Ground-based Characterization of Plant Water Management (PWM) Hydroponic Root Modules for Spaceflight

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INTRODUCTION

Hydroponic crop production in space is crucial for long-term space travel but faces numerous challenges – one of which is providing sufficient dissolved oxygen (DO) in nutrient solution. In microgravity environments, surface tension is the primary force acting on liquids, causing water to form into suspended spherical droplets. This can suffocate plants as the liquid clings onto plant roots and the lack of aeration deprives the plant of oxygen needed for growth (Fig. 1). To overcome these challenges, plant water management (PWM) systems explore options of growing plants in space autonomously and passively through capillary forces. From 2018-2023, there have been 6 PWM experiments conducted on the ISS (Fig. 2) (1). In past experiments conducted in microgravity, bubbles formed in test cells have disrupted fluid dynamics and may adversely affect plant growth (2). The accumulation of bubbles may lead to inconsistent nutrient delivery, break prime in tubing, and suspend plant roots in air, leading to plant stress and eventually death. Current research efforts focus on the oxygenation capabilities of the PWM system along with a comprehensive sensor array that will improve nutrient and DO monitoring capabilities.

Fig. 1. ISS006-E-44970 (9 March 2003) --- A closeup view of a water droplet on a leaf on the Russian BIO-5 Rasteniya-2/Lada-2 (Plants-2) plant growth experiment, on the International Space Station (ISS).

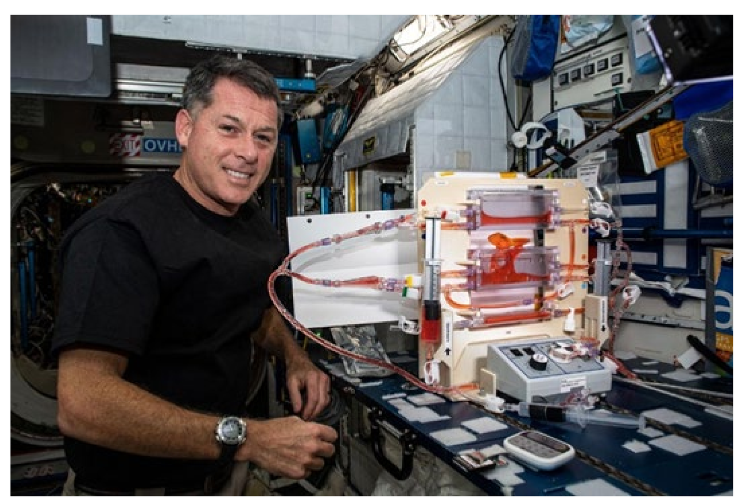


Fig. 2. ISS065E074538 (May 27, 2021) NASA astronaut and Expedition 65 Flight Engineer Shane Kimbrough conducts cylinder test channel operations for the Plant Water Management experiment.

METHODS AND MATERIALS

To evaluate the oxygenation capabilities of the PWM system, the OXYbase DO meter (Presens Precision Sensing, Regensburg, Germany) and flow sensor (Clarksol Solutions, Hudson, MA) were installed to monitor the flow rate. Oxygen in the system was displaced by introducing gaseous nitrogen to the system. Once the system was saturated with nitrogen, oxygenation rate and DO% were measured by allowing the system to run with and without engagement of the aeration module. All tests were conducted under 1-g conditions.

OXYGENATATION CAPABILITIES OF THE PWM SYSTEM

The O_2 transfer rate ($\frac{dC_{soln}}{dt}$) in a non-respiring system is related to concentration difference between saturated and actual concentration of dissolved O_2 in bulk solution by the volumetric liquid phase mass transfer coefficient (kLA).

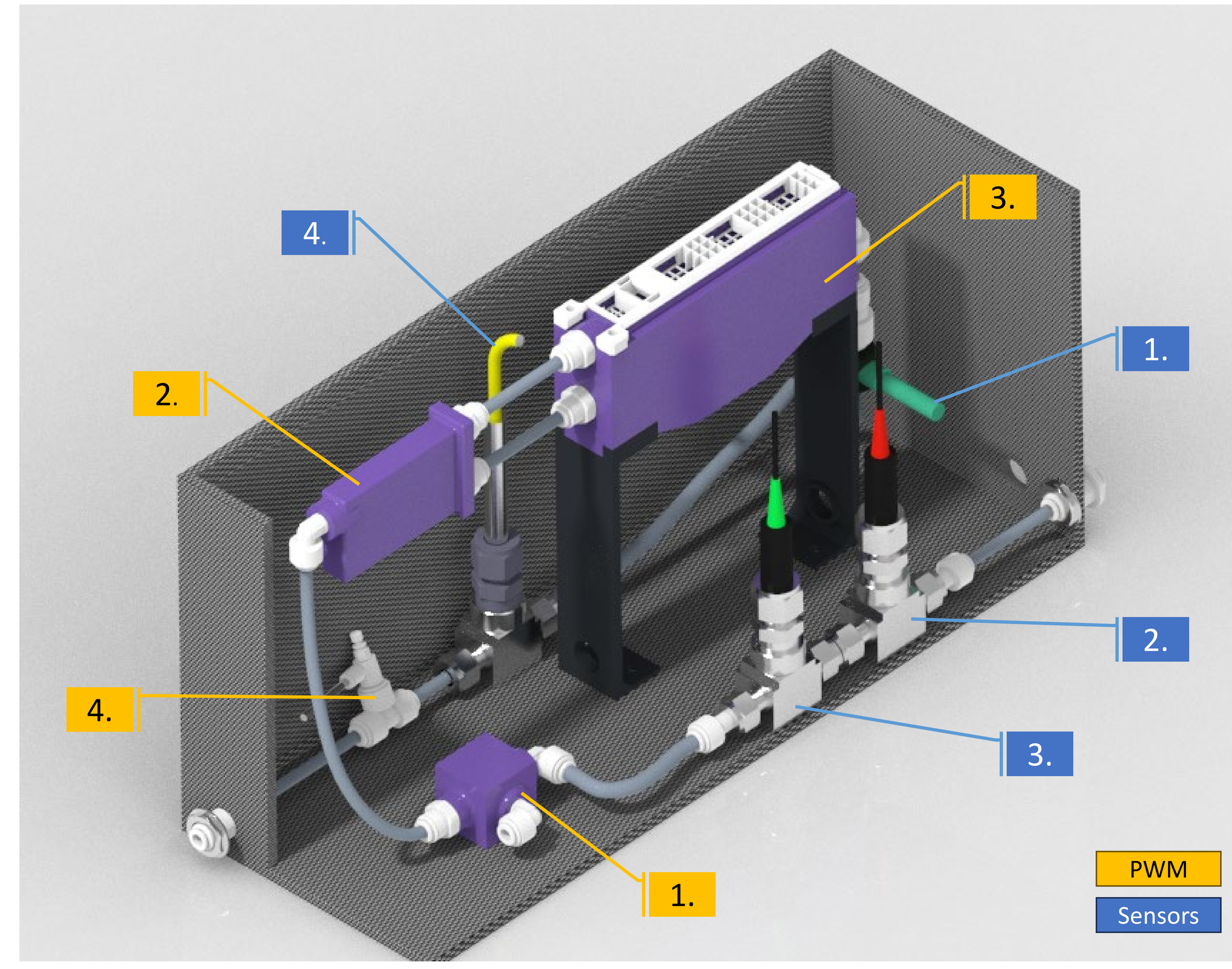
$$\frac{dC_{soln}}{dt} = kLA * (C_{sat}(\text{Tsoln}) - C_{soln}) \qquad (1)$$

In a non-respiring system with a fast response O_2 sensor, assuming $C_{soln} = 0$ at t = 0, the following equation yields where the slope equals $-kLA$ in a plot of ln($\frac{1-C_{soln}}{C_{sat}}$) vs. time (3).

$$\ln\left(1 - \frac{C_{soln}}{C_{sat}}\right) = -kLa * t \qquad (2)$$

To determine the O_2 transfer rate with plants growing in the system, the root respiration rate (Rr) is accounted for, and the oxygenation capabilities of the PWM system can be modeled for future PWM system operations using the modified equation.

$$\frac{dC_{soln}}{dt} = kLA * (C_{sat} - C_{soln}) - Rr \qquad (3)$$



#	PWM Parts
1.	Bubble separator
2.	Bubble diverter
3.	Test cell
4.	Aeration module

#	Sensor
1.	Flow sensor
2.	pH sensor
3.	EC sensor
4.	DO sensor

Fig. 3. A CAD model of the PWM system and list of PWM parts and sensor names.

PWM SYSTEM COMPONENTS

The PWM system can be categorized into two subsystems: the PWM hydroponic subsystem and the sensor array. The PWM hydroponic subsystem comprises of five main components: water pump, capillary bubble separator, bubble diverter, aeration module with a needle valve attachment, and the test cell (Fig 3.). The sensor array contains a flow sensor, a DO sensor, a pH sensor, and an electroconductivity (EC) sensor (Fig 3 & 4.).

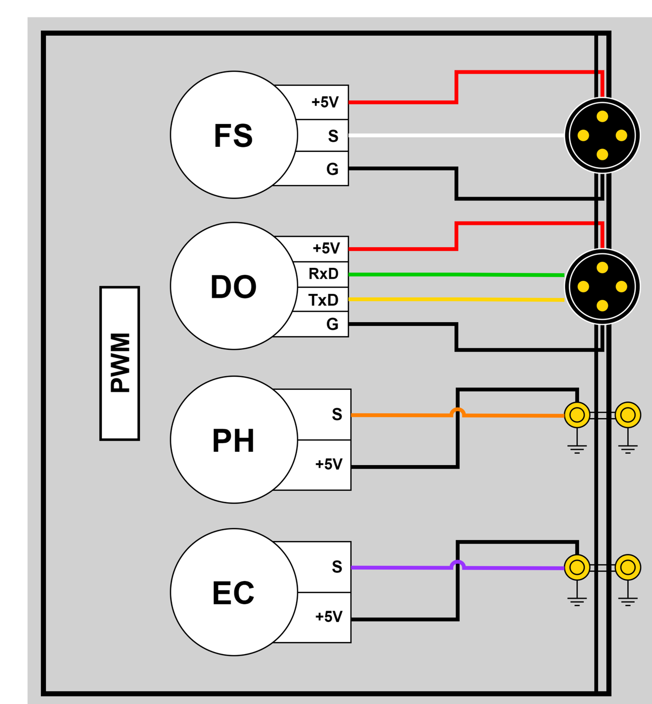


Fig. 4. A diagram of main sensors used to determine nutrient solution quality and flow rate.

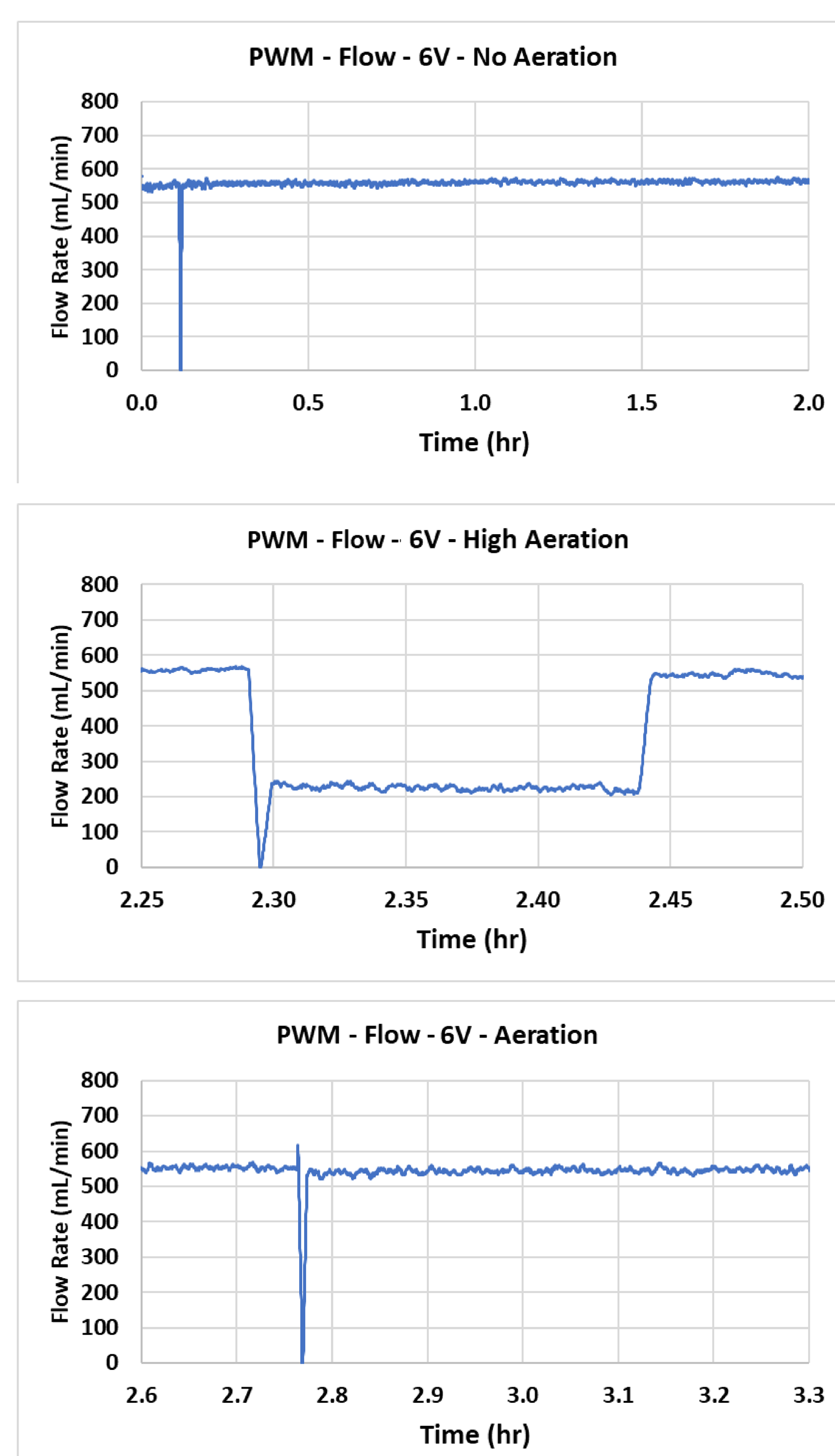


Fig. 5. Aeration levels (no aeration, high aeration, and aeration where there is slight module engagement) plotted as a function of flow rate over time.

RESULTS

- High Aeration:
  - Liquid flow rate decreases when there is high aeration (approx. 400mL/min gas flow rate) to just above 200mL/min (Fig. 5.).
- Without aeration and with slight aeration
  - Liquid flow rate hovers below 600 mL/min
  - All experimental runs with aeration, regardless of intensity, reach near 90% in DO2 concentration in less than 0.25 hours (Fig. 6).
- Once kLA is determined using equation 2 (table 1), the O_2 transfer rate can be modeled (Fig. 7).

Aeration Run	C_{sat}	kLa	T_{avg}
6 V no aeration	77.20	2.50	24.66
6 V high aeration	93.30	59.16	23.48
6 V aeration	91.30	13.02	24.13
7.5 V no aeration	88.00	0.89	26.05
7.5 V aeration	89.90	5.36	26.25

Table 1 Summary of O_2 transfer rate (C_{sat}), kLA, and average temperature of tests with 6 or 7 V, and varying aeration levels.

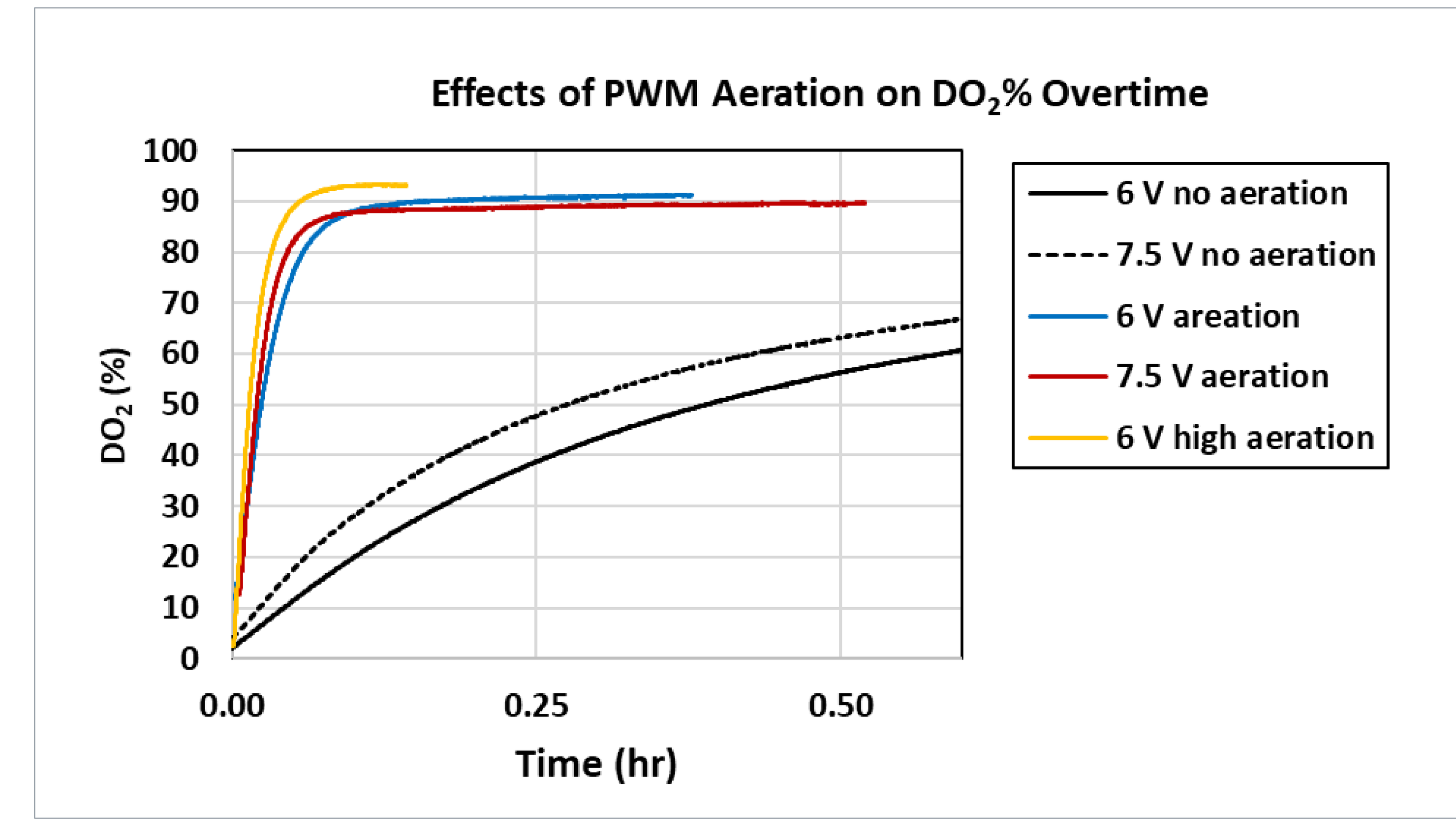


Fig. 6 Effects of aeration on DO_2 overtime in the PWM system.

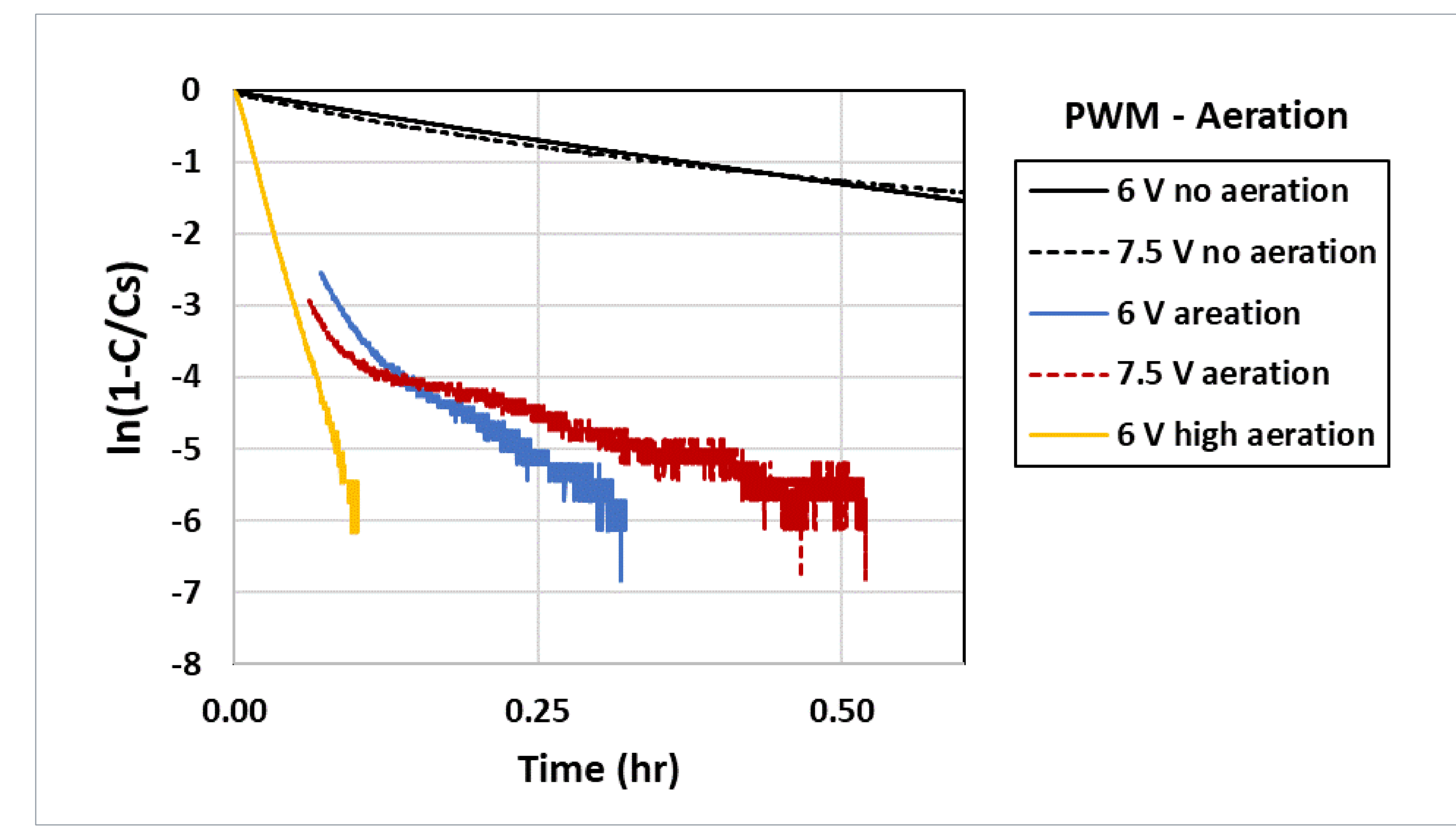


Fig. 7 O_2 transfer rate modeled with determined liquid mass transfer.

DISCUSSION & FUTURE RESEARCH

Exploring the capabilities of the PWM system provides future researchers with foundational knowledge and expands current technology and knowledge for space crop production in microgravity environments. Immediate future work will focus on identifying parameters of the PWM system beyond oxygenation, such as dynamic sensing and hardware compatibility testing. The potential for future experiments with the PWM system is vast – aeration of PWM systems in supporting plant growth, crop-system compatibility, and characterization of the PWM system with plants in a microgravity environment. The PWM system will undergo continual iterations and improvements with the aim of full integration into a space crop production system for long-duration space exploration missions.

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ACKNOWLEDGEMENTS

PWM was funded by NASA's Biological and Physical Sciences Division and by the ISS Program Office.