealed box with soil, where capillary water is supplied from the reservoir. The reservoir is placed on the scales with the division value of 0.1 grams, having an interface that allows to control the amount of water supplied to the plant according to its needs in the computer program. Thermocouples of the sensor allow to control the movement of the thermal front from the heater, removed from them at some distance and thus get the temperature difference of the coolant. As the coolant (xylem flow) moves from the heater to the remote sensor, its temperature, as a result of cooling, will decrease.

Fig. 6. Sap flow sensor appearance.

The higher the flow rate, the temperature front on reaching the remote sensor will cool down by a smaller amount than at lower flow rate and the temperature difference will have a smaller value.

The experimental results are presented in Tables 2 and 3.

Table 2. The experimental results. Tomatoes of "Alice" variety.

Δt	**0.34**	**0.52**	**0.84**	**1.06**	**1.37**	**1.55**	**1.77**	**2.17**	**2.55**
q (g/s)	0.4	0.28	0.16	0.12	0.1	0.09	0.08	0.07	0.06

Table 3. The experimental results. Tomatoes of "Cameo" variety.

Δt	**0.72**	**0.98**	**1.59**	**2.33**	**2.68**
q (g/s)	0.22	0.16	0.1	0.07	0.06

According to the results of experimental data and calculated data (Tables 1, 2 and 2) the combined graphs of dependencies (Figures 7 and 8) are constructed.

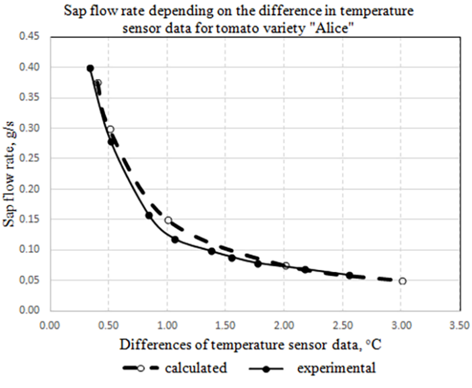

Fig. 7. Calculated and experimental dependences of xylem flow rate (sap flow) *q* (g/s) on the temperature difference Δt of the coolant of tomato variety "Alice"

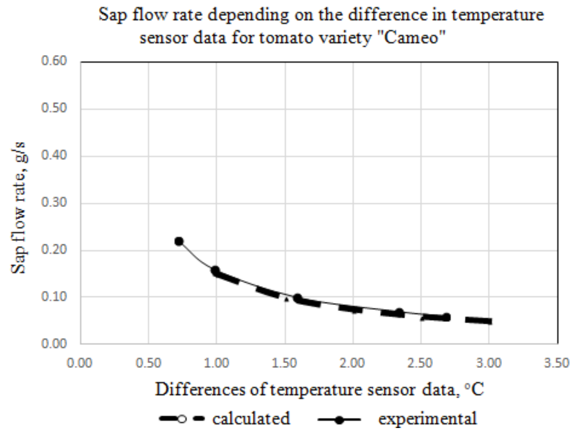

Fig. 8. Calculated and experimental dependences of xylem flow rate (sap flow) q (g/s) on the temperature difference Δt of the coolant of tomato variety "Cameo"

3 Conclusion

The dependence of the xylem flow rate (sap flow) q (g/s) on the temperature difference Δt of the coolant at the inlet of the stem system (heater) and at its outlet (remote sensor-thermocouple) was experimentally obtained.

The obtained dependence corresponds well with the hyperbolic function $q = 0.15 / \Delta t$, obtained by computational method, which confirms the possibility of its application in the processor of digital control of production processes in plant systems.

References

1. G.P. Tikhova, A.G. Pavlov, V.B. Pridacha, T.A. Sazonova, Siberian Forestry Journal **4**, 78-90 (2017)
2. K.R. Hultine, J.D. Marshall, Journal of Experimental Botany **52(355)**, 369-373 (2001). https://www.doi.org/10.1093/jexbot/52.355.369
3. A. Granier, Tree Physiology **3(4)**, 309-320 (1988). https://www.doi.org/10.1093/treephys/3.4.309
4. J. Yang, J.M. Michaud, S. Jansen, H.J. Schenk, Y.Y. Zuo, Tree Physiology **40(4)**, 433-444 (2020). https://www.doi.org/10.1093/treephys/tpaa006
5. R.T. Avila, C.N. Kane, T.A. Batz, C. Trabi, F.M. Damatta, S. Jansen, S.A.M. McAdam, Tree Physiology **43(1)**, 75-87 (2022). https://www.doi.org/10.1093/treephys/tpac110
6. X. Sun, J. Li, D. Cameron, G. Moore, Agronomy **12(1)**, 52 (2022). https://www.doi.org/10.3390/agronomy12010052
7. Heat carrier fluid flow rate in the system (2023). https://en.ppt-online.org/17274. Last accessed 08.08.2023