NASA Drop Tower Challenge: Paddle Wheel

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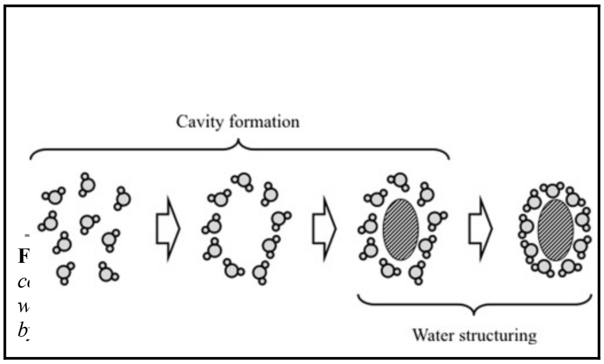
ABSTRACT

Microgravity presents unique challenges and opportunities for fluid manipulation and passive propulsion systems. This study explores the role of wetting phenomena, specifically capillary action, adhesion, and cohesion, in generating motion within a short-duration microgravity environment. Two paddle wheel designs were tested in a 2.2-second drop rig simulating microgravity: one composed of dry sponges (Paddle 1), and another utilizing 3D-printed paddles coated with hydrophilic and hydrophobic surfaces (Paddle 2). Both designs were exposed to varying initial water levels across two drop tests. Results indicate that Paddle 1 consistently produced greater angular displacement and more complex motion patterns than Paddle 2. Notably, Paddle 1's second drop showed a reversal in rotation direction mid-drop, correlated with water uptake by the sponge and the corresponding shift from hydrophilic to hydrophobic behavior. These outcomes demonstrate that capillary action in a microgravity setting can induce meaningful mechanical responses without reliance on external power sources. The findings offer promising implications for sustainable propulsion strategies in spaceflight, suggesting that passive systems leveraging liquid redistribution could reduce dependence on fuel-based methods, lower launch emissions, and support long-duration missions through more efficient resource utilization.

I. INTRODUCTION

The "iceberg model" is a suggested molecular structure of water that attempts to explain the thermodynamic reaction that occurs when nonpolar molecules come in contact with water molecules. This theory proposes that water forms a more ordered structure when combined with nonpolar molecules. Frank and Evans, the creators of this model, even went so far as to say that the molecular structure of water becomes ice-like or quasi-solid when this mixture is formed [2]. Although the idea from 1945 that water procures a frozen state when a nonpolar molecule is introduced has been disproven by modern-day science, Frank and Evans' theory of water's molecular structure was groundbreaking for introducing hydrophobics and hydrophilics.



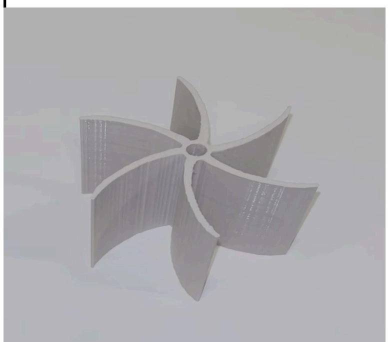
Walter Kauzmann was the first to officially introduce the hydrophobic effect in 1959. His explanation included the theory that hydrophobic solutes constrict water molecules' movement, decreasing their entropy [5]. As recognized by the second fundamental principle of physics, atoms inherently move towards states of increased entropy, indicating a repulsion from these hydrophobic interactions. Hydrophilic tendencies are often explained by the polarity of a substance and its readiness to bond with water molecules' hydrogen atoms [1]. The more unshared pairs of valence electrons a molecule has that are able to form a hydrogen bond, the more likely it is that the molecule will be "water-loving."

The understanding of hydrophilic and hydrophobic tendencies has many facets and quite a few accepted scientific explanations. However, the molecular behavior of water in microgravity is a somewhat modern and unexplored field. It is known that water, when entering an environment with microgravity, reacts by forming spherical droplets. This reaction is due to the water's molecular tendency towards cohesion, which induces surface tension. With the lack of gravity in this hypothetical environment, this surface tension becomes the dominant force. Using this surface tension force and the basic hydrophilic and hydrophobic tendencies has the potential for energy production and controlled movement. According to Dmitrii V. Antonov of the National Center for Biotechnology Information, using hydrophobic substances to create microfluidic channel walls allows scientists to direct the flow of water-based fluids precisely [1].

The use of sponges in relation to hydrophilics, hydrophobics, and microgravity is widely unexplored as well. The concepts that this experiment is based on include: adhesion, cohesion, and capillary action. Adhesion is the ability of water to stick to other substances or surfaces. Cohesion is the ability of water molecules to form hydrogen bonds with one another. Capillary action is the movement of liquid through porous materials due to the combination of cohesion and adhesion [2]. These concepts will be put into action with the use of sponges on our wheel. The discussion section will explain how these theories impact our paddle wheel's movement.

II. MATERIALS AND METHODS

Wheel Design



Two paddle wheel designs were created to investigate fluid dynamics and behavior under microgravity conditions. The experiment focused on the rotational motion of a paddle wheel subjected to hydrophobic and hydrophilic interactions. Two distinct paddle wheel designs were tested to evaluate the effect of different treatments on the wheel's rotation in free fall. As shown in Figure 2, the basic paddle wheel design features a central hole with a diameter of 6 mm, allowing the central axis to pass easily through the paddle wheel. Each paddle had a length of 32.5 mm, making the total diameter of the wheel 73 mm. The height of each paddle was 50mm, leading to the entire wheel height being 50mm. It was equipped with six evenly spaced paddles, each exhibiting a slight curvature to maximize interactions between water molecules and surface treatments, facilitating motion in a microgravity environment. Each paddle had slightly ridged surfaces, allowing for easier application and adhesion of the experimental variables to each wheel. This wheel was constructed using a MakerBot Sketch 3D printer that used PLA Filament, a lightweight, plastic material. Four identical wheels were printed- two to be shipped for submission and two to be used for tests.

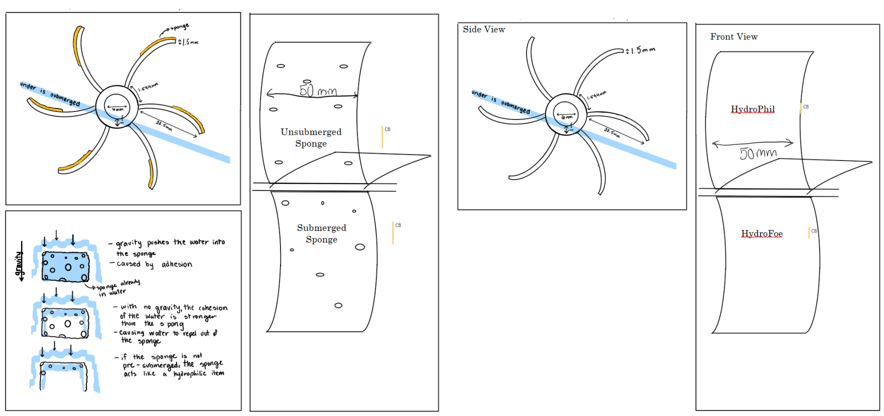


Figure 3 - Wheel Mechanics and Sponge Dynamics: *These diagrams explain the nature in which the adhered hydrophobic and hydrophilic variables affect our paddle's movement. To the left, you can see the diagram of the sponge interactions, and to the right, you can see our coated wheel's construction.*

Surface Treatments

Figure 4 - Sponge Wheel: *Wheel with sponges attached to each paddle*

After the basic wheel was constructed, two variations were developed for comparative analysis. The first wheel incorporated hydrophobic and hydrophilic coatings strategically applied to the paddles, creating distinct wetting properties that influenced fluid behavior upon contact. The hydrophobic coating was a hydrophobic ceramic polymer designed to repel water and have it bead up instead of distributing evenly. The hydrophilic coating used was an anti-fog treatment that has water-absorbing technology that attracts and distributes water molecules evenly across the surface. Figure 3 shows the sides of each paddle on which the hydrophobic and hydrophilic coatings were applied. The hydrophilic-coated sections were expected to attract and retain liquid, whereas the hydrophobic sections were designed to repel water, thus contributing to rotation. The second wheel was designed with sponge materials integrated into the paddles as shown in Figure 4. These sponges served as absorptive elements, allowing water retention and release cycles to play a role in the wheel's rotation. Figure 3 shows the mechanics of sponges under the conditions presented. Water is able to move through the sponge using capillary action, allowing it to soak and release liquid naturally. Since no external energy is needed, this type of passive fluid movement demonstrates a potentially effective way to generate motion in microgravity to help the wheel rotate.

III. RESULTS

Paddle 1 (Sponge-Based Design)

Drop 1:

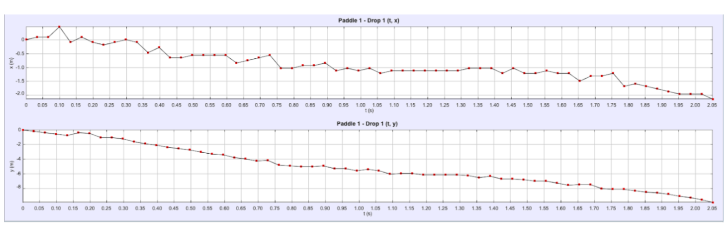


Figure 5: Paddle 1 Drop 1 X and Y Displacement

Paddle 1 had a smooth, predictable trajectory through the first drop. As seen in Figure 5, the paddle traveled 9.949 mm down the x-axis and -2.347 mm up the y-axis and rotated a total of 23° over the course of 2.2 seconds of microgravity. Once microgravity had started, the paddle's motion, with the sole exception of the initial acceleration, was extremely stable. This indicates the reality of microgravity that there was essentially no external force acting against the paddle, with the paddle having to move according to Newton's First Law. What motion did happen almost certainly resulted from how the sponge responded at the start of microgravity. Because most of the sponges were at the 18mm water level, the sudden loss of gravity would have redistributed a small amount of water within the sponge, generating a tiny force to set the paddle in motion initially. Once equalization was established, the internal forces within the sponge became stable, the consequence of which was steady, consistent motion for the remainder of the drop. If microgravity had been prolonged beyond 2.2 seconds, we can reasonably infer that the paddle would have kept moving down the same line of travel and roughly the same sense of rotation without deceleration or cessation. This linear path starkly contrasts with the more dynamic instability of Drop 2, demonstrating the importance of water content and sponge dynamics to free-falling stability.

Drop 2:

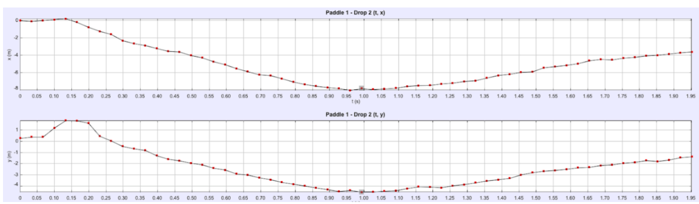


Figure 6: Paddle 1, Drop 2 X and Y Displacement

The second drop had more sudden changes. When the water level was adjusted to 14mm, Paddle 1's motion was reversed halfway through, as seen from the curved graph in Figure 6. The paddle initially rotated counterclockwise, then reversed at the halfway point, and rotated clockwise for the rest of the 2.2-second descent. The x and y displacements support this new motion: first displacing 8.538 mm in a particular way, then reversing back 4.906 mm. Likewise, the displacements of y are from -4.811 to 1.509. The angular displacement was 20.3° counterclockwise before the direction changes. This flip suggests an unstable or evolving force throughout the fall, possibly caused by uneven fluid expulsion or redistribution within the sponges. Unlike Drop 1, this paddle slowed down to a stop and then accelerated back up in the other direction and continued to accelerate until microgravity ended. This shows how microgravity is a time-dependent behavior and is heavily influenced by the water movement within the sponge. The reduced water level may have exemplified this, making the motion more volatile. The fact that this behavior was not seen in Drop 1 points to the importance of water volume in stabilizing or destabilizing sponge-based motion in microgravity.

Paddle 2 (Coating-Based Design)

Drop 1:

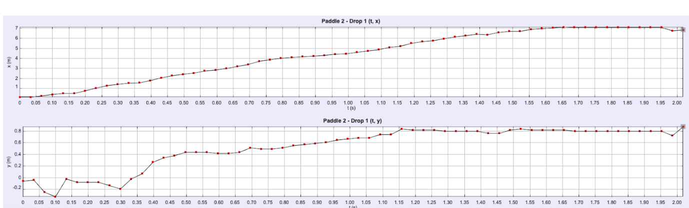


Figure 7: Paddle 2, Drop 1 X and Y Displacement

In the first drop, Paddle 2 had a "slow-then-fast" motion pattern, translating around 6.888 mm along the x-axis and 0.951 mm along the y-axis, with an angular change of 12.7°. This is what would be predicted for an object whose surfaces are chemically asymmetric: hydrophilic (water-attracting) on one side and hydrophobic (water-repelling) on the other. The fluid forces are initially balanced or canceled out, producing little motion. But when microgravity starts, liquid on the hydrophobic side begins to recede, whereas the hydrophilic side retains water, likely leading to a distortion in fluid distribution. This slowing of movement and the following acceleration reveals a lag in interaction between the surface and water as microgravity disrupts usual gravitational drainage. The raised water level in this drop (18mm) likely augmented contrast among surface behaviors, exposing more liquid to interaction and thereby creating more rotational torque over time.

Drop 2:

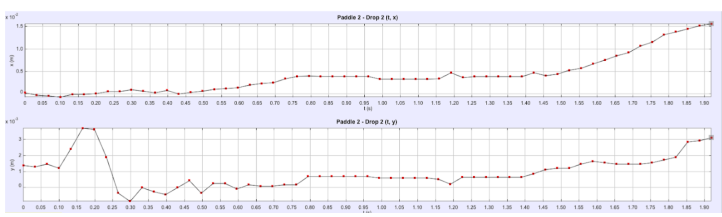


Figure 8: Paddle 2, Drop 2 X and Y Displacement

In the second drop for Paddle 2, the device was tested at a 14mm water level. The movement in microgravity was very minimal and similar to the first drop. The x and y displacements were minimal, with the paddle moving 1.499 x 10^{-2} mm and 1.951 x 10^{-3}mm respectively as seen in figure 8. The paddle rotated only 7 degrees, indicating that little force was acting on the device. Like the first drop, the motion started slowly and then increased slightly, but overall was very limited. The consistency between the two drops suggests that Paddle 2's design (hydrophobic and hydrophilic coatings with no sponge material) wasn't very effective at generating motion from wetting forces alone. The surface tension may generate force, but it is not enough to create torque or thrust. This could be because the water level for this drop was lower, causing less water to interact with the paddle surface. Overall, Paddle 2 was unresponsive in microgravity and reinforces the idea that coatings alone may not be as effective as structural changes (like sponges) for motion in this environment.

IV. DISCUSSION

Within our data, we found that Paddle 1 had a greater angular change than Paddle 2. Paddle 1, being the sponge-based wheel, we attribute this angular change to our sponge's capillary action. In test 2, initially, the sponges were empty because the water level was substantially lower than in test 1; because of this, they acted as a hydrophilic or attraction force when exposed to the water. While the sponge was experiencing a gravitational force, this and adhesion kept the water in the sponge. The concept of adhesion plays a role in this test because the water molecules are attracted to the sponge's porous surface. This caused the wheel to move in a counterclockwise direction. Then the experience of free fall reached the simulation of microgravity. Once the sponge was filled with water, it acted as a repelling force because, without the gravitational force, the cohesion of the water molecules was stronger than the adhesion of the molecules with the sponge surface. This caused the wheel to spin in a clockwise direction. This explanation of the wheel's movement is consistent with the results of test 1 with Paddle 1. In test 1, the sponges were already submerged in water because the water level was higher, meaning the cohesion force was at a maximum the entire time. This cohesion or hydrophilic force immediately overpowered the adhesion, unlike in test 2, because the water molecules from the sponge and the pool of water were already in contact.

This new knowledge has far-reaching implications for real-life microgravity applications, particularly using fluid dynamics for resource utilization and sustainable propulsion systems in space. The discovery that strategically placing sponges on a paddle wheel using only fluid interactions to generate movement implies that similar small, controlled interactions can lead to highly efficient systems. For example, these principles could revolutionize water recycling and purification in space, ensuring that long-duration missions have access to essential resources with minimal energy input and consumption. Additionally, this understanding could inform new propulsion mechanisms, where controlled liquid distribution and capillary action could generate motion, rather than conventional engines and thrusters. In the most energy-efficient drop, Paddle 1, Drop 1, the paddle wheel generated 853.939 watts between 1.985 and 2.018 seconds, shown in Figure 9. Water use would minimize the need for fuel, reducing emissions and preventing the accumulation of debris caused by traditional propulsion mechanisms that rely on fuel. These byproducts not only impact space but also the stratosphere of Earth. In 2022 alone, an estimated 1,000 tons of rocket soot were emitted, a quantity that can raise annual global temperatures by 0.5-2°C and slow the subtropical jet streams by 3.5% [4]. Since then, space exploration has only increased as we attempt to make new places habitable. With the traditional systems currently used, the Earth is paying the consequences. At a larger scale and optimized to its full potential, capillary action has the potential to produce enough energy to replace parts, if not all, of the environmentally harmful fuel-based mechanical systems, reducing the significantly detrimental impacts of space exploration on the planet. This transition would represent a major step toward a sustainable future. Starting with space exploration, this discovery has the ability to reduce the ecological footprint of human activity and preserve planetary health for generations to come.

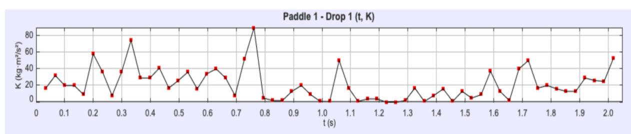


Figure 9: Paddle 1, Drop 1 Kinetic Energy Over Time

V. CONCLUSION

In conclusion, the experiments conducted provided valuable insights into fluid dynamics in microgravity. Initially hypothesizing that the paddle wheel with hydrophobic and hydrophilic coatings would be more successful, the data showed otherwise, proving the effectiveness of capillary action in microgravity. In relation to the very limited drop time, the wheel traveled significantly, implying that, given more time, this wheel design would be extremely practical in producing motion and energy. These findings suggest that capillary-driven mechanisms have the potential to play a crucial role in future space applications, leading to innovative and sustainable designs that enhance spacecrafts and scientific instruments. New possibilities can be unlocked by further investigating these principles, paving the way for advancements in resource management, propulsion, and overall spacecraft efficiency.

VI. REFERENCES

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