

Capillary Fluid Behaviour in Micro-gravity to Guide Innovation of Fuel Tank Geometry

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Abstract

To increase the longevity and reduce risk associated to space missions, there is a need to research the ability to manipulate and leverage fluid motion in microgravity to optimise fuel delivery. There is a connection between the fluid motion and several controllable thermodynamic variables, including temperature, surface energy, and volume. Properties such as these can be either directly controlled or uncontrolled, however this discussion aims to understand how surface energy of the fluid can be manipulated by altering the container geometry. Through determining the direct effect of manipulating geometry and using several controlled variables, the thermodynamic effect of geometry on microgravity fluid movement can be studied. This will provide the basis of future statistically determined research into the effects that can govern the motion of fluid in microgravity.

Keywords: fuel sloshing, microgravity, capillary geometries, fluid, refueling

Nomenclature

V_{water} – Volume of water in the capillary, in millilitres.

V_{cap} – Total volume of capillary in millilitres.

P – Parabola, subscripts indicate specific parabolas.

Acronyms/Abbreviations

Deionized (DI)

Gravity (g)

Isopropyl Alcohol (IPA)

Spinning Drop Tensiometer (SDT)

Rotations Per-Minute (RPM)

1. Introduction

Space-based fuel systems are currently a platform for innovation and research on designing more reliable, cost effective, and safe fuel tank geometries [1, 2]. To optimize these tank geometries, a fundamental knowledge of fluid motion in microgravity is essential. By quantifying the relationship between fluid and specified geometries, the fluid can be manipulated to the required location in a way that minimizes the need for pressurization. This is the basis of the proposed study, where the dynamics of the interface of fluid in a container will be observed in a micro-gravity environment simulated by parabolic flight.

While a parabolic flight experiment will be conducted in mid-May, preliminary experiments to support mission findings are conducted and discussed. During the technical session preliminary parabolic flight experiment results will be presented alongside the supporting experiments. While parabolic experiments will cover utilizing custom borosilicate glass capillaries of pre-determined geometries, the supporting experiments discussed here will cover straight capillaries with a specified diameter. The capillaries will be examined at different rotational speeds, to determine the resulting effects in a ground, Earth gravity, setting.

This preliminary groundwork will be retained to eventually compare to the data collected during the parabolic flight facilitating the investigation of the resulting configurations [3]. The experiment will be flown in a parabolic flight, where each parabolic manoeuvre manages to obtain results in Martian, lunar, and microgravity and 2g accelerations. The interface between the liquid and saturated vapour will be observed during the transition from earth gravity to either micro, lunar or Martian. To add the rotation component to the propellant tank, we also devised another experiment with rotating cylindrical capillaries.

When the parabolic experiment is reviewed and compared to the ground data, it will determine what effect several controllable parameters have on the ability of the fluid system to result in a metastable configuration. These parameters

include, surface energy of the container, the capillary geometry, the volume ratio between liquid and saturated vapour in the container, the system temperature, and the linear as well as angular acceleration of the system [3, 4]. Through control and variation of these parameters in the experiment, and comparison to ground tests, a method of determining the operating point for specific fuel tank geometries can be identified [5-8]. This leads to greater control over the motion of the liquid in each geometric shape, presenting the opportunity for future experimentation.

To achieve the theoretical understanding, the first principal energy minimization thermodynamics approach will be used. Further the parabolic experimental results will be compared with a theoretical model. The determined solution will then be reported to better understand how fluids in vessels act in various gravity scenarios. This approach will enable us to determine which configuration contributes to liquid sloshing in fuel tank and identify the optimal design for mitigating the sloshing effect.

Through the identification of the fluid behaviour due to the parameter changes, operating points can be identified to exploit custom scaled geometries for alternate fuel tank designs. Providing a base of knowledge that allows for exploration as to the optimum custom fuel tank geometry for space-based operation. This would see Canadian research as a leader for innovation of effective space-based fuel tank designs.

2. Material and methods

The apparatus being used in these experiments is the Spinning Drop Tensiometer (SDT), by following the capillary testing procedure the experiments can be performed for the specified fluid volumes, followed by discussion of postprocessing methods. This section also details information on the parabolic experiments expected to be performed in May, including the environmental conditions, and the planned experimental procedures.

2.1 Testing Apparatus

The apparatus used in these experiments is a KRUSS SDT, seen in Fig 1. This device rotates the specified capillary at a given rotational speed, with a minimum increment of 50 rotations per-minute (RPM). This device provides several functional abilities, such as temperature control, angle control of the capillary chamber, temperature control, and backlight intensity. This device provides imagery of the capillary using the cold-source backlight to highlight the fluid interface, leading to a shadow-based image that uses grayscale to highlight the specific fluid locations. These images are then postprocessed using shadowgraphy methods, to help identify key variables that describe the changes experienced by the fluid interface.



Fig. 1. KRUSS SDT, sitting in a vibrationally dampened frame designed for the parabolic flight.

2.2 Capillary Testing Procedure

To use the SDT and collect the necessary data, there are two main steps, preparing the capillary and performing the SDT experiment. Firstly, the preparation of the capillary focusses on how the capillaries are cleaned, looking specifically to ensure there is no interference with the surface of the capillary. Secondly, performing the SDT experiment focusses on how the SDT is prepared and initiated to collect the necessary information.

The preparation of the capillary starts by ensuring that the syringe and borosilicate glass capillary are cleaned, using isopropyl alcohol (IPA). Once this has occurred then the syringe is filled with deionized (DI) water, and the capillary filled with the predetermined amount, and a cap placed at the end to avoid leakage. The outer surface of the capillary is then cleaned with a wipe with a small amount of IPA, then a dry wipe is used to remove any moisture or residue before proceeding with the experiment. The volumes used, and corresponding volume ratios, are seen in Table 1, with the total capillary volume calculated to be 0.4216mL, and a capillary inner diameter of 3.25mm. For the final

comparison, and for the parabolic experiments, the capillaries will be degasified to ensure the fluid interface is as pure as possible.

Table 1. DI water volumes and corresponding volume ratios of a 3.25mm diameter capillary.

Sample	1	2	3	4	5
V_{water} (mL)	0.04	0.10	0.22	0.32	0.38
$V_{\text{water}}/V_{\text{cap}}$	9.49%	23.72%	52.19%	75.91%	90.14%

When the capillary preparation is complete and the experiment is ready to be performed the prepared capillary is placed into the chamber of the SDT, ensuring both the clamp and the chamber lid are secured. Then an automated SDT program is run, which incrementally increases the RPMs from 0 to 5000RPM. Through prior testing, it is noted that, over 5000RPMs the shape of the fluid cannot be tracked in the camera's narrow field of vision. The automated program runs through a connected laptop where the video is recorded to facilitate shadowgraphy postprocessing. This process is repeated for each volume being considered.

2.3 Postprocessing Shadowgraphy

Once the experiments have been performed, they are then analysed through image processing software. The grayscale images are used to highlight the exact point of interface between the fluids. Since the capillary internal diameter, and the pixel width between the capillary walls, Fig. 2, can be related then any measurement taken from the image can be converted to millimetres. Primarily the contact angle of the fluid at the wall, as well as the resulting radii of the interface, determined through chord length and height, are collected to highlight the results.



Fig. 2. Sample image of the air-water interface, with water volume of 0.1mL, and at 4500RPMs.

2.4 Parabolic Flight Testing Conditions

For the parabolic flight the experiments will be performed in a Falcon 20 plane that has a temperature-controlled cabin. The parabola will follow the trend shown in Fig. 3, where the plane experiences between 1- and 2-times Earth gravity (g) forces during the pull-up and pull-down acceleration phases. When the plane enters the microgravity stage, between 0s and 20s period there is approximately $10^{-6}g$. This information on the acceleration profile can be used to inform a microgravity thermodynamic model to provide a comparison to the data that will be collected in May.

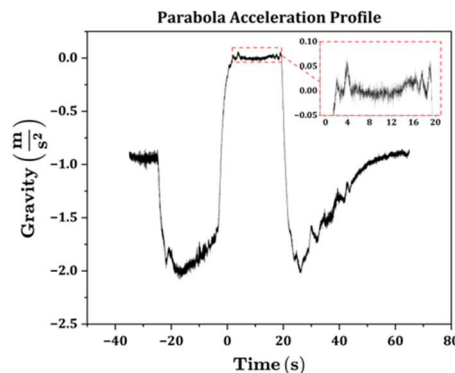


Fig. 3. Acceleration profile of the parabola arc, undertaken to achieve microgravity testing environment.

The parabolic flight will allow for anywhere between 10-15 experimental data collections, with each collection lasting for about 18-20s. This requires a concise and effective plan for the execution of the experiments on the flight. The currently proposed plan seen in Table 2 will utilize the 3 different geometry capillaries seen in Fig. 4, which include the original small diameter straight capillary, the large diameter straight capillary, and the bubble capillary. These geometries will expand on the standard small diameter capillary, providing depth to the understanding of how geometry effects properties and fluid motion. The flight plan varies volume ratio and geometries, while keeping temperature and pressure constant, it should also be noted that parabolas 1-3 are reference cases used to determine the base effect of microgravity on the geometries.

Table 2. Currently proposed parabolic flight plan, showing varied parameters.

Parabola	RPMs	Volume Ratio	Geometry	Parabola	RPMs	Volume Ratio	Geometry
P ₁	0	0.5	Small Straight	P ₉	0-5000	0.7	Large Straight
P ₂	0	0.5	Large Straight	P ₁₀	0-5000	0.3	Bulb
P ₃	0	0.5	Bulb	P ₁₁	0-5000	0.5	Bulb
P ₄	0-5000	0.3	Small Straight	P ₁₂	0-5000	0.7	Bulb
P ₅	0-5000	0.5	Small Straight	P ₁₃	0-5000	0.5	Small Straight
P ₆	0-5000	0.7	Small Straight	P ₁₄	0-5000	0.5	Large Straight
P ₇	0-5000	0.3	Large Straight	P ₁₅	0-5000	0.5	Bulb
P ₈	0-5000	0.5	Large Straight				

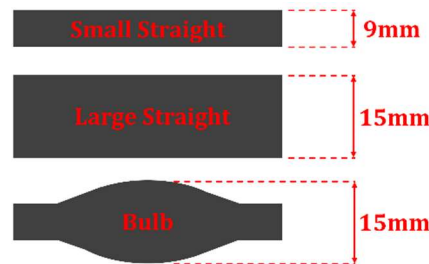


Fig. 4. Capillary geometries, with maximum outer diameters, to be used in parabolic flight experiments.

3. Theory and calculation

The theoretical ideas presented here discuss the application and background associated with the planned experimental procedure. This section also discusses the method of extracting data from the shadowgraph images being recorded as part of the procedure.

3.1 Theoretical extension

The purpose of the outlined parabolic flight experiment is to extend previously published work on fluids in microgravity, to consider both rotational effects on fluid capillaries along with surface energy effects. Previous work has shown, with a focus on interfacial pressure, that fluids can achieve certain configurations in microgravity, along with the effects of microgravity on the fluid behaviour [3-4]. To further this knowledge would require the addition of surface energy effects into the equations, ensuring that a method of determining the effects of non-standard geometries can be mathematically determined.

By developing a thermodynamic model that can encapsulate both microgravity effects and other controllable variables, such as rotational speed, surface energy, and changing volume it is proposed that this may provide a new method of optimising fuel tank geometries. Through development and comparison against a comprehensive set of test data, a distinction will be determined as to the efficiency and accuracy of this model to perform these functions.

3.2 Shadowgraphy Calculation

Two values are extracted from the captured images, firstly the contact angle, between the fluid and the wall of the capillary, secondly the radius of the interface. Any distance from the image is calculated using ratios of the known inner diameter of the capillary, and the measured pixel width between the capillary walls, Fig. 2. This allows for ease

in converting from the image data to the measurement data. The radius of the interface was determined using cord length and height, giving the approximate change in the interface shape as the RPMs increased.

4. Results

The results found from the small straight capillary, are shown in this section, specifically the contact angle and radii of the interface, with different volume ratios. The changing contact angle, Fig. 5, shows a significantly increasing angle as the RPMs increase, while the radii of the interface, Fig. 6, decreases as the RPMs increase.

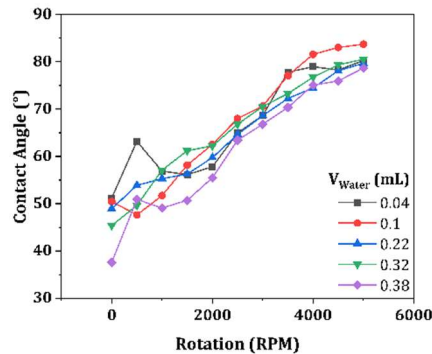


Fig. 5. Small straight capillary's changing contact angle as the RPMs increase.

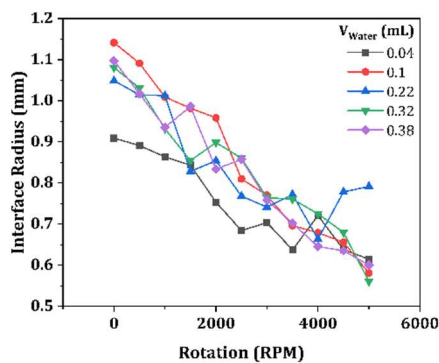


Fig. 6. Small straight capillary's changing interface radius as the RPMs increase.

5. Discussion

The resulting preliminary information found for the small straight capillary shows the change as both the volume increases, and the RPMs increase. It is expected that with an inner diameter of 3.25mm that the results for all volumes would follow a similar trend and have potential overlap. This is because the fluid will be heavily influenced by the capillary effects that govern the interface of the fluid.

The demonstrated results have some variation due to data clarity, causing irregular spikes, but there is still clear change occurring that is influenced by the rotational speed of the capillary. This outcome reinforces the premise of the proposed experiments that varying both geometries, to achieve different surface energy states, along with the rotational speed can potentially advance current understanding of fluid manipulation.

While the parabolic experiment results will be discussed in the future, it is expected that the alternate geometries will have much more variability in their results, as they will not be as constrained by the capillary effects of the small straight capillary. This only furthers the need to perform experiments with varied geometries, as they will provide framework data for expansion to even larger, tank-like, geometries.

6. Conclusions

The results shown here indicate that RPMs directly increase the contact angle and directly decrease the radius of the interface. This is expected but there is still some variation between the different fluid volumes that indicate further experimentation is required to determine what pattern is to be expected from changes in fluid volume.

Future work will focus on testing a completed thermodynamic model, and comparing it to both the ground data, and the data collected from the parabolic flight. This along with testing with more geometries should provide

significant amounts of data to determine with statistical significance whether the fluid can be manipulated through controlling the surface energy, or through rotational control.

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