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Chang-Soo Kim
Missouri University of Science and Technology, ckim@mst.edu

Sandeep Sathyan

D. M. Porterfield
Missouri University of Science and Technology

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A New Microsensor System for Plant Root Zone Monitoring

Chang-Soo Kim[1,2], Sandeep Sathyan[1]
1 Dept. of Electrical & Computer Engineering
2 Dept. of Biological Sciences
University of Missouri-Rolla, Rolla, MO, USA
ckim@umr.edu

D. Marshall Porterfield[1,2]
1 Dept. of Agricultural & Biological Engineering
2 Dept. of Horticulture & Landscape Architecture
Purdue University, W. Lafayette, IN, USA
porterf@purdue.edu

***Abstract* - The objective of this work is to develop a new microsensor system that can monitor dissolved oxygen and hydration environment at the plant root zone. A miniaturized plant growth system is prepared including the root zone layer, either a porous ceramic tube or porous ceramic wafer on which the plant will be grown, and an underlying fluidic channel to deliver nutrients and water to the root zone. We demonstrate the feasibility of using a flexible microsensor array for dissolved oxygen detection, and a four-electrode impedance microelectrode for wetness detection on the surface of a porous tube nutrient delivery system. The unique features of the microsensor array and microelectrodes include small size, simple structure, mechanical flexibility and multipoint sensing. The new plant root microsystem technology is anticipated being a novel tool for plant root physiology.**

I. INTRODUCTION

The plant root system has been referred to as the "hidden half" because of limitations in analytical and quantitative techniques to viably study the biology of that portion of the plant [1]. Consequently, the plant root and root-environment interactions are the least understood and most challenging aspect of plant physiology. The total yield loss of field crops is related mostly to nutrient deficiency, drought, and contaminated soil. A possible solution to this problem can be obtained only from better understanding of the interactions between the roots and the immediate surrounding root zone to help the food security that loom in the near future [2].

Several laboratory controls of the growth environment had been performed based on traditional 3-dimensional horticulture setup to see the influences of oxygen stress, water stress and mechanical stress [3]. We propose to develop a novel microsystem technology for advanced control and analysis of the local environment in root zone and rhizosphere with better temporal and spatial resolution. Artificial growing conditions will allow improved monitoring and control of root activities with minimal disturbance, but may not reflect root behavior in the natural medium such as soil. However, systematic analyses of the effect of root environment are crucial for a better prediction of root behaviors under variable and fluctuating environments.

II. EXPERIMENTS

A. Miniaturized plant growth microsystem

Figure 1 shows miniaturized plant growth microsystems being developed including porous alumina tubes and wafers (the root zone) on which the plant will be grown, and underlying fluidic channels to deliver nutrients and water to the root zone, respectively.

The porous tube plant nutrient delivery system in figure 1(a) [4] includes a 1 liter liquid reservoir to store the plant nutrient solution. A gear pump (Cole Parmer, 7521-50) is utilized to draw out the solution from the reservoir and into the alumina porous tube (Refractron, porosity 0.5 µm, outer diameter 13 mm, inner diameter 8 mm, length 100 mm) at a controlled flow rates. The internal pressure of the tube can be either positive or negative depending on the polarity of the pump direction. A valve on each side of the tube controlled the internal pressure between -4 kPa to +4 kPa. Two pressure gauges (3D instruments, DTG-6000) at both ends of the porous tube provided the internal pressure reading. The difference of pressure at these ends was negligible.

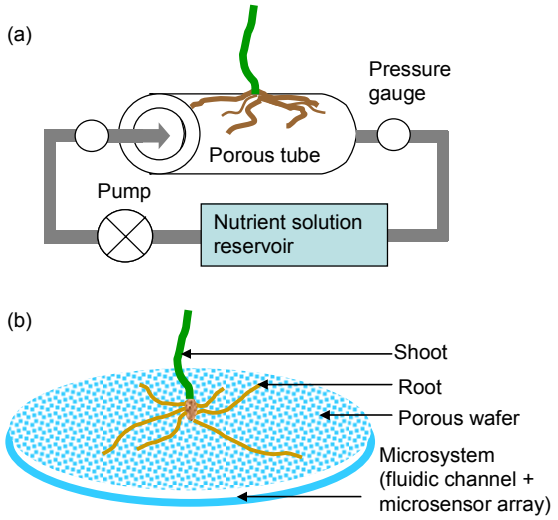

Figure 1. Plant growth microsystem on (a) a porous ceramic tube and (b) a porous ceramic wafer.

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B. Flexible microsensor array

Photographs of a flexible prototype microsensor strip including an array of four amperometric dissolved oxygen microsensors is shown in Figure 2. We designed an amperometric microsensor based on a three-electrode electrochemical cell configuration and a impedance microelectrode based on the four-electrode impedance cell configuration, respectively. The three-electrode cell minimizes the ohmic voltage drop through the electrolyte between the anode and cathode and prevents the consumption of reference electrode material (usually Ag/AgCl). The strip is 58 mm long and 6 mm wide. The impedance-based microelectrodes strip consists of 4 identical electrodes of diameter 500 µm with the outer pair electrode acting as current probes and the inner pair electrode acting as voltage probes, respectively. The spacings between the two current probes and between the two voltage probes are 80 mm and 76 mm, respectively.

Details of the fabrication using flexible substrates is similar with our previous study [5]. All the electrodes were made of platinum. On the Kapton® (polyimide) substrate, a thin film of chromium as an adhesion layer was first deposited and then the platinum deposition followed. A photosensitive polyimide layer was patterned over the platinum to define the active electrode area and to enca[sulate the electrodes. The reference electrode of the oxygen microsensor was electroplated with Ag/AgCl. The fabricated strip was dip-coated with poly-HEMA (poly 2-hydroxyethyl methacrylate), a hydrophilic membrane, by dipping method. This layer reduces stir sensitivity and acts as a protective membrane.

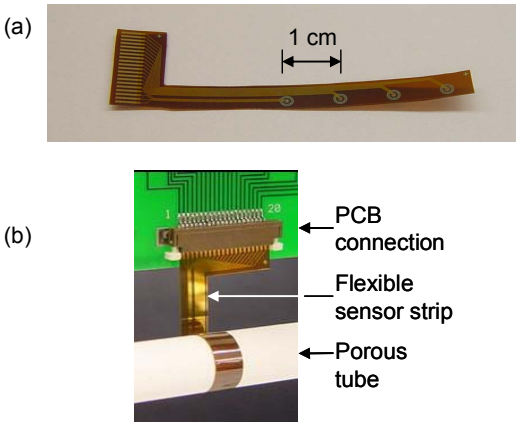

Figure 2. Photographs of (a) a prototype microsensor strip on a flexible Kapton® substrate including an array of four amperometric dissolved oxygen microsensors, and (b) the sensor strip enwrapping the porous tube.

C. System assembly and measurements

In this work, the prepared flexible arrays were applied to the porous tube system in Figure 1(a) to monitor dissolved oxygen concentration and water content at the root zone. The microsensor array was connected to the instrument using a zero-insertion force connector as shown in the photograph in figure 2(b). Initially the microsensor array was placed in a measuring vessel and pre-polarization (pre-conditioning) of the sensor was performed for 15-20 minutes before the actual measurements. Later, the microsensor array was mounted on the porous tube and calibration and measurements were performed at various oxygen levels of internal solution and different internal pressures. The oxygen microsensor array was enwrapped around the porous tube as in figure 3(a). Each oxygen microsensor was placed equidistantly at 10 mm. The impedance microelectrodes were placed on the tube surface along the length of the tube as in figure 3(b). The use of outer pair current probes minimizes the influence of interface impedance between the electrode and the solution during the impedance measurement. All measurements were performed at room temperature (23° C ± 1° C).

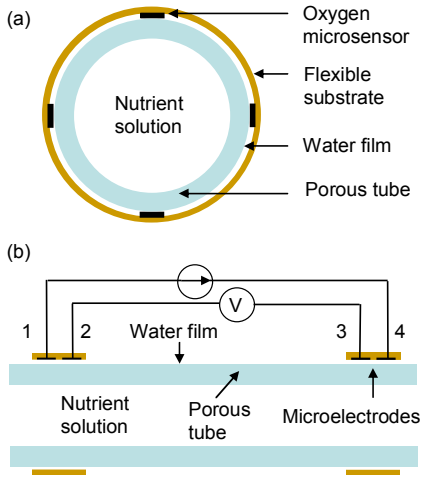

Figure 3. (a) Transversal cross-section of the dissolved oxygen sensor strip enwrapping the porous tube. (b) Longitudinal cross-section of the impedance microelectrode strip in contact with the surface of the porous tube.

III. RESULTS & DISCUSSION

A. Dissolved oxygen measurements

The microsensors were first subjected to pre-polarization for 15-20 minutes before the measurements on the porous tube. Each microsensor in the strip was sequentially multiplexed by the pulsatile cathodic oxygen reduction voltage. The response values as in Figure 4(a), for a fixed oxygen saturation level, increased as water film thickness on the surface increased. The microsensor reflects oxygen levels properly with enough water film on the tube surface at positive pressures. The responses at negative pressures, however, were scattered around the zero oxygen value and measurements were not reliable due to surface dryness. Due to the absence of a hydrophobic permeable

membrane, the microsensor surface (coated only with a hydrophilic membrane) becomes dry and thus the conducting path between the electrodes was lost. Additionally, given that calibration was performed only once at highest positive pressure, the microsensor response deviates from the actual values as the pressure decreases. Therefore, the deviation along with scattering is significant at zero and negative pressures due to an insufficient volume of the surface water film. The calibration curve in figure 4(b) shows that the slope was positive in the presence of a water film on the porous tube surface and increased with an increase in the liquid film thickness for a fixed oxygen concentration level. Further increasing the film thickness, by increasing the internal pressure of the porous tube, did not yield any substantial increase in the slope of the calibration curve.

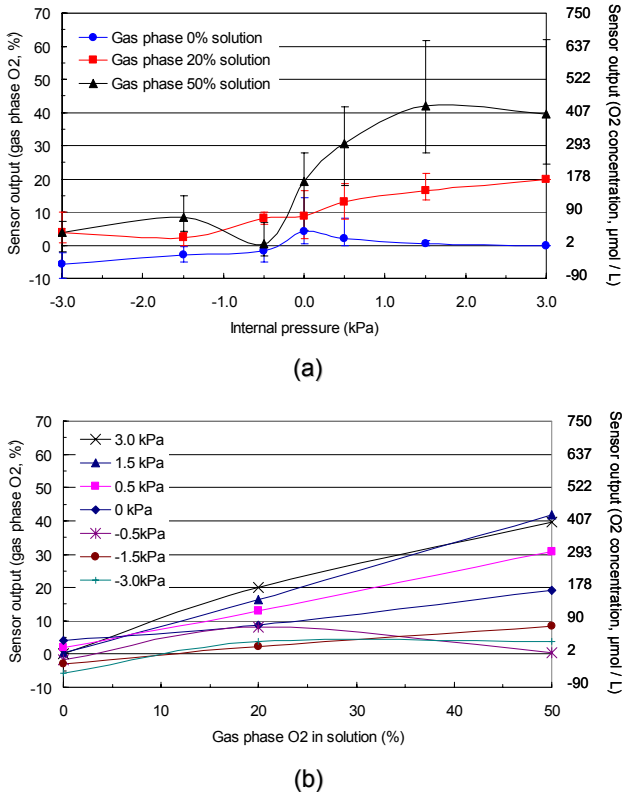

Figure 4. (a) Dissolved oxygen concentration measured with the oxygen microsensor on the surface of the porous ceramic tube. (b) Re-plot of (a) to show sensitivities depending on the internal solution pressure.

B. Hydration measurements

When the surface is dry, impedance between the probes is very high as there is no suitable conducting medium (plant nutrient solution). A gradual decrease of impedance in the negative pressure region as shown in figure 5 implies that the water content within the porous tube media is increasing due to the decreasing suction capability. An observed steep transition towards lower impedance value at a moderate negative pressure is considered to be due to the capillary effect to contain the solution within the porous tube media. Once the pore portion in the tube is saturated with solution solely by the capillary force at zero pressure, the impedance showed a near minimal value. For positive pressures, there was no clear differentiation between the different liquid film thicknesses on the wet tube surface. This implies that the contribution of surface water film to conductivity is negligible compared to that of saturated porus media. The results for both two-electrode and four-electrode impedance measurements were compared and it was found that four-electrode configuration demonstrated lower average impedance values along with higher percentage of difference between wet and dry surface values. This effect is attributed to the fact that the four-electrode configuration minimizes the effect of interface impedance between the electrode and the solution.

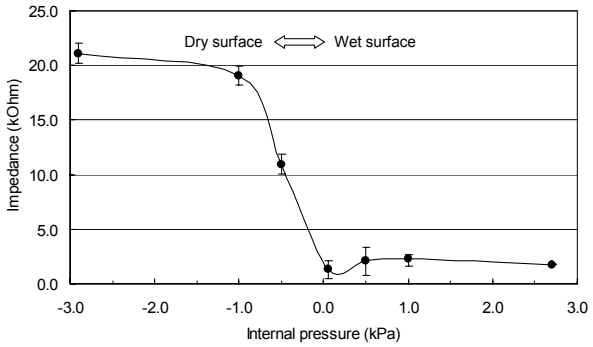

Figure 5. Impedance change measured with the microelectrodes on the surface of the porous ceramic tube with respect to the internal solution pressure.

IV. CONCLUSIONS AND FUTURE WORK

The microsensor works effectively in the presence of water film. These results suggest that the microsensors are capable of determining dissolved oxygen concentration on the porous tube surface, where the sensors stir-sensitivity would be minimized, yet would ensure maximum sensitivity. Additionally, the impedance microelectrodes for wetness detection in the porous tube system is discussed. The microelectrodes clearly differentiates between wet and dry surfaces, which suggest that the microelectrodes are capable of determining porous media wetness on the porous tube surface.

These microsensors and microelectrodes could be employed to measure oxygen concentrations under standardized conditions and wetness levels in a variety of fluid delivery systems that are being developed as in Figure 1(b). Direct control of the root zone environment is possible with the microsystem with the integrated microsensor and microelectrode arrays monitoring the rhizosphere *in situ*.

The proposed microsystem is a new development for plant science research based on microfabrication and

microfluidic technologies. Applications of this system will be broad across plant root research including: abiotic stress-physiology, biotic stress and plant pathology responses, symbiotic nitrogen metabolism, and “rapid prototyping” of phytoremediation technologies.

V. ACKNOWLEDGEMENT

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