MONITORING OF PLANT GROWTH ENVIRONMENT IN THE SVET-3 SPACE GREENHOUSE: MEASUREMENTS OF PLANT SHOOT ENVIRONMENT

Svetlana Sapunova, Slaveyko Neychev,
Tania Ivanova, Plamen Kostov, Iliana Ilieva

Space Biotechnology Department, Space Research Institute, Bulgarian Academy of Sciences, 6 Moskovska Str.,1000 Sofia, Bulgaria, (+359 2) 9793467, e-mail: svetlas@space.bas.bg

The object of this paper is to describe the Environmental Monitoring System of the SVET-3 SG that is being developed for exact and detailed monitoring of the plant shoot environment. In the process of development the environmental parameters that should be monitored and controlled so as to provide adequate conditions for plant growth and the ones necessary to currently evaluate plant status are determined. Using experimental data obtained from the SVET-2 SG and other plant growth facilities flied onboard the MIR and ISS the technical requirements to the measuring systems are specified. Some first developments of the main measuring systems using commercial sensors are presented. The high quality 16 bit/500 kHz, 16-channel, expandable computer system for data acquisition ME-Jekill/ME-4610 is used to collect sensor data and to control the actuating mechanisms.

Keywords: (Monitoring, Plant Growth, Measuring Systems, Sensors)

1. INTRODUCTION

The SVET Space Greenhouse (SG), developed in the Space Research Institute, Bulgarian Academy of Sciences (SRI-BAS) on a joint project with the Institute of Biomedical Problems, Moscow, was designed to accommodate long lasting plant experiments under the conditions onboard the MIR Space Station (SS) in flight. Launched inside the Krystal module in 1990 SVET SG was the first and the only automated plant growth facility flied onboard the MIR SS in 1990-2000 [1].

According to an agreement between NASA and the Russian Space Agency, signed in 1994, the American Gas Exchange Measurement System (GEMS) was developed in the Utah State University and added to the Bulgarian SVET Instrumentation System to monitor more environmental and plant physiological parameters [2]. The original SVET SG has a Plant Chamber (PCh), open type, allowing contact with the MIR cabin atmosphere. The GEMS measurements required PCh enclosure. For that purpose two transparent plastic bags, called Leaf Bags, were placed to enclose plants above each RM section before starting gas-exchange measurements. The same year a set of SVET-2 SG equipment with improved technical characteristics was developed in the SRI-BAS (financed by NASA) and the advanced SVET-2+GEMS equipment was launched onboard the MIR SS. During the period 1990-2000 a series of successful long-term plant space experiments, named GREENHOUSE (GH) was carried out in the SVET-2+GEMS hardware complex onboard the MIR SS by international crews [3]. These experiments gave us a possibility to determine the environmental variables in a human space habitat having an impact on plant development under microgravity, to collect valuable data for the root and shoot environment and to gain experience about the technology and instrumentation for plant growing under microgravity. They also helped us to make some conclusions which predetermined the object of our further investigations:

1. The successful *Brassica rapa* and *Apogee* wheat experiments showed that the lack of gravity is not an obstacle for normal plant development in space [4, 5].

2. The experiments proved that adequate control of plant growth environment is required to grow plants in space. In most of the plant growth facilities, flied onboard the International Space Station (ISS), the environmental control came down to maintaining constant root and shoot environment parameters. Changing some of them and taking samples for analysis at different stages of plant development they recorded the functional dependence of plant growth on these parameters so as to differentiate the influence of microgravity on the growing plants.

3. The first successful measurements of the plant growth environment carried out during the second stage of the GH2B experiment in 1996-1997 suggested that it could be possible to monitor plant development in real time by measuring precisely the gas-exchange rates and without current sampling [6].

Having in mind all these considerations we developed a Concept for an advanced SVET-3 SG with automatic environmental control. Our Concept provides a feedback in the chain "monitoring – control" which allows optimising plant growth conditions during the experiment. For that purpose the absolute parameters of the air entering and exiting PCh and some plant physiological parameters are measured and processed in real time. Using these data the Control Computer (CC) calculates transpiration and photosynthesis, evaluates plant status and performs adaptive environmental control in order to provide most favourable conditions for plant growth at every stage of plant development in autonomous mode [7].

2. PROBLEM STATEMENT

The biological results obtained during the GH experiments show that a wide and precise monitoring of the root and shoot environment is required so as to build a reliable, controllable system for plant growing under microgravity.

The SVET-2 SG equipment provided measurement of some plant shoot environment parameters - Air Temperature (AT) and Air Humidity (AH) within and out of PCh. SVET-3 is based on a semi-closed PCh air volume with controllable air flow and filters for removal of contaminants from the cabin air.

In the process of development of the SVET-3 SG environmental monitoring system we had to specify the problem task including the following steps:

1. To select the plant shoot environment parameters that should be monitored in order to obtain most detailed information about the conditions in the leaf area;
2. Using experimental data from the SVET-2+GEMS and other experiments to determine the real possible values of these parameters and on this basis to specify the requirements to the main measuring systems;

3. To develop the framework of the system for measurement of the plant shoot environment;
4. To set up a laboratory model of the system for plant shoot environment monitoring and to start the main sensor systems development.

Block Diagram of the System for Measurement of the Plant Growth Parameters in the SVET-3 SG is shown on Fig. 1. SVET-3 SG provides two separate sensor system: Plant Environment Measurement System (PEMS) and Gas-Analyzer System (GAS).

2.1 Plant Environment Measurement System

PEMS can function independently (without GAS) and provides continuous monitoring of the environment within and out of the PCh. Parameters measured by PEMS with their possible boundary values are given in Table 1.

The SVET-3 SG Light Unit provides white light from luminescent lamps selected by spectrum for plant experiments. The Light Period (LP) can be regulated. The value of 500 μmol/m^2.s PPF light intensity is determined as a reasonable level having in mind the existing plant requirements and power restrictions.

The MIR cabin environment was not constant during the experiments what reflected on PCh environment parameters [8]. Cabin Temperatures (CT) ranged normally excepting some particular moments when they reached values from 15 to 35^{o}C. PCh Air Temperatures are usually 2^{o}C higher in the day but sometimes they differed significantly. Leaf Temperatures (LT) which are usually 0.5÷2^{o}C higher or lower than PCh air temperatures sometimes showed higher deviations. The total Cabin Air Pressure (AP) varied within the normal 95 to 100 kPa excepting some jumps up to about 105 kPa which occur during the docking procedures.

2.2 Gas-Analyzer System

The GAS system provides accurate measurements of the absolute and differential values of the CO_2 and water vapour attended by simultaneous accurate measurements of the temperature, air flow and absolute and differential values of the barometric pressure in the PCh environment. Using these data the CU calculate photosynthesis, transpiration and respiration rates.

Measurements of net photosynthesis are necessary for calculating growth rates without taking samples. Respiration measurements are a strong indicator for plant health and differences in physiology compared to ground control. Respiration from root decay shifts the net photosynthesis curve and these measurements are used as a corrective factor [8]. Transpiration measurements provide a real time monitoring of plant growth. They are necessary for determining water potentials in the root zone in order to manage adequately the watering regimes in microgravity. Simultaneous measurements of transpiration and root zone moisture content are important for providing enough water for stress free growth in microgravity.

SVET-3 SG system has a feedback which allows CU using data for plant transpiration to maintain adequately air humidity and CO_2 concentrations by a fan controlling the rate of air flow entering the PCh from the cabin [7].

Simultaneous measurements of the plant leaf area are necessary to normalize measurements on different stages of the biological cycle. Since leaf area measurements are difficult to fulfill in such small plant area they are usually replaced by earth measurements in which leaf area is measured and assigned to different plant height.

3. RESULTS

A laboratory model of the system for plant shoot environment monitoring is set up. The ME-Jekill/ME-4610 high quality expandable computer Data Acquisition and Processing System (DAPS) (MEILHAUS ELECTRONIC, Germany) is used to collect sensor data and to control the actuating mechanisms. It provides 16 single-ended A/D channels. The input channels are routed through a high impedance input stage to a 16 bit, 500 kHz A/D converter. The input voltage range is ±10 V. The digital I/O section has 4x8 TTL digital I/O channels, grouped in 8 bit ports. Each port can be configured independently as input or output. The system is open for further optimizations and new sensors addition.

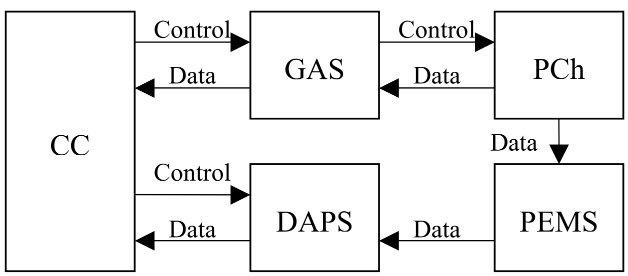

Fig. 1 Block-diagram of the System for Measurement of the Plant Growth Parameters in the SVET-3 SG.

Parameter [dimension]	Lowest Value	Highest Value
PPF [μmol/m^2.s]	0	500
LP [h]	0	24
AT [^{o}C]	15	40
AH [%]	40	80
LT [^{o}C]	15	35
AFV [m/s]	0	3
CO_2 in PCh [ppm]	>2000	10000
CT [^{o}C]	15	35
Cabin AH [%]	40	80
Cabin AP [kPa]	95	105
Cabin CO_2 [ppm]	>2000	10000
Cabin O_2 [%]	19	22

Table 1

As a first step towards our object – to work out the SVET-3 SG environmental monitoring system the main measuring sub-systems are being developed:

1. Air Humidity in the plant shoot zone is measured by the Honeywell humidity sensor HIH-3602-C. The supply voltage is 5 V DC and the consumption is within 20 ÷ 100 μA. The output is a buffered voltage that goes from 0.8 V (0% RH) to 3.9 V (100% RH) at 25^{o}C.

$$Vout = V_{supply}[0.0062 \, . \, (Sensor\ RH) + 0.16] \quad (1)$$

The humidity sensor has temperature dependence, which is strongest when the humidity is highest. To make temperature compensation the sensor element includes both a humidity sensor with signal conditioning electronics and a Pt_{1000} temperature sensitive resistor of 1000 Ω±0.2% at 0^{o}C (α = 0.0037 Ω/Ω/^{o}C) integrated in the package. The true RH value is calculated as in (2):

$$True\ RH = (Sensor\ RH)\ (1.0546 - 0.00216)\ T^oC \quad (2)$$

To reduce the measurement error caused by the supply voltage instability the DAPS Reference Voltage is used as a sensor supply voltage. To achieve higher resolution the sensor output voltage is processed so as to be compatible with DAPS, i.e. it ranges from 0 V to 9 V when the Sensor RH varies from 0 to 100%. The sensor output is also buffered to reduce the interferences in the output signal.

2. The Pt_{1000} temperature sensitive resistor, integrated in the humidity sensor package is used to measure the Air Temperature in PCh. The value of 0.3 mA of the measuring current through the resistor is chosen so as to reduce the measurement error due to sensor self-heating. In such a case the power delivered to the sensor at 25°C is 96 μW and the output voltage is 29 mV. The output signal is normalized by amplification and shifting so that the output voltage delivered to DAPS ranges from 0 V (at 0°C) to 5.8 V (at 25°C). The sensor resolution is $1.3.10^{-3}$°C.

3. Cabin Air Pressure is measured in the range 0 ÷ 780 mm Hg by the Siemens sensor KPY10. The sensor works on a piezo-resistive principle and its sensitivity is 10 mV/Bar.V. The temperature coefficient is $K_{(T)}$ = –0.18%/°C and the maximum offset voltage is 0.5 mV/V. The temperature dependence of this sensor calls for temperature compensation. Such compensation is usually made by including a thermistor with a negative temperature coefficient in the sensor's power supply circuit. Unfortunately it is impossible to achieve full temperature compensation using this way because of the thermistor non-linearity on one hand and its fixed temperature coefficient which is different for each series of sensors on the other. This was the reason to use another way of achieving temperature compensation. We use an active two-terminal network consisting of a bipolar transistor with terminals emitter - collector and a multiturn potentiometer whose wiper is connected to the transistor base. Changing the wiper position we change the network temperature coefficient.

In 10 V supply the sensor output voltage is 100 mV/Bar. A differentiating amplifier with a gain of 100 times is used to normalize the output voltage so as to make it fit for the DAPS input. Since the DAPS input voltage ranges within –10 ÷ 10 V we use half the range which corresponds to a resolution of 0.024 mm Hg. The amplifier also provides the necessary load capacity of the sensor.

4. The Air Flow Velocity (AFV) is an important parameter that is used when calculating the SVET water balance. The maximum air flow velocity in the Plant Chamber does not exceed 2÷3 m/s. Heat method is used to measure this parameter. The sensor unit contains two miniature transistors blown by the air flow. The first transistor temperature is equal to the one of the ambient air. The temperature of the second transistor is maintained by an electron unit so that the temperature difference between both transistors is always constant. The energy necessary to maintain this constant difference gives information about the air flow velocity. An experimental sensor unit was produced and its first tests showed that it allow measuring air flow velocities in the range from 2 cm/s to 5 m/s. The sensor characteristic is non-linear which requires preliminary sensor calibrating and recording in the CC memory.

5. Light Intensity in the plant shoot zone is a parameter of vital importance for plant growth. During photosynthesis plants use energy in the 400÷700 nm spectrum region. LI in this range is measured as Photosynthetic Photon Flux density (PPF) in $\mu mol.s^{-1}.m^{-2}$. The LI-COR LI-190SA Quantum Sensor is used to accurately measure

this parameter. It represents a silicon photodiode whose response is tailored to the desired quantum response by filters. LI-190SA sensitivity is 5μA/1000 $\mu mol.s^{-1}.m^{-2}$. It has good linearity (maximum deviation of 1% for ranges up to 10000 $\mu mol.s^{-1}.m^{-2}$). The temperature dependence is 0.15%/^{o}C. The sensor is designed to work in wide temperature (–40^{o}C÷65^{o}C) and humidity (0÷100%) ranges. In Light Intensity of 1000 $\mu mol.s^{-1}.m^{-2}$ the output current is 5μA. To achieve maximum linearity the sensor, functioning as a current generator, is connected in the circuit of a current-voltage converter – an inverting amplifier whose input resistor has a value close to zero. The output resistor value of 2 MΩ is calculated having in mind the output voltage level of 10 V required from DAPS and the output current of 5 μA. The TL061 operational amplifier is chosen for the current-voltage converter because of its low input current (it must not exceed the admissible measurement error).

4. CONCLUSIONS

Earth tests of the laboratory system for plant shoot environment monitoring with the use of the ME-Jekill/ME-4610 DAPS system and the sensor sub-systems developed up to now were made. They showed that the system functions properly. The rest sensor sub-systems are under development.

5. ACKNOWLEDGMENT

This research is supported in part by the Bulgarian Ministry of Education and Science under Contract Number KI-1-01/03.

6. REFERENCES

[1] Ivanova T., Yu. Berkovich, A. Mashinskiy, and G. Meleshko, *The First "Space" Vegetables have been Grown in the "SVET" Greenhouse Using Controlled Environmental Conditions,* Acta Astronautica, vol. 29, pp. 639-644, 1993.

[2] Ivanova T., P. Kostov, S. Sapunova, I. Dandolov, F. Salisbury, G. Bingham et al., *Six-Month Space Greenhouse Experiments - a Step to Creation of Future Biological Life Support Systems,* Acta Astronautica, vol. 42, pp. 11-23, 1998.

[3] Ivanova T., Greenhouse Aboard Mir Shows Plants Can Thrive in Space, *21st CENTURY – Science and Technology*, vol. 15(2), pp. 39-47, 2002.

[4] Musgrave M., A. Kuang, Y. Xiao, S. Stout, G. Bingham, L. Briarty et al., *Gravity Independence of Seed-to-seed Cycling in Brassica rapa*. Planta, vol. 210, pp. 400-406, 2000.

[5] Levinskikh M., V. Sychev, T. Derendyaeva, O. Signalova, I. Podolsky, S. Avdeev et al., *Growth and Development of Plants in a Row of Generations under the Conditions of Space Flight (Experiment Greenhouse-5)*, Aviakosm. Ekolog. Med., vol. 35(4), pp. 45-49, 2001.

[6] Monje O., G. Bingham, J. Carman, W. Campbell, F. Salisbury, B. Eames, V. Sytchev, M. Levinskikh, and I. Podolsky, Canopy Photosynthesis and Transpiration in Microgravity: Gas Exchange Measurements aboard MIR, *Adv. Space Res*., vol. 26(2), pp. 303-306, 2000.

[7] Kostov P., T. Ivanova, I. Dandolov, S. Sapunova, and I. Ilieva, *Adaptive Environmental Control for Optimal Results during Plant Microgravity Experiments*, Acta Astronautica, vol. 51, pp. 213-220 2002.

[8] Bingham G., S. Brown, F. Salisbury, W. Campbell, J. Carman, G. Jahns et al., *Plant Growth and Plant Environmental Monitoring Equipment on the Mir Space Station: Experience and Data from the Greenhouse II Experiment,* 26th Intern. Conf. on Environmental Systems, Monterey, CA, USA, 8-11 July 1996 (SAE 961364).