Design of a Microgravity Aeroponics Root Chamber

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Abstract

Deep space crewed missions are rapidly becoming the focus of space missions. With such long-duration missions, a major challenge is resupply, in particular the provision of fresh food for crew dietary requirements. Plant cultivation in space is one such enabling technology. Previous and current cultivation techniques primarily use soil or bead matrices and/or porous tube systems. One problem in these systems is non-uniform water distribution to the root zone, resulting in lower plant yields. As such, this paper develops a design for a microgravity aeroponics root chamber. Even though, aeroponics is a well-developed system terrestrially, it has not yet been tested in-orbit. Some tests have been conducted on parabolic flights, where issues with root asphyxiation were found. This paper is designed to overcome these issues, and also help improve practical aspects of plant cultivation in space. For initial testing purposes, the size of the box is aimed to fit inside a mid-deck locker on the ISS, including other components such as pumps and a water tank.

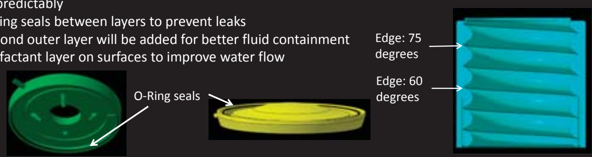
Aim

To enable more practical plant cultivation systems in microgravity, to provide fresh food and psychological support for astronauts. And to develop an aeroponic system that should be able to provide uniform water distribution to the root zone of plants.

Design

3-Section Box

- Designed for 3-D printing
- Multiple sections allow for easier manufacture and access for maintenance as root system can grow unpredictably
- O-ring seals between layers to prevent leaks
- Second outer layer will be added for better fluid containment
- Surfactant layer on surfaces to improve water flow



Edge

- Larger dihedral angle in lower half of mid-section helix, to direct water flow by means of capillary pressure

Meshes

- Act as barrier to prevent root growth into drain holes
- Create layer of water near root tips, to act as buffer in-case of insufficient watering to root zone
- Detachable mesh and supports

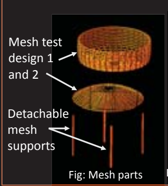


Fig: Mesh parts

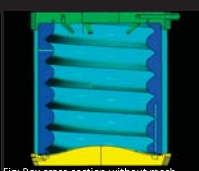


Fig: Box cross-section without mesh

Air Jets

- Direct misted water towards root zone
- Dislodge excess water from root zone
- Provide oxygenated air for roots
- Valves on jets prevent water flow back into air jets

Pumps

- Suction pump at drain helps create pressure gradient to remove fluids (both air and water)
- Low suction pressures required. Pressures of -250 to -1250 Pa shown to produce best plant performance in capillary tube experiments
- Mister and Air pumps, and suction pump control fluid in/out mass balance, hence helping to maintain root zone pressure

Small Box Size

- In microgravity, roots are not required for support, therefore the aim is to maintain a small but efficient root zone, by supplying sufficient but not excessive water

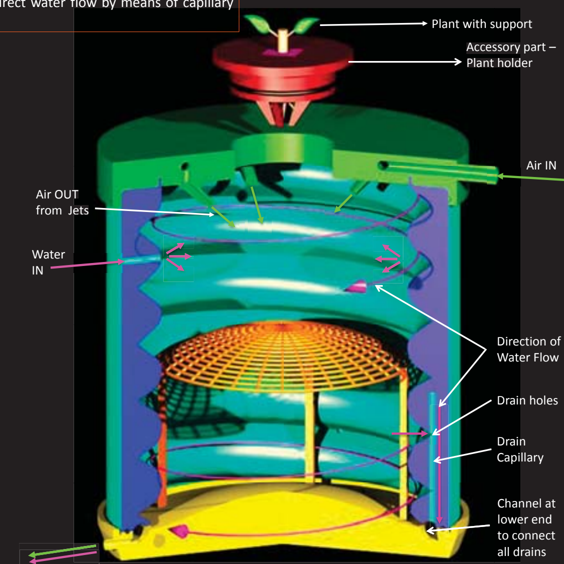


Fig: Root Chamber / Root Box

Misters

- Channels/holes to feed high pressure pipes to the misters. As box is 3D-printed, attaching misters directly to pipes instead of the box creates a more secure connection and it is easier to replace the misters
- Research suggests best droplet size in 1g environment is approximately 30 µm, for effective impingement into root zone


Fig: Example mister nozzle. (Retrieved from: https://www.amazon.com/Orbit-10106-Stainless-Nozzle-5-Pack/dp/B000A16TE0)

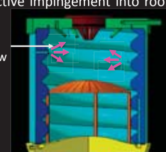


Fig: Mist droplet flow directions

Drains

- Capillary effect to collect and direct water towards drain pump
- Drain holes on side of box further from root zone to allow water to be distributed throughout the box before removal
- Small drain capillary diameter facilitates movement of water out of root zone section

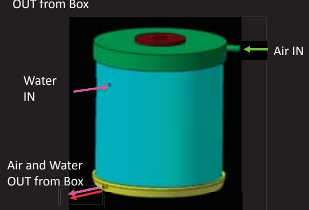


Fig: Box design

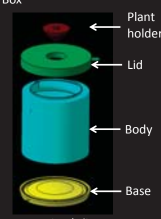


Fig: Box sections' alignment (not showing mesh)

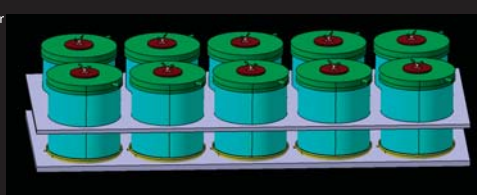


Fig: Example of multi-box system

Design Inspiration and Theory

The inspiration for this design comes from the Zero Gravity Coffee cup, which used the design theory behind rocket fuel tanks. Concus and Finn described this effect in 1974, where the fluid surfaces represent the state of minimum energy. The fluid must penetrate into a solid edge if :

$$\alpha + \gamma < \pi/2$$

This is the Capillary Effect, which is the basis of my design. The flow is towards decreasing capillary height, due to capillary pressure.

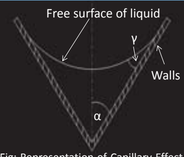


Fig: Representation of Capillary Effect. (Adapted from Langbein, 1990.)


Fig: The International Space Station. (Ranger, 2017. *The ISS just got its own Linux supercomputer.*)


Fig: Astronaut Don Pettit, aboard ISS, drinking from Zero Gravity Coffee Cup. (Phillips, 2013. *The Zero Gravity Coffee Cup.*)

Why Use Aeroponics

Aeroponics is the intermittent spraying at regular intervals of a mist of hydroponic solution onto a plant root zone. It is a tried and tested method, widely used in terrestrial applications.

- Should provide a uniform distribution of water throughout root zone, with precise root zone moisture control, which results in faster root growth
- Better stress resistance of plant roots compared to continuous fogging/watering systems
- Does not require extra medium such as bead beds or growth mats, reducing transport **weight**, and reduction of (disposable) **waste** material and costs, and easier to upscale from test phase
- Limits disease transmission between plants
- Easier sterilization and liquid replacement compared to hydroponic systems
- Easier to study root growth

Disadvantages:

- More complex systems
- Previous experiments have shown reduced water control in microgravity compared to other system

Testing

The box will be tested in microgravity environment initially in a drop-tower, i.e. ZARM. Initial testing will focus on the behaviour of water within the box in microgravity. The testing phase of the box will involve five major criteria:

1. With and without roots (simulated by wires or strings) to test effect of root systems
2. Roots of different sizes to test water distribution at different stages of the plant cycle
3. With and without mesh, to see effect of mesh on water flow
4. Different meshes to test how the meshes interact with the root systems
5. Different mister droplet sizes, water pressure/velocities to test penetration of mist droplets into root zone

Possible Future Modifications

- Sensor feedback system to control pumps' duration and intervals, instead of timers for pump
- Coupling of multiple boxes to single pump could potentially improve energy efficiency of the system
- Initial tests with single plant per box to study fluid distribution and absorption in root zone. Larger boxes with multiple plants can be later designed to improve space utilization
- Current design is a rigid structure, however future models could be expandable/collapsible units
- Possible use of electrolysis in box system to provide oxygen to root zone

References

- Langbein, 1990. *The shape and stability of liquid menisci at solid edges.*
- Clawson et al. 2000. *Re-examining aeroponics for spaceflight plant growth.*
- Hoehn et al. 2000. *Microgravity root zone hydration systems.*
- Weislogel et al. 2011. *Quasi-steady capillarity-driven flows in slender containers with interior edges.*

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