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Paper Session III-D - The Effects of Hydrophilic and Hydrophobic Coatings and Container Shape on Fluids and Containers in a Microgravity Environment

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The Effects of Hydrophilic and Hydrophobic Coatings and Container Shape on Fluids and Containers in a Microgravity Environment

Abridged Report

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1. <u>Abstract</u>

This experiment demonstrates the fluid property of hydrophilic attraction and hydrophobic repulsion and their relation to surface tension. This study gives an approximation of the amount of control that can be exerted passively over a mass system of fluid. By using cylinders of various sizes and shapes that are coated with various substances, in various patterns, containers along with baffles, a demonstration of the force of attraction between fluid and coating can be observed.

The properties studied in this experiment are of great use to the aerospace industry. The control of fluids in a microgravity environment is of major concern to any space project. In the case of a rocket or similar launch vehicle, the fuel of the spacecraft can make up to 70 percent of the weight. If this fluid were to start oscillating, the results would be catastrophic. If the fluid drifted away from the side of the fuel tank that the fuel need to be drawn from while in orbit, the spacecraft would have no way of using the fuel.

Life support systems can also benefit from this technology. Water must be stored aboard just like fuel. In fact, the storage of water might be considered even more crucial because it is carried throughout the entire flight, where fuel is usually spent in the initial stages of the flight. Water and other life supporting fluids are a direct necessity for astronauts and cosmonauts and must be readily available.

By studying the relationship between fluid, coatings of containers, and the shape of the container, NASA, the aerospace industry, and science in general will learn to control fluids passively, not actively, conserving energy weight, and increasing efficiency.

3. <u>Hypothesis</u>

How can microgravity fluids be controlled by using passive means, such as container coatings and container shapes, only?

4. <u>Experiment Description</u>

This experiment consists of a series of containers with various coatings on them filled with silicon oil. These containers were flown aboard a parabolic aircraft, which simulates microgravity. Depending on what the cylinder is coated with, how it is coated, the cylinder shape, what sort of baffles it contains and it's orientation with the aircraft, the fluid will behave differently. Usually the behavior of the fluid can be predicted, but it needs to proven and proven to be a repeatable effect.

The Wetting Test

The first part of the experiment needs to be done before the flight is even underway. The type of materials and coating must be determined ahead of time. Then they must be tested with the fluid to determine how the fluid will react to the coating.

A rectangle of the acrylic material that will be used for the cylinders should be laid flat in a horizontal position. The first test involves no coating. A drop of fluid should be placed on the material. Depending on what the fluid does, we can determine it's hydrophilic or hydrophobic effects. If the drop bubbles, then the angle in which the fluid and air interface strikes the material can be measured as the **contact** angle. This angle is a direct result of the attraction between fluid and material. If the fluid is attracted to it, the drop will spread out into a thin film and the contact angle will approximately zero. If the fluid is not attracted to the coating, or material, then the fluid will ball up and the contact angle will be relatively large.

The contact angles measured will give an early indication on how the fluid might react to a container coated with these coatings in microgravity. In microgravity, the fluid should migrate away from a hydrophobic surface and toward a hydrophilic surface.

Variables to Be Tested

Variables	Containers That Will Test Variable
Different Types of Coatings	1, 2, 9, 10, 4, 8
- no coating (contact angle = 0 degrees)	
- Formula 77 (contact angle = 10 degrees)	
- FC724 (contact angle = 60 degrees)	
Length to Diameter Ratio of Cylinders	3, 4, 5, 21
Coating Pattern	4, 7, 18
Fill Level of Containers	6, 4
Initial Orientation	8, 10, 21, 4
Effects of Spirals and Baffles	12, 14, 15, 16, 17
Shape of Container (Rectangular Prism and Cylinder)	RP1, RP2, 1, 4

5. Materials Needed

· Parabolic Aircraft - NASA's KC-135A
· 37 Cylinders made of plastic as specified in section 6.
· 4 Rectangular Prisms made of plastic as specified in section 6.
· Two different hydrophobic surface modifiers to coat the containers
  1. FC724 from 3M
  2. Formula 77 from 3M
· Silicon Oil, preferably dyed
· 2 Video Cameras
  1. (SVHS or Hi-8 format)
  2. Small handheld 8mm camera.
· Payload Box to store everything
· Accelerometer
· Data Platform

6. The Containers

The containers can be divided up into two groups. The first group consisted of 1 inch diamater cylinders of various lengths, orientation and coating patterns. The second group consisted of rectangular prisms with various orientation and coating patterns.

7. The Cells

The cells are the boards of carbon-fiber that hold the containers. Four containers are fixed to each side of the cell. Two containers on the left are identical to each other and two containers on the right side are identical to each other. Data placards are mounted below the containers. These placards hold the entire information imperative to the container. Each pair of containers is numbered, and when mounted vertically, the left container is considered “A” and the right container is considered “B” among identical containers. When mounted horizontally, the container on the top is considered “A” while the container on the bottom is considered “B”.

There are five cells, four with containers on both sides, and one with containers on only one side.

8. The Payload

The payload is considered to be the box in which the cells, containers, and accelerometer are stored. This box is made of carbon fiber and resin. Aluminum U channels make up the slots which enable the cells to slide in and out of the payload. Velcro keeps the cells in place when in microgravity. Aluminum brackets and screws affix the containers to the cells.

9. The Data Platform

The Data Platform is made of carbon fiber. This platform allows the SVHS camera to be bolted securely to the floor of the aircraft while at the same time videotaping the cell in the payload. Also, a small handheld 8mm camera has a place where it can be velcroed down to be used when needed. The Data Platform also features handholds where experimenters can grab onto to prevent floating away from the cameras.

10. Data Acquisition System

The Data Acquisition System of this experiment consists of two video cameras, a still camera and the verbal analysis of the experimenters as the experiment is conducted.

The primary means of data acquisition is a SVHS camera that is fixed to the data platform as described above. This camera is fixed on the front of the payload at all times and records the entire flight from this vantage point. After the flight, the tape can be used for further qualitative analysis as well as timing the motion of the fluid for some quantitative results.

If something of interest is occurring with the containers and the experimenters wish to obtain more data than just the SVHS camera, the handheld video camera can be used for extreme close-ups of individual containers. Also a still camera can be used to gain better resolution than the video cameras.

11. Structural Analysis

NASA set forth a rigid set of requirements the must be met for any experiment to fly aboard the KC-135. The payloads were then subjected to a Test Readiness Review (TRR) conducted at Ellington Field. This TRR verified the payload has met the requirements and also addressed any safety concerns to protect other experimenters.

All payloads must be able to with stand the following g forces: 9 gs forward, 3 gs aft, 2 gs laterally, 2 gs upwards, and 6 gs downward.

12. In-flight Test Procedures

A detailed checklist was developed after the containers were constructed and the payload container was developed. The wetting test was also performed prior to the development of the checklist.

The experiment consists of 37 cylinders, 4 rectangular prisms, with five cells of four containers per cell, per side. Each cell should undergo four trajectories per side, per flight. Also container 21 was not attached to a cell, but was affixed to a cell in flight. This container required an additional two parabolas. This means that 38 trajectories are required to perform this experiment correctly.

Abridged Checklist-

A complete checklist was developed for the experimenters. What follows is an abridged checklist to give understanding as to the flow of the experiment.

Before parabolas

The experiment is loaded in a protected setup where no cylinders face out and the accelerometer is not installed. Before the parabolas begin the payload needs to be assembled ready for the first parabola.

Parabola 1-2

The first two parabolas are designated as "microgravity orientation" for the sake of the experimenters. Although data is collected, it is not required and the experiment runs unmanned while the experimenters become accustomed to their radically new environment.

Parabola 3-6

Data is collected on cell number one, cylinders 1 and 2. These two cylinders are the control cylinders. Cylinder one has absolutely no coating and cylinder two is completely coated with FC724.

The experimenter reports verbally on turbulence, accidental bumps, negative g's, and any other unforseen factors that might influence the data collected. He also reports on movement of the fluid so that when the video is reviewed, his observations can be correlated to the data observed on the tape.

After Parabola 6, cell one is turned around and cylinders 3 and 4 are ready to be videoed.

Parabola 6-10

Data is collected on cell number one, cylinders 3 and 4. Cylinder 3 samples a 1:1 Length to Diameter Ratio. Cylinder 4 is a 2:1 Length to Diameter Ratio. Again, the experimenter reports verbally.

After Parabola 10 there is approximately a 10 minute break where cell one is placed back in the storage area of the payload, and cell two is brought to the front.

Parabola 11-14

Data is collected on cell number two, cylinders 5 and 6. Cylinder 5 samples a 1:4 Length to Diameter Ratio. Cylinder 6 demonstrates that the fluid will not move unless in straddles the interface between coated and non-coated surfaces. Again, the experimenter reports verbally.

After Parabola 14 cell two is turned around and cylinders 7 and 8 are ready to be taped.

Parabola 15-18

Data is collected on cell number two, cylinders 7 and 8. Cylinder 3 has the left half of a vertically mounted cylinder coated. Cylinder 8 is a horizontally mounted version of cylinder 4. Again, the experimenter reports verbally. After parabola 18, cell two is moved into the storage area of the payload and cell three is brought forward.

Parabola 19-22

Data is collected on cell number three, cylinders 9 and 10. Cylinder 9 samples a different coating material. Cylinder 10 is a different coating material mounted horizontally. Again, the experimenter reports verbally.

After parabola 22, cell three is set aside and cell 5 is brought forward so that cylinders 12 and 14 can be video taped in order. Cylinder 12 and 14 were manufactured last and so were not in order with the rest of the cylinders, thus the inconvenience.

Parabola 23-26

Data is collected on cell number five, cylinders 12 and 14. Cylinder 12 contains a small acrylic spiral in it's center. Cylinder 14 has a spiral coating of FC724 along it's. Again, the experimenter reports verbally.

After Parabola 26, cell five is moved to the storage area of the payload and cell 3 is moved back to the front with cylinder 15 and 16 facing forward.

Parabola 27-30

Data is collected on cell number three, cylinders 15 and 16. Cylinder 15 contains an asterisks shaped baffle but no coating. Cylinder 4 also contains an asterisks shaped baffle but has FC724 on its outside wall. Again, the experimenter reports verbally.

After Parabola 30 there is a ten minute break in which cell three should be moved to the storage area of the payload and cell four is to be brought forward with cylinders 17 and 18 facing forward.

Parabola 31-34

Data is collected on cell number four, cylinders 17 and 18. Cylinder 17 has a different kind of asterisks baffle. Cylinder 18 has FC724 coated in a striped fashion on the bottom of the container. Again, the experimenter reports verbally.

After Parabola 34 cell four is turned around so that rectangular prisms 1 and 2 face forward.

Parabola 35-38

Data is collected on cell number four, rectangular prisms 1 and 2. Rectangular prism 1 has no coating. Rectangular prism 2 has the bottom coated with FC724. Again, the experimenter reports verbally. After parabola 38, cylinder 21 is attached to the bottom of cell 4 so that it may be videotaped in a horizontal position.

Parabola 39-40

Data is collected on cylinder 21. Cylinder 21 samples an 8:1 Length to Diameter Ratio. Again, the experimenter reports verbally.

After Parabola 40

Once the parabolas are completed, the payload is stored in its protective mode once again, and the video equipment is stowed in a safe location for landing.

13. Specific Conclusions and Qualitative Analysis

1. Coated versus Non-coated- Container 1 was, in essence, the control cylinder. It contained two thirds Silicon-Oil, and was not coated. The reaction between pure acrylic and silicon oil is hydrophillic, and thus the fluid in the container was equally attracted to all sides of the container. Container 2, however, was completely coated with FC724, making the reaction between oil and cylinder wall hydrophobic. The fluid was equally repulsed by all sides of the container.

2. Half Coated, Half Uncoated- Containers 3,4,5,8 and 21 were coated on one half with FC724, while the other half of the container remained uncoated. The average time that the fluid spent in the uncoated, and predicted, half of these five containers was a disappointing 50.7%. However, it must be noted that all containers began with at least half of the fluid in the coated end, and containers 3,4 and 5 began with nearly all of the fluid resting entirely in the coated end. This means that some of the parabolic time was spent in transition from one side to the other.

It can be reasonably deduced that if cylinders 3,4 and 5 were mounted upside-down, or hydrophobic (coated) side up, the fluid would spend more time in the predicted area, or hydrophilic side, than measured in this experiment.

3. Length to Diameter Ratio- The length to diameter ratio had a large effect on the stability of the fluid. In container 3, a length to diameter ratio of 1:1 was tested, and the fluid was very unstable. The fluid moved whenever turbulence arose, indicating that there was not a lot of control over the fluid. Cylinder 4 was similar but showed a little more stability. The fact that it's average time in the predicted area was less than that of cylinder 3 can be attributed to a turbulence-filled first day. Although cylinder 3 experienced the same amount of turbulence, it's small fluid system allowed it to recover from a jostle faster than cylinder 4. Cylinder 5, of length to diameter ratio of 4:1, was much more stable although its transition time was longer.

Cylinder 21, with a length to diameter ratio of 8:1, was the most stable of them all. However, an unpredicted event occurred during one of the flights. The fluid system in the cylinder was large enough that at one point the fluid was jostled to the point of separation. The fluid became two smaller systems, and because neither straddled the interface (as will be discussed later), the fluid did not move. On the second day, this did not happen, and consequently, the entire fluid system remained in the predicted area despite turbulence.

The possible explanation of the increase in stability with increase in length begins with looking at the effect of the ends of the cylinders. As will be discussed later, a 90 degree angle attracts the fluid. This affects the way the fluid moves in the cylinder. The cylinders, by nature, are round, but the joining of the endcaps create a 90 degree angle with the cylinder. This attraction, depending on the nature of the fluid system, can be more powerful that the attraction of a hydrophilic surface, or the repulsion of a hydrophobic surface. As the length to diameter ratio increases, the ends get further and further apart. Thus, their influence over the fluid system lessens. Also, the force applied to the fluid system via the attraction of the container surface is directly related to surface area. As the length to diameter ratio increases, so does the amount of fluid contained in the cylinder, and therefore so does the surface area. However, the attraction felt by the corners remains basically the same, as their size does not change. Because of these features, the stability of the fluid increases proportionally with the length to diameter ratio.

4. Fill Level- The make up of cylinder 6 is exactly identical to that of cylinder 4. It has a 2:1 length to diameter ratio, it has the same coating, coating pattern, and initial orientation, and the fluid is silicon oil. However, cylinder 6 only has a fill level of one quarter the length. This is substantially less than the fluid contained in cylinder 4, and is not enough to straddle the interface between coated and uncoated portions of the cylinder. This interface occurs at half the cylinder's length.

What drives the fluid is really a pressure difference. A fluid that is hydrophillic at one end and hydrophobic in another, creates a pressure difference such that the hydrophillic side of the fluid is at a lower pressure than that of the hydrophobic side and thus the fluid moves toward the hydrophillic end. If the fluid does not come into contact with the hydrophillic side of the cylinder, the fluid will have no pressure change, and will not move.

Cylinder 6 was specifically designed to test this theory, and it proved to be the most conclusive of all. Cylinder 6 spent 93% of its time in the same place that it started. In essence, it did not move. The only reason it did not spend all of it's time in the same place that it started is because the cylinder experienced a negative g force that moved into the upper chamber of the cylinder.

This was also observed with cylinder 21. Due to some turbulence, the fluid system broke into two smaller portions.

5. Coating Pattern- The effect of coating pattern was tested in a number of ways. First, the bottom half of containers 3,4 and 5 were coated with FC724. Cylinder 7 also had half of the

cylinder coated, but the left half. In other words, the interface was perpendicular to the cylinder along the radial plane rather than the longitudinal plane. Cylinder 14 had one strip of FC724 spiraled around the outside, and cylinder 18 had a striped bottom half.

The most control of the fluid was exhibited when the fill of the cylinder was two thirds the length, and the coating was applied to half of the cylinder as in cylinders 3,4,5,8, and 21. However, very little influence on the fluid was exerted by cylinder 7. The coating covered the same surface as the former five, but was not effective. This undoubtedly has to do with the fluid's stability and container shape. In all cases, the fluid's meniscus ran perpendicular to the longitudinal axis. Essentially the meniscus was most stable when it spanned the least area. Therefore, a coating pattern that tried to push the meniscus across a wider area rather than the smallest area, was less successful than the coating pattern that is found in cylinders 3,4,5,8 and 21.

6. Initial Orientation- In an idealized situation, the initial orientation should not have mattered. In a true microgravity environment, there is no difference between up and down. However this flight was not a pure microgravity environment as there were many incidence of turbulence and jostling that upset the fluid. In this experiment, the initial orientation made a large difference over the stability of the cylinders.

Cylinder 8 was the first cylinder to test to see if mounting it horizontally on the cell, rather than vertically, made any difference. As shown in Table 5, cylinder 8, which was identical to cylinder 4 with the exception of it being mounted horizontally, spent and average of 74.3% of it's time in the uncoated portion of the cylinder. Cylinder 4 only spent 26.4% of its time in the uncoated portion of the cylinder. The reason for this is three-fold.

When the cylinder is mounted horizontally, the fluid lies halfway between coated and uncoated portions of the cylinder. When mounted vertically, all of the fluid is in the bottom of the cylinder, and there is less contact with the uncoated portion of the cylinder. When the cylinder enters microgravity, the fluid in a horizontally mounted cylinder has less distance to move, because half of it is already in the predicted area.

Second, as discussed before, the fluid is more stable when its meniscus spans the least amount of area. When the cylinder begins the parabola, the meniscus spans the most amount of area. So naturally, the fluid will move so that the meniscus runs vertically to become more stable. With the coating effects driving the fluid to do that anyway, the combined effect is to shorten the meniscus.

Lastly, and probably most importantly, the turbulence experienced in the airplane ran up and down along the yaw axis of the aircraft. When the cylinder was mounted vertically, the meniscus ran horizontally and perpendicular to the force of the minor jostles. This had a large effect on the fluid and countered the force place on the fluid from the coating effects. When mounted horizontally, the force of the coating effects also ran horizontally and perpendicular to the majority of the turbulence. This provided for a more stable fluid system and allowed the fluid to spend the majority of its time in the predicted area of the cylinder.

7. Different Types of Coatings- It has already been clearly illustrated that when one side of the cylinder is coated with a hydrophobic surface like FC724, and the other side has a hydrophilic effect on the fluid, like the uncoated acrylic, the fluid will be driven from the hydrophobic side to the hydrophilic side, provided it straddles the interface between the two sides. However, cylinders 9 and 10 tested the effects of a surface modifier that, when a wetting test was conducted, produced a contact angle of only 10 degrees. This is not that much of an advantage, and as will be discussed later, is most likely not do to the chemical interaction between the two materials.

Cylinder 9 showed a slightly better average of time in the predicted area than cylinder 4. However the standard deviation is the highest among all the cylinders. With the standard deviation of 28.2 percent, and a second day average of only 4.4%, this coating has an effect, but is not as reliable as the FC724. This was expected.

Cylinder 10 has a 61.3% time which is quite an improvement over cylinder 9, and again this is a matter of initial orientation (discussed above). However it is significantly less than the stability shown in cylinder 8.

The reason these cylinders, with the Formula 77 coating, do not perform like those of FC724 coating, is because during a wetting test, the contact angle of Formula 77 is only 10 degrees, when compared with FC724 that has a 60 degree contact angle. This indicates that the FC724 is much more hydrophobic than the Formula 77.

8. Effects of Spirals- Cylinders 12 and 14 tested the effects of spirals on the fluid system. Cylinder 12 contained a spiral made of acrylic placed in the middle of the container. Cylinder 14 contained a spiral of FC724 applied to the wall of the cylinder.

Cylinder 12 gave some extremely interesting results. The fluid actually wrapped itself around the spiral, and when the container experienced any mild jostling, the fluid just rotated around the spiral. Two big factors could explain this phenomenon. On, the spiral is made out of the same hydrophilic material of which the container is made. The fluid is attracted because of this reason.

Cylinder 14 brought back conclusive data that merely a strip of coating on the outside of the container is not enough to separate or have any effect on the fluid.

9, Effects of Baffles- Cylinders 15, 16 and 17 brought back the most interesting data when the cylinders contained baffles made from hydrophilic acrylic. In fact, the numerical values in tables one through four, read **C** for Inconclusive data. As described in the experimental observation section of the cylinder description, the fluid formed a ring around the outside of the cylinder, but also stayed away from the corners where the cylinder meets the end plate. This is curious because in almost every other cylinder, the fluid system is attracted to the corners of the cylinder. Therefore, there must be some stronger force acting to keep the fluid away from the corners.

10. Different Container Shape- Rectangular Prism 1 and 2 showed something quite unexpected. The fluid in all four containers acted exactly alike, although RP2 was coated on the bottom half of the prism by FC724 much like cylinder 4 was. One principle that could possibly explain this, is that the attraction of the corners of the container dominated over any movement that the hydrophobic/hydrophilic pressure differential might have caused.

It is also possible that the costing was not applied properly during construction, or that coating wore off.

14. General Conclusions

The following generalizations can be made about microgravity fluids. These generalizations can be substantiated by the data collected in this experiment.

1. Fluid in a container can be controlled by coatings on the outside of the container, provided that the fluid straddles the interface between a hydrophilic surface and a hydrophobic surface.
2. The initial orientation of a container only matters if there is going to be jostling in a certain axis. If jostling is expected, then the interface between hydrophilic and hydrophobic surfaces should run parallel with the axis aligned with the jostling.
3. The greater the Length to Diameter ratio, the more stable the fluid is, provided the fluid remains as one fluid system and does not break into two smaller fluid systems.
4. A fluid is attracted to a corner or angle provided that the angle is greater than or equal to the contact angle of the fluid and the surface in a one-g environment.
5. A coating that has a large contact angle (as determined from a wetting test) is more

hydrophobic and will serve to better drive the fluid than a coating with a small contact angle.

6. The surface must be clean and free from debris if a hydrophilic attraction is to drive a fluid contacting a surface.

7. A coating pattern is more effective if it's design is to keep the meniscus parallel to the shortest distance across the container.