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Omni-gravity Hydroponics System for Spacecraft

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Overview

On earth, spilling a glass of water is predictable: the fluid will spread out across the table and drip onto the floor until it reaches its lowest energy state. In space, however, everything changes—fluids are no longer dominated by gravity, but rather by surface tension, electrostatic and other forces often negligible on earth. Understanding fluid behavior in the absence of gravity is of particular interest to NASA as there is currently a need to water and grow food on the International Space Station.

Effective omni-gravity hydroponics will allow astronauts to supplement nutrition with fresh fruits and vegetables as well as help close the life cycle of water in orbit as well as in lunar and Martian conditions.

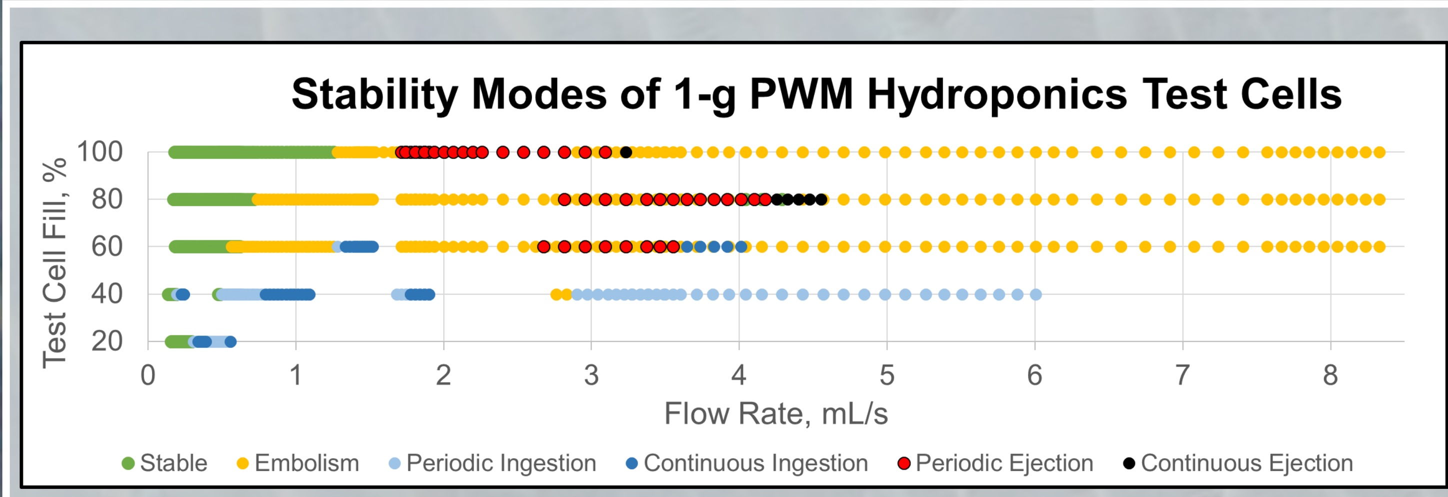
To survive, plants need nutrients and oxygen-rich water delivered to the roots. Unfortunately, bubbles in space do not simply rise to the surface. Coalescence on earth is driven by gravity-induced buoyancy. In the absence of such buoyancy, researchers at the Dryden Drop Tower and NASA have developed open channels that replace the role of gravity with the combined effects of surface tension σ, wetting forces, and channel geometry. The flow rate Q and liquid profile are related by [2]

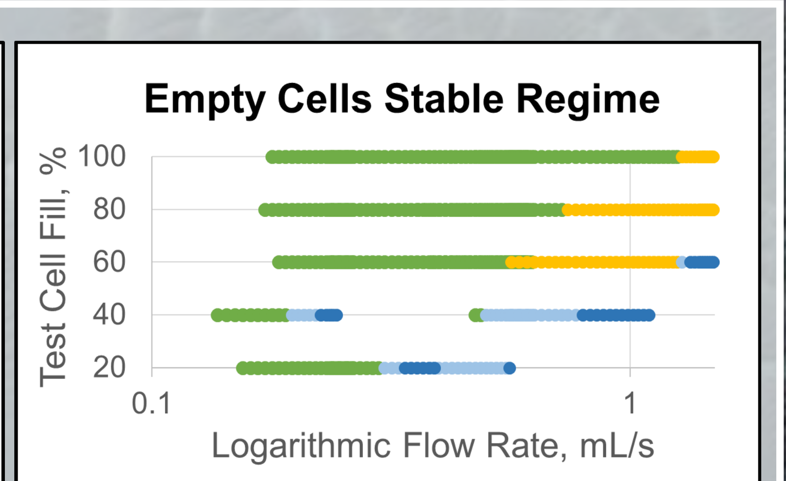
$$Q = \frac{\sigma}{\mu}\frac{F_A H_1^3}{3L}\frac{F_i \sin^2\alpha}{f}\left(1-\left(\frac{H_2}{H_1}\right)^3\right)$$

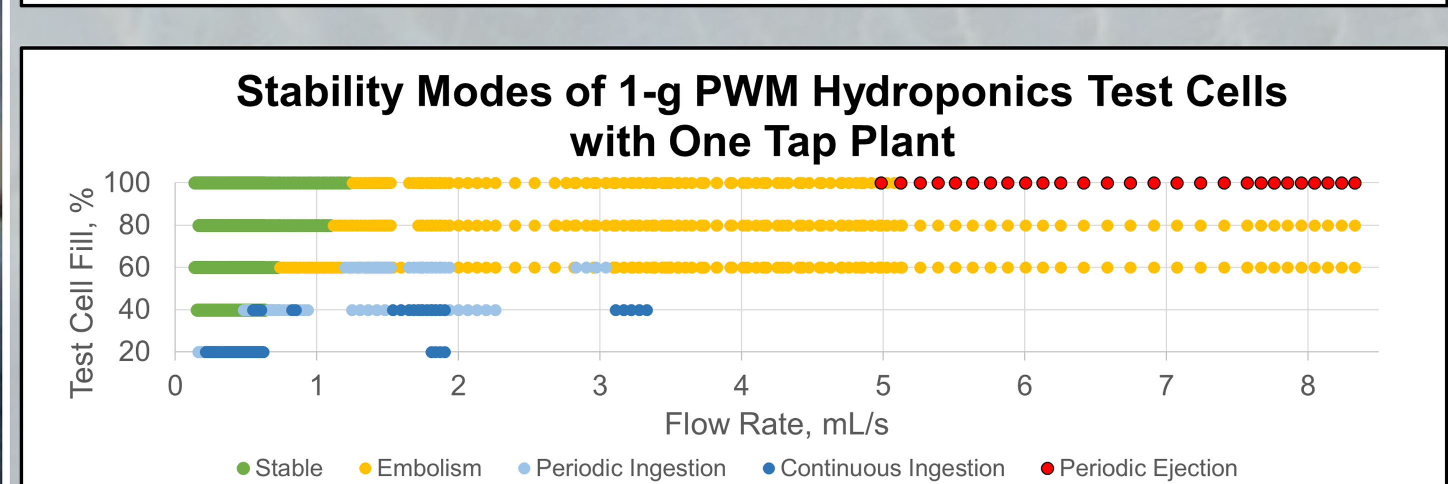
where μ is dynamic viscosity, α is the interior channel half angle, F_i is a dimensionless flow resistance parameter, F_A and f are dimensionless area and free surface curvature functions, and H_1, H_2 describe the inlet and outlet liquid profile heights, respectively.

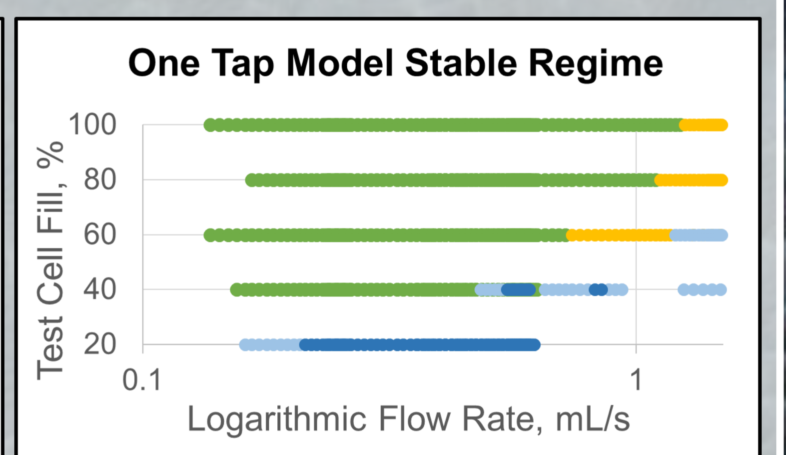
This project seeks to find the limits of operation of these geometries and identify failure modes that could pose a safety risk in space, ideally leading to the development of a successful semi-passive, self-aerating hydroponics system driven by such capillary forces.

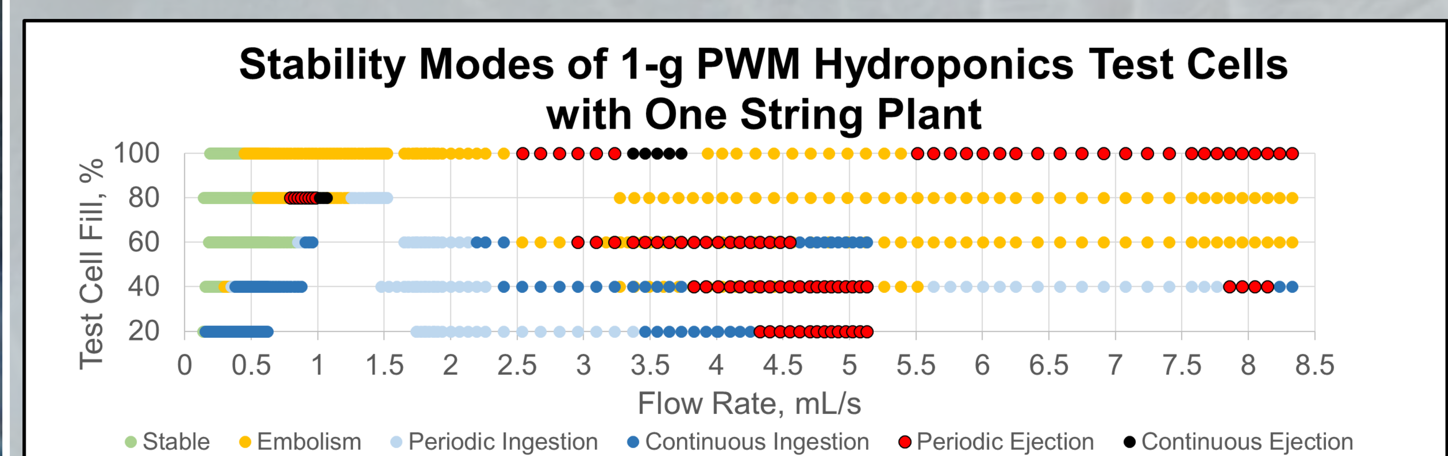
Data Summary

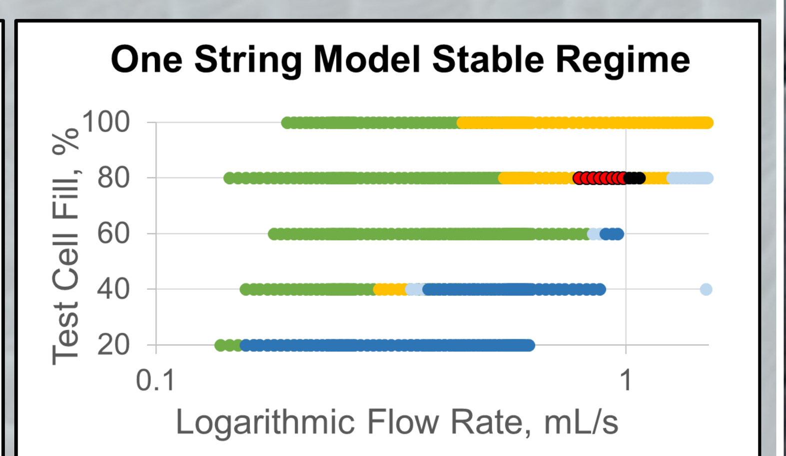












Several key limits of operation were identified and are plotted above as a function of fill percentage and flow rate with a detailed view of corresponding logarithmic stable regimes on the right. Higher fills can withstand more flow, however as plants are introduced and the flow is disrupted, stable operational limits decrease dramatically. Embolism formation, as shown in Figure 2C, could produce either stable or unstable free surfaces as they vary in size. It is important to note that while testing with plant models, some embolisms may have ejected droplets that were reabsorbed due to collision with the model stem or foliage.

Experiments & Results

To determine the long duration operational limits of the Plant Water Management Hydroponics for space operations, a scaled 1-g channel was designed to mimic full-scale performance in microgravity that could be tested terrestrially. Designed by Rihana Mungin, the Formlabs V4 SLA 1-g test cells were 3D printed at Portland State University. Each cell was tapped, fitted with lure lock connectors, and sealed with Teflon tape. Figure 1 shows the 1-g test cell schematic with a detailed view of the superhydrophobic textured surface coated with CYTONIX WX-2100™. By minimizing the Bond number *Bo* and performing experiments horizontally, the effects of gravity are minimized, surface tension phenomena dominates, and 'low-gravity' conditions are simulated, where

$$Bo = \frac{\Delta\rho g L^2}{\sigma} \ll 1 \qquad \rho, \text{fluid density} \quad L, \text{characteristic length}$$

A tube harness was constructed to closely model the hardware for the upcoming Plant Water Management hydroponic technical demonstration on the International Space Station. The fill procedure ensured that no bubbles were introduced prior to operation. The harness included modular adapters for a peristaltic pump to drive flow rates between 0 and 8.33 mL/s. Model plants were saturated prior to insertion into the channels to ensure fill levels were not distorted.

At lower fills, the downstream liquid profile approached bubble ingestion on the outlet as flow rates increased, shown in Figures 2A and 2B. At higher fills, embolisms form as shown in Figure 2C, indicating a trend toward instability. In some configurations, mass ejections occurred as inertial forces overcame capillary forces, shown in Figure 2D, which corresponds to Weber numbers

$$We = \frac{\rho v^2 L}{\sigma} > 3 \qquad v, \text{fluid velocity}$$

In the 1-g test cell demonstrations, new stability regimes were identified. This phenomenon is independent of the effects of gravity, and therefore must be taken into consideration as an upper limit to operation in space. As plants are introduced to the system, the roots disrupt the flow even further, causing droplet ejections at lower flow rates. These regimes will provide the foundation for experiment crew procedures and safety protocols. The first flight demonstrations will launch aboard Space X-18 in July 2019.

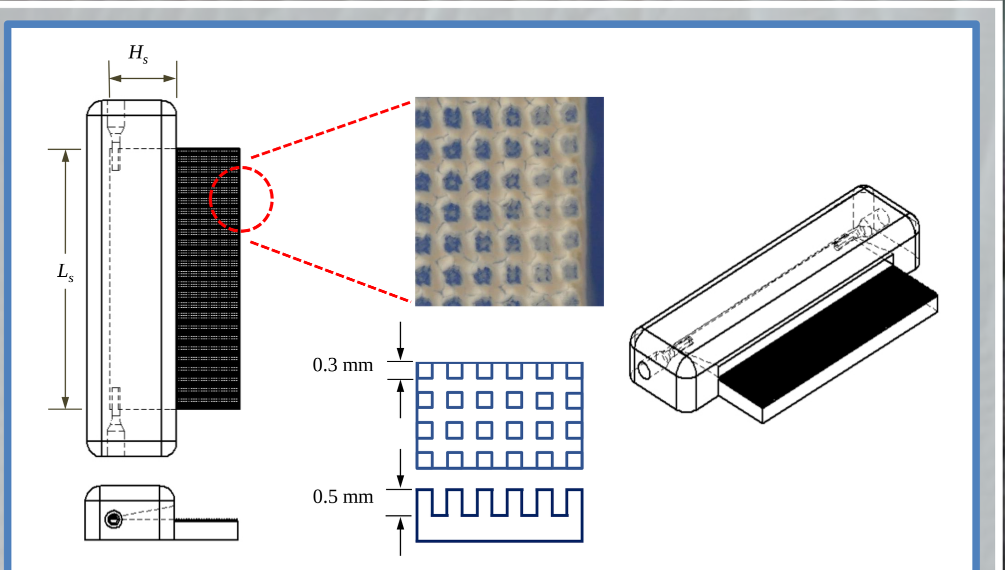


***Figure 1**: 3D Printed 1.55 mL 1-g test cell, designed with textured superhydrophobic surface [1]*

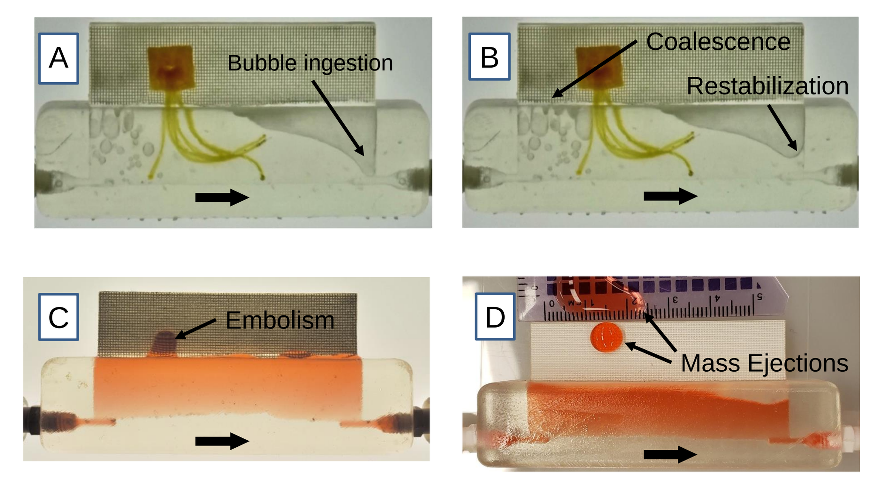
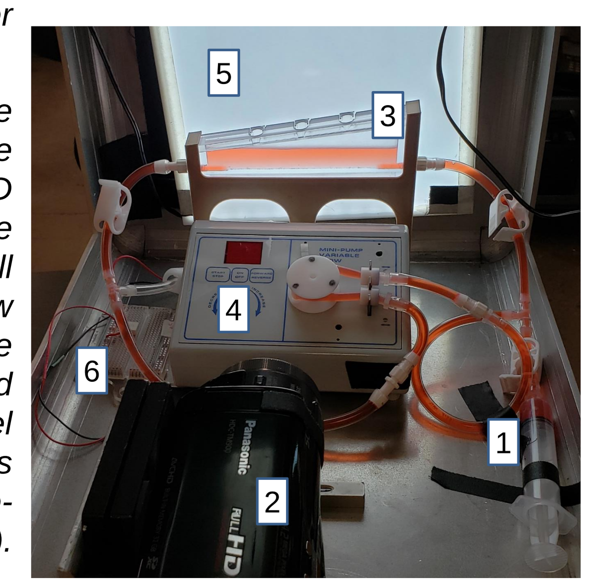


***Figure 2**: 1-g test cells during (A) Bubble ingestion [1], (B) Re-stabilization and coalescence [1], C) Semi-stable liquid embolism, (D) Mass ejections*

***Figure 3**: Drop tower test apparatus*

After priming the system with syringe reservoirs (1), an HD camera (2) will take video of the test cell liquid profile (3) as flow is driven by the peristaltic pump (4) and backlit by a light panel (5). The flow rate is controlled by a voltage-regulating circuit (6). Batteries not pictured.



Future Work & Acknowledgements

- Further data collection and analysis will be conducted for 1g tests with simulated plants with both tap and string root models.
- Drop tower experiments with the full-scale hydroponic test cell, shown in Figure 3, will be performed in the coming weeks to confirm the terrestrial long-duration test results. Simulated plants will be scaled up to check operational limits in disrupted flow.
- Once stable operating limits are confirmed, further control of oxygen intake and delivery to plant roots will be investigated. Plant needs vary, which requires the system to self-regulate to keep a constant supply of nutrients, water, and gases available to the plant roots.
- Flight demonstrations aboard ISS are schedule for 2019 which will provide first confirmation of models developed herein.

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I also wish to thank Christof Teuscher and the Undergrad Research and Mentoring Program for providing this opportunity.

[1] Mungin, R., Weislogel, M., Hatch, T., and McQuillen, B., "Omni-gravity Hydroponics for Space Exploration," 49th International Conference of Environmental Systems, ICES-2019-242 (not yet published).
[2] Weislogel, M. M., "Capillary Flow in an Interior Corner," NASA TM-107364, Nov. 1996.

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