THE CAPILLARY FLOW EXPERIMENTS: HANDHELD FLUIDS EXPERIMENTS FOR INTERNATIONAL SPACE STATION

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Abstract

NASA is constructing a series of handheld test vessels to study key characteristics of low-g capillary flows aboard the International Space Station (ISS). The Capillary Flow Experiment (CFE) consists of 6 approximately 1 to 2 kg flight units designed to probe certain capillary phenomena of fundamental and applied importance, such as; capillary flow in complex containers, critical wetting in discontinuous structures, and large length scale contact line damping. Quantitative video images from the simply performed flight experiment crew procedures are anticipated to provide immediate confirmation of the usefulness of current analytical design tools as well as provide guidance to the development of new ones.

A description of the experiment requirements, flight hardware, and challenging time constraints imposed on the design team is provided for the project to date. The CFE flight experimental program (conception) was initiated in February 2003 as part of a fast-paced unscheduled payloads/experiments program. Two of the flight units are tentatively planned for launch to ISS in Fall, 2003. The experiments will be performed in stand-alone mode by a single crewmember on the Maintenance Work Area of the ISS. The specific experimental objectives are briefly introduced by way of the crew procedures and a sample of the as yet unverified theoretical predictions of the fluid behavior is provided. The potential impact of the flight experiments on the design of spacecraft fluid systems is discussed.

Program Overview

Recent developments in NASA's shuttle program have allowed new opportunities for science experiments aboard the ISS. Since the shuttle is unable to ferry planned science equipment to the ISS, NASA sought substitute candidate science experiments to take advantage of available crew time. The design constraints for such experiments are stringent and include:

- Safe operation
- Low mass < 2.5kg
- Low volume < 2 liters
- Minimal electrical interfaces
- Minimal power requirements
- Minimal to no crew training
- Short hardware delivery schedule (months)
- Low cost

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This list is not exhaustive, but certainly restrictive, and stems from NASA's plan to use the Russian Progress vehicle to deliver science experiment hardware to the ISS—the available cargo weight and volume for science hardware aboard Progress is limited.

Fortunately, a class of fluids experiments can be posed that fit this description and the Capillary Flow Experiment (CFE) was proposed to NASA and competed on the basis of science and strategic research merit for NASA. The experiments address questions of both scientific and engineering importance and concern certain capillary phenomena as it relates to the large length scale fluid systems that arise commonly aboard spacecraft. Such systems and phenomena cannot be reproduced in terrestrial laboratories.

In this paper CFE for the ISS is introduced as a work in progress. The simple handheld experiments are designed to be operated on the Maintenance Work Area in the United States Laboratory of the International Space Station with the primary quantitative data being digital video images from an ISS onboard camcorder. Three experiment types are proposed for rapid development, the first of which is scheduled to launch to ISS via Russian Progress Module flight 13P in Fall 2003 for performance in Winter 2004. The experiments constituting CFE are Contact Line (CL), Interior Corner Flow (ICF), and Vane Gap (VG).

The Capillary Flow Experiment

Motivation

Capillary flows and phenomena are critical to myriad fluids management systems in low-g: fuels/cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing in the liquid state. In fact, NASA's near term exploration missions plan larger liquid propellant masses than have ever flown on interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such large mission-critical systems perform predictably. The Capillary Flow Experiments presented here is a simple fundamental scientific study that can yield quantitative results from a safe, low-cost, short time-to-flight, handheld fluids experiments. The experiments aim to provide results of critical interest to the capillary flow community that cannot be achieved in ground-based tests. Specific applications of the results center on particular fluids challenges concerning propellant tanks. The knowledge may help spacecraft fluid systems designers increase system reliability, decrease system mass, and reduce overall system complexity.

Description of Hardware

Three Capillary Flow Experiments (2 units per experiment—6 units total) are proposed, each addressing important problems and open questions concerning large length scale capillary flow and phenomena that are unique to the low-g environment. Parametric ranges and test cell dimensions are selected that cannot be easily achieved in ground-based experiments.

All units use similar fluid injection hardware, have simple and similarly sized test chambers, and rely solely on video for highly quantitative data. Differences between units are fluid properties, contact angle, or test cell cross-section. The experiment procedures are simple and intuitive.

- Mass per flight unit: ~1 to 2 kg
- Volume per flight unit: ~ 10cm x 14cm x 15cm
- Crew training by uplink is acceptable
- No electrical interface
- No power requirement
- Low toxicity level fluids (silicone oils)
- Color video camcorder only
- Preferred crew time is 2-3 hours per unit, up to 4 hours per unit has been recommended by candidate ISS astronaut Mike Foale
- Associated risks: Fluid containment (fluids are flight qualified)

Interior Corner Flow (ICF)

Spontaneous capillary flows in containers of increasing complexity are currently under investigation to determine important transients for low-g propellant management[1-4]. Significant progress has been made for complex containers that are cylindrical, but many practical systems involve containers/geometries that are tapered. Schematics of the two flight units proposed to investigate this phenomenon are provided in Figs. 1 and 2.

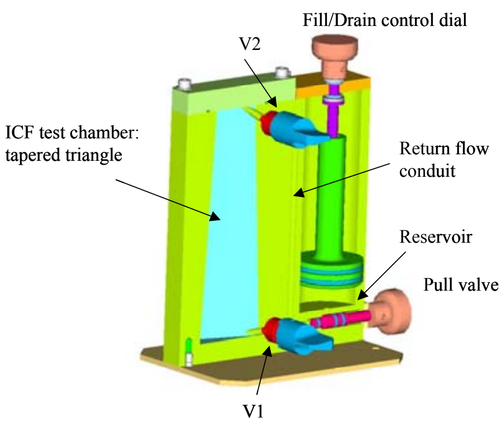

Fig. 1. ICF-1 tapered isosceles triangle section.

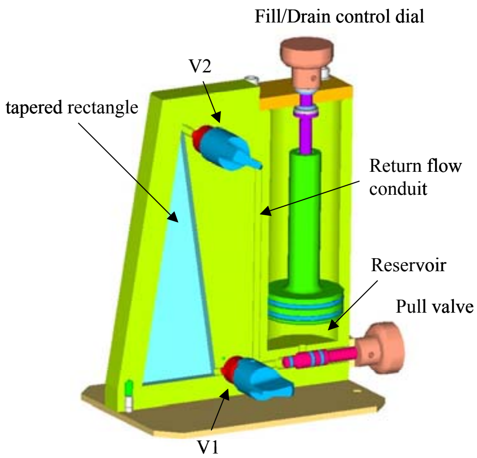

Fig. 1. ICF-2 tapered rectangular section.

The taper of the irregular polygonal cross section of the test cells provides particular design advantages in preferentially locating the liquid where desired. Passive capillary flow in such containers is called imbibition and cannot be tested on the ground for 3-D geometries with 'underdamped fluids'—a most common characteristic of low-g fluids systems. The equations governing the process are known but have not been solved analytically to date because of a lack of experimental data identifying the appropriate boundary conditions for the flow problem. Early indications are that the overall pressure difference for the flow may actually be constant—even for fairly complex 3-D shapes—which would greatly simplify analyses. Experimental results will guide the analysis by providing the necessary boundary condition(s) as a function of container cross section and fill fraction. The benchmarked theory can then be used to design and analyze capillary devices such as 3-D vane networks and tapered screen galleries for bubble-free collection and positioning of fuels for satellites, an important and outstanding problem for propellant management aboard spacecraft. A schematic of the test cell cross sections is provided in Fig. 3. The tapered triangle section does not change proportion with height whereas the aspect ratio of the rectangular section does.

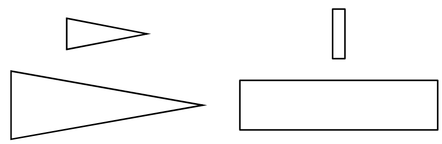
Fig. 3. ICF container sections near base and lid of test cells ICF-1 (Fig. 1) and ICF-2 (Fig. 2), respectively (not to scale).

Further ICF design details are provided below:

ICF-1
1. Test cell: tapered 75-75-30 isosceles triangle
2. Height of vertex at base 1.575"
3. Height of vertex at top 1.024"
4. All faces taper at 3.155º
5. Test cell is 5" long
6. Fluid: 5cs Silicone Oil
7. Fluid volume is 10.00cc in test cell

ICF-2
1. Test cell: tapered rectangular section
2. Side faces taper only at 8.95º
3. Test cell is 5" long and 1.575" wide at base
4. Test cell is a constant 0.394" deep
5. Fluid: 2cs Silicone Oil
6. Fluid Volume is 9.02cc in test cell

Several simple experiments may be performed with the apparatus. The first test after the initial fill determines the imbibition rate for the particular fluid (~20 minutes), container cross-section, and taper angle. Using the inline valves the experiment may be repeated any number of times. The piston may then be reversed producing bubbles and demonstrating the phase separating nature of the corner flows. Flow rate data and transient interface shapes will be determined by digitizing the video recording as is common for such experiments. A perfectly wetting silicone oil will be used for these tests.

Vane Gap (VG)

The Concus-Finn critical wetting condition[5,6] is eliminated and/or significantly altered for interior corners that do not actually contact; such as in the gap formed by a vane and tank wall of a large propellant storage tank (a commonality in practice), or the near intersection of vanes in a tank with complex vane network[7]. Two CFE flight units are proposed to investigate this phenomenon using a right cylinder with elliptic cross section and a single central vane that does not contact the container walls as depicted in Fig. 4.

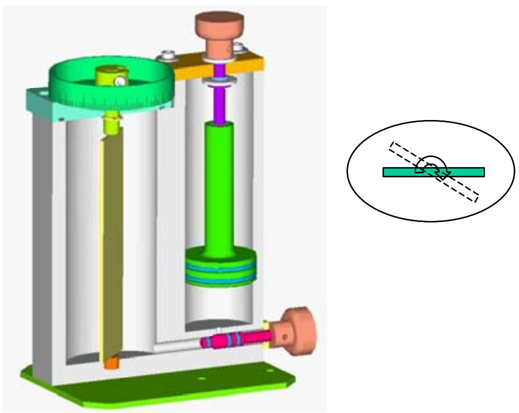

Fig. 4. VG flight unit with elliptical section and rotatable vane shown at right.

The vane can be pivoted changing both the angle between the vane and the wall and the size of the vane-wall gap. The vane is slightly asymmetric so that two 'gaps' can be tested for each container. After injecting the prescribed amount of fluid the crewmember rotates the vane at set intervals allowing significant time (up to 5min.) for the fluid to equilibrate between each interval. Static interface shapes recorded by video will be compared quantitatively with shapes computed using the *Surface Evolver*[8] algorithm. At a critical vane angle the fluid will spontaneously wet the corner at which point the vane angle will be measured for comparison to theory. Example interface profile using *Surface Evolver* are shown in Fig. 5 just below and above the critical angle.

This experiment is unique in the long-duration low-g environment of the ISS because sufficient low-g time is available to assure local equilibrium and more importantly, because it can be reversed and repeated (potentially sweeping out a hysteresis band), providing data for a common and uninvestigated problem while serving as a complex benchmark problem for the *Surface Evolver* numerical design tool.

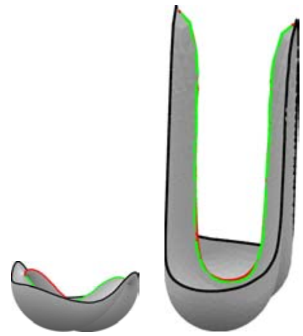

Fig. 5. Numerical predictions of critical wetting in corners with gaps using *Surface Evolver*: (left) slightly sub-critical, (right) super-critical.

Further VG design details are provided below: The units are identical in every aspect except wetting condition and vane dimensions.

1. Ellipse Section: 2" by 1.333". Height is 5".
2. Large Bond number limit, Bo >> 1 (i.e. 1-g, flat surface), liquid fill level is 1.5" from base.
3. Vane dimensions:
   VG-1—1.234" by 0.079" by 4.5"
   VG-2—1.234" by 0.197" by 4.5".
4. Vane pivot axis is coaxial with ellipse but gap dimensions are 0.033" and 0.066" when vane is aligned with minor diameter of ellipse. These gap dimensions represent a 0.95 and 0.90 dimensionless gap using the minor axis radius for normalization.
5. Vane angle rotation 360º with < 2.5º resolution
6. Contact angles are 0º (VG-1, no coating) and 60º (VG-2, FC724 coating).
7. Fluid is 10cs Si Oil. Fluid volume is 49.1cc.

<u>Contact Line</u> (CL)

Two capillary flow flight units are proposed to study an important fundamental and practical concern for low-g fluid phenomena: the impact of the dynamic contact line. The contact line controls the interface shape, stability, and dynamics of capillary systems in low-g. A very simple experiment is proposed here that if completed successfully could provide a direct measure of the extremes in behavior expected from an assumption of either the free or pinned contact line condition. The two units are identical—only a coating is used in one to vary the wetting characteristics. A sketch is provided in Fig. 6 for one of the flight units.

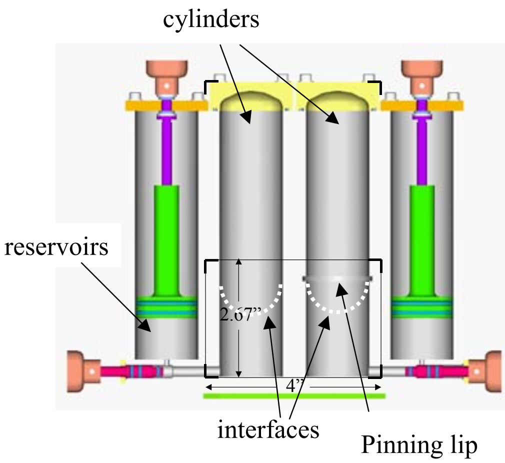

Fig. 6. Design for CL flight units with free and pinned contact lines. Dashed lines identify equilibrium menisci shapes in microgravity environment. The primary camera FOV is identified by the 4" by 2.67" window.

A brief description of the experimental procedure is to fill the cylinders to identical levels with the same fluid. The only difference between the cylinders is that one of the contact lines is pinned at a pinning edge created by a groove machined into the cylinder walls. Because the cylinders are closely and rigidly coupled, disturbances to the flight unit will produce nearly identical disturbances to both of the cylinders. Frequency and damping rates will be measure from the video recordings. Comparisons of the data for a variety of disturbances will clearly identify the bounds that can be expected for the assumptions of free and pinned contact lines. One unit will test a perfectly wetting fluid (i.e. Silicone oil) and the other a fluid with a contact angle of approximately 50º (i.e. Silicone oil on FC724, a transparent coating manufactured by 3M). The cylinder is sized to be as large as possible yet not too large that the crewmember would easily breakup the interface. The results of this simple experiment could provide clear guidance to NASA and the aerospace community as to whether to increase or decrease practical concerns attributed to the wealth of unknowns still surrounding the moving contact line boundary condition as it relates to the fluid phenomena on spacecraft.

Further CL design details are provided below:
1. Cylinder diameter: 1.5"
2. Fluid: 2cs Si Oil
3. Cylinders are identical except for pinning lip

CL-1 specifics;
1. Contact angle is 0º.
2. Height from base to pinning lip is 2.0",
3. Volume of fluid is 43.44cc.
4. Interior surfaces of lids are coated with FC-724.

CL-2 specifics;
1. Contact angle is 50º.
2. Height from base to pinning lip is 1.451",
3. Volume of fluid is 39.04cc.
4. All interior surfaces of cylinders are rinse coated with FC-724.

<u>Additional CFE Design Detail</u>

As highlighted above, the flight units are all basically the same (ref. Fig. 1-4). Each one consists of at least one test cell and at least one reservoir that are connected by a passageway and valve. The main difference between the units is the test cell. The reservoir is similar for all flight units. It holds the test liquid and also contains a piston that is used to displace the liquid into the test section. Turning a knob connected to a drive screw moves the piston.

The main body for the units is made of polymethylmethacrylate (PMMA or Plexiglas). While the CL units are machined from one piece, the ICF and VG units are made from multiple pieces that have been glued together with methylene chloride. The pistons are made of aluminum. The valves and piston drive screws are made of stainless steel. Each unit sits atop an aluminum base plate with a hole that is used to attach the unit to the Maintenance Work Area (MWA). Additional details about the MWA are included as Appendix.

The parts that contain the liquid in the reservoir and test section (lids, pistons, valves) are sealed with fluid compatible O-rings made of either nitrile (Buna-N). The test cells are 'blind' cavities and are thus slightly pressurized during fill and operation procedures.

The CL flight units are the simplest of the three. However they are different from the others in that each flight unit consists of two test cells and two reservoirs.

The main difference in the ICF units is an extra passage that connects the top of the test cell to the bottom of the test cell. There are two valves in this passage, one each located near the top and bottom of the test cell. The purpose of the valves and passage is to allow test fluid located at the top to be transferred to the bottom of the test cell clockwise (ref. Figs. 1 and 2), via iterative operation of the valves and reservoir piston. The method for transferring the test fluid to the bottom of the test section is accomplished in two steps. The first step is to close the bottom valve, open the top valve, and retract the piston. This draws the liquid into the reservoir. The second step is to close the top valve, open the lower valve, and displace the liquid in the reservoir with the piston. This returns the liquid to the bottom of the test section.

The test section of the VG flight units is elliptical in cross section. Running along the length of it is a thin, rectangular plate (vane) that can pivot about its long axis. The angular position of the plate is controlled by an external dial. As the angular position of the plate changes, it reaches a point where it has the desired affect on the test fluid.

Status of CFE

To meet the aggressive delivery schedule the experiment design, fabrication, and flight qualification tests have been conducted in a staggered parallel manner. The ICF units were scheduled to fly first, however due to a leak path identified during the assembly of the flight hardware, it was decided to move ahead with the CL units, followed by the ICF and VG units. Eight of the 28 flight video tapes have already launched to ISS on 12P.

A history of the CFE project as of October 2003 is provided below:

- February: CFE Concepts
- March: Downselection CL, ICF, VG
- March 17: Authority to proceed, begin parallel design and fabrication
- May 16: Offgas test
- June 5: ICF Assembly complete
- June 9: ICF Preliminary Fill
- June 16: ICF Functional Tests
- July: CL Assembly complete, Cleaning, Fill, Post Assembly Functional, Vibe, Proof Pressure Test
- Aug.: CL Post-Proof Pre-Leak Test Fill, Post-Proof Pre-Leak Functional, Leak Tests, Post Leak Test Functional, Clean, Fill
- Sept.: CL Executive Preship Review, Hardware Turnover (NASA JSC), Phase III Safety Review

Near term projections:

- Nov.: CL Scheduled Shipment to Russia
- Nov.: CL launch to ISS on 13P
- Dec.: CL on-orbit operations

A photograph of the prototype CL unit is provided in Fig. 7. The prototype unit is identical to the flight units that have already been delivered for launch. The important field of view for the video recordings is sketched schematically in Fig. 6. This field of view is visible from the LCD screen pictured in Fig. 8 during a lighting check conducted using the prototype in the ISS/MWA mock-up at NASA JSC.

Fig. 7. Photograph of CL fluid-filled, prototype engineering unit. Left reservoir is filled, right test cell is filled.


Fig. 8. CL engineering model on MWA in ISS mock-up. Primary FOV shown in Camcorder monitor.

The current CFE hardware consists of 2 Contact Line units (CL-1 and CL-2) and 20 DV Camcorder Tapes. The CFE hardware will utilize the MWA, some of the MWA accessories, and ISS video recording equipment (camcorder, power supply, etc) while being operated in the United States Laboratory (USL) on the ISS.

Acknowledgment

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Appendix

The Maintenance Work Area (MWA) provides a rigid surface on which to perform maintenance tasks. The MWA consists of a folding tabletop and two detachable arms. The arms attach to the seat track, providing the table with a solid connection point. To aid in quick placement, each arm has a seat track locator. Once the arms are placed in the seat track, the handles can be rotated to lock the arms in position. Also, by actuating handles underneath the front edge, the work surface can be rotated in 15 degree increments within a 180 degree range. Seat track, 12 pairs of slots, and a 6 x 9 grid pattern of #10 tapped holes can be found on the work surface assembly for restraints. Other MWA accessories that CFE is planning to use, are the utility strip and #10 captive screw. Lighting and video are provided by an ISS camcorder, and portable utility light if necessary. Currently, it appears that reflective lighting may not be necessary since ISS lighting may be sufficient. The camcorder will be powered using the utility strip and the necessary power/video cables.