The Capillary Flow Experiments Aboard the International Space Station: Increments 9–15
August 2004 to December 2007

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September 2009
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Chapter 1

The Capillary Flow Experiments aboard ISS: Executive Summary

Summary. This paper highlights the experimental, analytical, and numerical results of the Capillary Flow Experiment (CFE) performed aboard the International Space Station (ISS). The experiments were conducted in space beginning with Increment 9 through Increment 16, beginning August, 2004 and ending December, 2007. Both ‘primary’ and ‘extra science’ experiments were conducted during 19 operations performed by 7 astronauts including: M. Fincke, W. McArthur, J. Williams, S. Williams, M. Lopez-Alegria, C. Anderson, and P. Whitson. CFE consists of 6 approximately 1 to 2kg handheld experiment units designed to investigate a selection of capillary phenomena of fundamental and applied importance, such as large length scale contact line dynamics (CFE-Contact Line), critical wetting in discontinuous structures (CFE-Vane Gap), and capillary flows and passive phase separations in complex containers (CFE-Interior Corner Flow). Highly quantitative video from the simply performed flight experiments provide data helpful in benchmarking numerical methods, confirming theoretical models, and guiding new model development. A brief history of the experiment is provided before introducing the science investigated. A selection of experimental results and comparisons with both analytic and numerical predictions is given. Despite the simple nature of the experiments and procedures, many of the experimental results may be practically employed to enhance the design of spacecraft engineering systems involving capillary interface dynamics.

1.1 Introduction

Following the Space Shuttle Columbia accident, developments in NASA’s shuttle program allowed new opportunities for science experiments aboard ISS. Since the shuttle was temporarily unable to ferry planned science equipment to ISS, NASA sought substitute candidate experiments to take advantage of any possible 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 interfacing, minimal power requirements, minimal to no crew training required, short hardware delivery schedule (i.e. months), and low cost. This list is not exhaustive, but is certainly restrictive, and stems from NASA’s desire to use in part the Russian Progress vehicle to deliver science experiment hardware to ISS—the available cargo weight and volume for science hardware aboard Progress being 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. The experiments address questions of both scientific and engineering importance and concern certain capillary phenomena as it relates to large
length scale fluid systems that commonly arise aboard spacecraft, but not in terrestrial laboratories.

CFE is composed of six vessels including three experiment pairs—Contact Line (CL), Vane Gap (VG), and Interior Corner Flow (ICF), performed essentially in this order. All vessels use similar fluid injection hardware, have similarly sized test chambers, and rely solely on video for quantitative data. The general engineering design characteristics common to the CFE vessels include: (1) mass < 2kg, (2) volume < 2.1L, (3) No electrical interfaces or power requirements, (4) experiment operation time < 3hr, (5) brief to no crew training needed, (6) low toxicity fluids (i.e. Silicone oils) and (7) double seals against fluid leak. The objective of the different CFE vessels are summarized as follows:

- The Contact Line (CL) experiments are highlighted in Section 1.3. These experiments required the most extensive data reduction effort in CFE and a database was established to categorize the greater than 350 tests performed. The primary objective of the CL experiments is to investigate the effect of contact line boundary conditions on dynamic interface response following a variety of perturbations. Both pinned- and smooth-wall conditions for both perfect and partial wetting conditions are studied in hopes of bracketing all possible responses between the two extremes of fixed and free contact line boundary conditions. Experimental and numerical results are presented along with extra science events depicting phenomena not part of the primary objectives.

- The Vane Gap (VG) experiments are reviewed in Section 1.4 and concern gap-wetting in a cylinder with elliptic cross-section. When rotated, an asymmetric vane oriented along the axis of the chamber achieves a variety of critical geometries leading to nearly discontinuous wetting and de-wetting of gaps formed between the vane and the container wall. The critical wetting conditions are compared to theoretical and numerical predictions and may be exploited for the purposes of controlling large quantities of liquids in reduced gravity environments. Both static and dynamic interfaces are studied.

- The Interior Corner Flow (ICF) experiments are outlined briefly in Section 1.5 and address passive capillary-driven corner flows in weakly 3-dimensional geometries. Experiments demonstrating passive phase separations are conducted. Comparisons of the heavily geometry-dependent flow with developing theoretical models are made.

1.2 Background and Motivation

As has been stated on numerous occasions by numerous investigators, capillary flows and phenomena are critical to myriad fluids management systems in low-g including: 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. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such mission-critical systems perform predictably. CFE is a simple fundamental scientific study that can yield quantitative results from a set of safe, handheld fluids experiments. The experiments aim to provide results of value to the capillary flow community that cannot
be easily achieved in ground-based tests. Specific applications of the results tend to center on fluids challenges concerning propellant tanks. However, the knowledge gained may help spacecraft fluid systems designers in general by increasing confidence in current design tools to predict such large scale capillary phenomena.

1.2.1 Hardware and Setup

The handheld experiments are designed to be operated on the Maintenance Work Area (MWA), a portable workbench in the United States Laboratory of the ISS shown in Figure 1.1. Set up and operation are simple and intuitive, requiring minimal preparation. All of the experiments require use of an ISS video camera and a diffuse paper screen employed as a backlight. The camera is a standard rate Sony 720x480 CCD DVCam and is mounted to an ISS rail. Astronauts are allowed freedom in where and how the camera and experiment are configured with the primary requirement that the camera be perpendicular to the test vessel front face. The CFE vessels are rigidly mounted to the MWA by a setscrew.

1.3 Contact Line (CL)

The CFE Contact Line experiment consists of two vessels each containing two right circular cylinders, one smooth and the other with a machined groove serving as a pinning edge. Both cylinders are filled to identical levels and since the containers are closely and rigidly connected, any disturbance imparted to the vessel is felt by both fluid surfaces. Differences in fluid response is thus expected to be solely a result of differences in contact line boundary condition, which is readily observed in Figure 1.2. The simple operation of CL requires the astronaut to impart a variety of disturbances to the vessel allowing the interface oscillations to decay naturally in the field of view of the camera. Dynamic Bond numbers as low as $10^{-5}$ and greater than 20 are achieved spanning both visco- and inertial-capillary flow regimes. Video data is collected from which both the disturbance input and passive liquid response can be digitized. The brevity (5s–30s) of each experiment event (disturbance and damped fluid response) permitted a large number of tests to be conducted, the reduced data set of which comprises over 350 primary science events not counting numerous other tests referred to as ‘extra science’ tests.
Figure 1.2: Image of CL2 interface: (a) equilibrium states, (b) arbitrary dynamic state.

Figure 1.3: Photo of CFE CL1 on left and solid model at right showing Smooth and Pinning cylinder from camera view.

1.3.1 CL Hardware Description

A photograph of the CL2 flight unit is provided in Figure 2.2 along with a solid model of the design with key components noted. The two units are identical in all respects save wetting properties, fluid volume, and pinning lip location. The main body is machined from a single piece of cast acrylic and fitted with aluminum pistons and stainless steel piston drive screws. The right circular cylindrical test chambers have flat bases but elliptical acrylic lids. Each unit is secured to an aluminum base plate with a single slotted hole that is used for attachment to the ISS MWA via a captive fastener allowing for as much as 40mm lateral motion or adjustment. Turning a knob connected to a drive screw displaces the piston. The knob diameter and screw pitch are selected so that a slow and stable manual fill process is assured. The double O-ring sealed reservoirs, charged at atmospheric pressure (∼P_{atm}), contain the silicone oil test liquid and employ pistons to dispense the liquid into the respective test sections. Thus, the blind test chambers are somewhat pressurized.
Table 1.1: CL physical dimensions and properties.

<table>
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<tr>
<td>Cylinder Diameter</td>
<td>38.10 ± 0.05mm</td>
</tr>
<tr>
<td>Cylinder Height, $H$</td>
<td>146.0 ± 0.1mm</td>
</tr>
<tr>
<td>Pinning Lip Height</td>
<td>7.6 ± 0.1mm</td>
</tr>
<tr>
<td>Pinning Lip Diameter</td>
<td>43.7 ± 0.1mm</td>
</tr>
<tr>
<td>Acrylic Refractive Index, $N_D$</td>
<td>1.491</td>
</tr>
</tbody>
</table>

**CL1 Specifications**

- Base to Pinning Lip, $h$ 36.9 ± 0.1mm
- Maximum Fluid Volume 39.04mL

**CL2 Specifications**

- Base to Pinning Lip, $h$ 50.8 ± 0.1mm
- Maximum Fluid Volume 43.44mL

**Fluid Properties at 25°C**

<table>
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<th>Fluid Type</th>
<th>Silicone Oil</th>
</tr>
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<tbody>
<tr>
<td>Kinematic Viscosity, $\nu$</td>
<td>2cst ±2%</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>872 ± 5kg/m$^3$</td>
</tr>
<tr>
<td>Surface Tension, $\sigma$</td>
<td>0.0187N/m ±5%</td>
</tr>
<tr>
<td>Refractive Index, $N_D$</td>
<td>1.390</td>
</tr>
</tbody>
</table>

**CL1 Specifications**

- Receding Angle, $\theta_{rec}$ 47.3° ± 2°
- Equilibrium Angle, $\theta_{eq}$ 48.7° ± 2°
- Advancing Angle, $\theta_{adv}$ 52.2° ± 2°

($\sim 1.3P_{atm}$) when the liquid is fully deployed. The design meets a single level of containment requirement for a ‘zero-hazard’ test liquid enabling the experiments to be performed by any crew member in the open ISS laboratories.

The CL1 unit tests a partially wetting liquid with a nominal contact angle of $\sim 50^\circ$ while the CL2 unit tests a perfectly wetting (spreading), zero contact angle liquid. The selection of a 38.1mm cylinder diameter is constrained by an ISS safety requirement for maximum fluid volume. The cylinder diameter is sized to be as large as possible within this constraint to access uniquely low-g inertial-capillary regimes without introducing overbearing depth effects. The liquid volume and height of the pinning lip are selected such that the liquid depth from the centerline of the low-g menisci to the cylinder base is the same for both CL1 and CL2 at 31.75mm (depth/radius = 1.67). These and other container specifics are summarized in Table 2.1.

Certain wetting barriers are applied to the containers to enhance control during the experiment operations. The surface coating conditions vary between CL1 and CL2. The entire interior surface of CL1 is rinse coated with FC-724, a transparent fluoro-polymer surface coating manufactured by the 3M Corporation. CL2 is intended to be a perfectly wetting experiment thus for the Pinning cylinder the interior surfaces above the pinning lip are coated, including the groove making up the pinning edge. The discontinuous wetting
boundary established across the pinning lip in CL2 creates a passive means of returning the fluid from above the pinning edge to below it via a favorable wetting discontinuity. The lid of the Smooth cylinder is also coated. All other surfaces of CL2 are uncoated and exhibit perfect wetting, $\theta = 0^\circ$. The equilibrium contact angle for the silicone oil on the FC-724 surface is determined by measuring advancing and receding contact angles using a tilted FC-724 coated glass capillary tube [1]. These values are listed in Table 1. The equilibrium angle is computed [2] to be $48.7 \pm 2^\circ$ but is frequently referred to as $50^\circ$ in reference to CL1. Contact angle values identified during the flight experiments confirm these values despite the test unit being stored for approximately 2 years prior to testing.

1.3.2 CL Disturbance Types

A variety of disturbances were imparted by hand to the CL vessels by the astronauts and are briefly described here.

- **Tap**: This disturbance is a single tap imparted to the rigidly mounted container. The disturbance begins with small taps progressing to light knuckle raps. The fluid response is characterized by small amplitude high frequency oscillations which can only be marginally resolved.

- **Axial**: With the CL vessel rigidly mounted to the MWA, the axial mode disturbance is imparted by manually depressing and releasing the MWA in a similar manner as a diver on a diving board. The amplitude (acceleration) of the disturbance is controlled by the crew and a wide range is achievable from marginally discernable (0.21mm) to well beyond destabilization, and break-up of the interface ($>13.60$mm).

- **Push**: The Push disturbance consists of a single lateral translation of the vessel. The set screw mounting the vessel to the MWA is loosened, allowing the astronaut to push the container left or right in the field of view creating an impulsive slosh-type disturbance. The translation distance begins small and increases to up to 33mm (spanning linear and nonlinear regimes until breakup of the interface).

- **Slide/Slosh**: This extension of the Push disturbance is called Slide or Slosh, and consists of a full period lateral oscillation. The input frequency is approximately that of the natural frequency of the interface as identified by the crew, and is held approximately constant while varying the amplitude.

- **Multi-Slide**: As the name suggests, the Multi-Slide disturbance is a sequence of Slide/Slosh disturbances imparted without pause and composed of more than one period. The frequency of oscillation is held approximately constant while the displacement amplitude is varied.

- **Swirl**: To impart the Swirl mode disturbances, the CL vessel is moved in a circular or elliptical pattern of approximately 30 to 40 millimeters in diameter in a motion consisting of 1–5 periods on the MWA surface. Large amplitude swirls create centrifugal force-dominated vortical flows. Such disturbances were only performed for CL2 and the data has not been reduced to date.
1.3.3 CL Flight Operations Summary

CFE-CL was performed 6 times aboard ISS by astronauts M. Fincke (2), W. McArthur (1), J. Williams (2), and P. Whitson (1) on Expeditions 9, 12, 13, and 16 between August 28th, 2004 and November 16th, 2007. The highlights of each operation are outlined below:

1. August 28th, 2004 (GMT 2004-241), CL2-1, M. Fincke, Nominal Science Run
   - Successfully completed all primary science objectives with the Pinning lip flooded in many cases
   - Introduced the method for imparting Axial mode disturbances.
   - Extra Science: Droplet ejection, ‘hourglass’ draining phenomena in Smooth cylinder, and droplet-wall impact and rebound dynamics.

   - Demonstrated a centrifugal spinning method used to clear the Pinning lip of liquid and reset the experiment. The method was only partially successful as the Pinning lip was not completely cleared of liquid
   - Repeat Push, Slide, and Axial mode disturbances
   - Supplemental Science: Depth effect on the Push disturbance type

   - Successfully cleared the Pinning lip of liquid using a refined version of Fincke’s centrifuge method, resulting in the ability to repeat the experiment indefinitely
   - Repeat Push, Slide, and Axial mode disturbances with the camera mounted to the MWA, which resulted in the inability to obtain certain Axial mode disturbances data due to the loss of a stationary reference point.
   - Extra Science: Additional droplet-wall impact and rebound dynamics and liquid jetting event due to large Axial disturbances

   - Revision and perfection of McArthur’s centrifuge method used to clear the Pinning lip
   - Repeat Push, Slide, Multi-Slide and Axial mode disturbances with the camera correctly mounted to the ISS rail
   - Extra Science: Significant droplet/jet ejections, and droplet impact & rebound dynamics

5. August 30th, 2006 (GMT 2006-242), CL1-1, J. Williams, Nominal Science Run
   - Improvised method to address wetting anomaly
   - Successful completion of Axial and Push science objectives for Pinning and Smooth cases
Supplemental Science: Depth effect on Push disturbance mode


- Large amplitude Axial disturbances with destabilization and droplet ejection
- Due to increased stability of droplets residing in the Pinning lip (due to the larger contact angle), large accelerations were needed to clear the Pinning lip. Apparently, such high accelerations could not be easily generated by hand. During attempts to clear the Pinning lip, excessive force led to damage of the CL1 hardware resulting in premature termination of the experiment.

1.3.4 CL Primary Science Summary

Over 350 primary and extra science events have been reduced to date, where significant contributions include both experimental results and numerical comparisons. Only a small subset of the data is provided here. The complete database may be found at http://cfe.pdx.edu. To date, only damped interface oscillations (frequency and decay) as functions of fluid properties, wetting, contact line condition, disturbance type, and amplitude have been pursued. Representative results for Axial and lateral mode passive fluid response is shown in Figure 1.4 for CL1 (partial wetting) and CL2 (perfect wetting). In each figure Pinned and Smooth contact line boundary conditions are compared. There is a clear difference in damping rate, frequency, and qualitative waveform depending on the contact line condition.

- The ‘stiffer’ pinning condition produces higher frequencies for all disturbance modes.
- Pinning interfaces generally exhibit lower damping rates than their Smooth cylinder counterparts.
- Larger contact angles produce higher frequencies and lower damping rates. This is immediately obvious by comparing CL1 and CL2 and gives rise to a CL1 natural frequency of approximately 2.5-fold that of CL2.
- The most prominent difference between Pinning and Smooth responses is found in the partially wetting CL1 lateral mode case in Figure 2.15. The first inertial peak of the Smooth response abruptly decays between 2 and 4 seconds while its pinned counterpart decays more gradually.
- The damped oscillation profiles diverge between Pinning and Smooth cylinders as disturbance amplitudes increase.
- For the current CL test conditions, fluid depth has only a slight effect on passive interface response–depth to radius ratios down to 0.26.

1.3.5 CL Numerical Comparison

The CL database may be used to benchmark ‘large’ length scale CFD models. As part of such a demonstration, and in collaboration with J. Klatte and M. Dreyer (of ZARM and NASA/CR—2009-215586.
Figure 1.4: Comparisons of passive fluid response in Pinned and Smooth cylinders to Axial and Push disturbances for CL1 ($\theta = 48.7^\circ$) and CL2 ($\theta = 0^\circ$).
the University of Bremen, Germany), blind numerical predictions were made using the open source OpenFOAM CFD package in an effort to model the CL experiments. Details of the numerical configuration can be found elsewhere [3] with a brief overview and summary of results presented here.

The numerical model was configured without knowledge of the experimental results; i.e. no hints were given as to run time, required mesh resolution, or any other numerical input parameters. Only physical dimensions, fluid properties, wetting conditions, and input accelerations were provided to the numerical analyst. [Note that the input disturbance acceleration was computed using the input disturbance position data, smoothed using a Loess method before central differences were computed. The smoothing methods were varied, but the CFD results were insensitive—coarse and highly smoothed data produced nearly identical results.] Optical distortions were accounted for in both numerical predictions and experimental data.

Comparisons were made for several Push and Axial mode disturbances possessing smooth and pinning boundary conditions. Example comparisons for Axial and Push modes are presented in Figure 1.5. In general, agreement is most favorable for the perfectly wetting condition of CL2, Figures 1.5(c) and 1.5(d). This is in part due to the highly damped nature of these flows, which naturally reduces the sensitivity of the flow on the particular boundary condition applied at the contact line—Smooth and Pinning cylinders respond similarly. Discrepancies arise most noticeably for the partial wetting case of CL1, where despite the poorer agreement the Pinning cylinder results (Figure 1.5(b)) fair better than those of the Smooth cylinder (Figure 1.5(a)). The increased inaccuracy is primarily due to the choice of contact line boundary condition, and is readily observed over the manifold weakly damped oscillations.

Several practical conclusions may be drawn for these oscillation comparisons: (1) The current OpenFoam model does surprisingly well to predict the large length scale capillary phenomena for highly wetting systems with a simple fixed contact angle boundary condition at the contact line. (2) The model may be successfully tuned via pre-calculations improving the likelihood of accurate and efficient ‘blind’ computations for design and analysis. (3) The greatest efforts to further improve the general numerical approach should focus on the boundary conditions necessary to specify partial wetting systems with contact angle hysteresis. Spacecraft fluid systems employing such fluids (i.e. water processing systems) will likely require parametric studies for the various conditions that can arise at the contact line represented in their extremes by perfect slip and perfectly pinned conditions.

1.3.6 CL Database Description

The CL database is publicly available at http://cfe.pdx.edu with digitized events categorized for subsequent data reduction and research. Each CL event is accompanied by an MPEG-1 video and corresponding datasheet describing physical parameters, tracking methods, raw data, and preliminary results. Datasheets are designed such that all information is presented in a manner such that one can repeat the data reduction exactly if desired. A summary page is also provided where information about each individual datasheet is presented in a single location along with video and datasheet links. The intent is to provide pertinent numerical information spanning all of the data in a single location allowing comparison of various
Figure 1.5: Representative numerical comparisons with sample CL experiments: triangles are numeric, circles are experiments.
parameters. An overview of how the database can be used is shown in Figure 1.6. The primary components of the database are the summary page, MPEG-1 video, and the individual datasheets corresponding to each video or event. Each datasheet and corresponding video can be accessed through the summary page. In addition, the summary page contains select statistics and results obtained from the individual datasheets. The arrows 1-F and 5-F indicate this type of flow where ‘F’ indicates ‘File Open.’ In addition to simply reading the data, one can take the original video, prepare it, and digitize it on ones own terms. This is achieved by following the procedure between 2-Read, 3-Convert, and 4-Digitize.

The original MPEG-1 video is read into the freeware program VirtualDub [4] and saved as an uncompressed AVI, which completes the conversion process. The converted video can then be digitized using the freeware program Spotlight-8 [5]. At this point the datasheets accompanying the video can be reconstructed by the user. The complete database along with video, updates, and current information can be found at http://cfe.pdx.edu. Custom versions of the data and video may be obtained on DVD by contacting the lead author (R.M.J.).

1.3.7 Extra Science

Numerous ‘extra science’ events were also captured on video and include liquid jetting, droplet impact and satellite rebound dynamics, air entrainment during Axial disturbances, annular ‘hourglass’ film draining, wetting gradient effects, contact line stability, and more. A selection of these extra events are briefly discussed here with the expressed purpose of demonstrating the range of phenomena that may be further mined from the CL experiments.

- Jetting: During CL operations the disturbance amplitudes were increased until surface breakup occurred. If an Axial mode disturbance is large enough, destabilization
of the interface occurs resulting in droplet ejection. If the disturbance is further increased a liquid jet is formed which eventually breaks up into a stream of drops. Several parameters affect whether jetting occurs, including disturbance amplitude, frequency, and waveform. As amplitudes become large the possibility of ejection increases; however, it is found that it must be coupled with a sufficiently high frequency and appropriate waveform. This is evident in Figure 2.31 where the ‘below’ event produces no ejection, ‘critical’ produces a single stationary droplet, and the ‘above’ event results in jetting. The similarity between disturbances but very different fluid responses indicates that a narrow region in which drop ejection and jetting occurs. [Note that the critical frequency for CL2 is approximately 2.50Hz or 2.5-fold the natural frequency. Note also that the velocity waveform for the ‘critical’ case is nearly symmetric about the t-axis, while the ‘above’ (jetting) case has a net positive velocity, and the ‘below’ case has a net negative velocity.]

- **Contact Line Stability:** An analogous situation arises when lateral mode disturbances become large in the Pinning cylinder. In this case the contact line de-pins from the Pinning lip causing it to flood with liquid as shown in Figure 1.8. Such destabilization occurs repeatedly during the CL experiments providing opportunities to establish the critical acceleration environment that leads to depinning of the contact line.

- **Droplet Impact and Rebound Dynamics:** On numerous occasions following interface breakup, the astronauts would subject the vessel to very large axial mode
disturbances before resetting the experiment. The intent was to produce jetting and stream of droplets that would then bounce, slide, and roll about the chamber eventually adhering to dry walls or coalescing with liquid films or bulk interfaces. Several such images are displayed in Figure 1.9. It was found that if a droplet is greater than a certain size, when impacting and adhering to a dry wall of partial wettability a satellite droplet is ejected. The process repeats until the ejected droplet is small to the point viscous forces prevent further ejection. Several such events are provided in the CL database with only a handful being analyzed to date [3].

- **Contact Angle Variation:** During the CL1 experiments anomalous wetting was observed in the Smooth cylinder. Various static interfaces are shown in Figure 1.10 as a function of fluid depth. The local essentially axial wetting variations, caused either by a poorly applied coating or by a locally crazed surface (observed in the flight hardware), led inadvertently to new science since an array of contact angles could be tested in a single cylinder by varying liquid depth. Contact angles were backsolved using the equilibrium surface curvature.

- **Hourglass Formation and Draining:** During the first Slide tests of CL2, Astronaut M. Fincke quickly observed the gradual development of an ‘hourglass’ configura-
tion following repeated large amplitude disturbances in the perfectly wetting smooth cylinder only. An example may be observed in the first frame of Figure 1.9, Smooth cylinder. The configuration was a nuisance for the primary objectives and was frequently erased using the centrifuge methods, but data on the rate of its formation to a variety of input disturbances, its dimensions, its passive recovery to the desired equilibrium state, and its drainage under noticeable background accelerations was recorded and is available for further investigation. Such configurations are of practical interest because they readily form in highly wetting systems subject to various disturbances and time-dependent acceleration fields not uncommon to spacecraft fuel tanks. They are also of interest in that they contribute to axial pumping of the fluid in response to lateral excitations, a phenomena of which might be exploited or of concern to any number of applications. This non-equilibrium configuration is addressed in greater, but still superficial, detail elsewhere [3].

These extra science examples demonstrate the range of phenomena occurring during the CL operations as a byproduct of the primary science investigation. All cases of such ‘extra science’ events were not investigated exhaustively, but a number of the events are noted in the database and provide potential science opportunities for interested parties. Additional extra science data includes bubble entrainment due to Axial disturbances, entrained bubble coalescence, annular film draining, droplet-wall coalescence, droplet film rebound, swirl mode disturbances, and probably others. Original video can be found at http://cfe.pdx.edu.

1.4 Vane Gap (VG)

It is well known that careful selection of geometry has the potential to control large amounts of fluid in a reduced gravity environment. Containers with interior corners are one such choice as the corner tends to act as a capillary conduit driving spontaneous flows along its length. It is essential in such systems that the fluid ‘wets’ the corner which can be determined from the Concus-Finn critical corner wetting condition [6, 7]. Unfortunately, this condition is significantly complicated 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. Intended or unintended positional changes of such vanes can have a dramatic impact on the fluid configuration. Two CFE VG test vessels are devoted to investigate such phenomenon using a right cylinder with an elliptic cross-section and a single and rotatable central vane that does not contact the container walls as shown in Figure 1.11. Critical vane gap wetting, dewetting, and an asymmetric bulk fluid shift occur in such containers as a function of vane angle.

1.4.1 Hardware Description

The two VG vessels are identical in every aspect except wetting characteristics and vane dimensions. VG1 is perfectly wetting ($\theta = 0^\circ$), while VG2 is partially wetting ($\theta \approx 48^\circ$). The major and minor diameters of the cylindrical ellipse are 5.08cm and 3.378cm, respectively. The internal height of the fluid chamber is 12.7cm measured from the base to the lid. A volume of 49.1cc of 10cs red-dyed Silicone oil is used in both vessels where the fluid depth is 3.81cm assuming a flat surface. The central vanes in both VG1 and VG2 are rectangular
Figure 1.11: VG image, solid model, and a cross-sectional schematic indicating the quadrant number, gap distances, vane angle $\phi$, and absolute acute interior angle $\alpha$.

with dimensions 3.134cm by 11.43cm, and vane thicknesses 0.20cm and 0.50cm, respectively. The vane pivot axis is coaxial with the ellipse but gap dimensions are 0.0838cm and 0.167cm when the vane is aligned with the minor diameter as shown in Figure 1.11. These gap dimensions represent a 0.95 and 0.90 dimensionless gap using the minor axis radius for normalization. Thus two ‘gaps’ can be tested for each vane angle, $\delta_1$ and $\delta_2$. The vane is able to rotate $\pm 360^\circ$ with $< \pm 1^\circ$ resolution. After the fluid is deployed, the crew rotates the vane at prescribed increments allowing significant time (up to 15 minutes) for the fluid to equilibrate between each rotation.

1.4.2 VG Flight Operations Summary

CFE-VG was performed aboard ISS during nine operations performed by astronauts J. Williams (1), S. Williams (6), C. Anderson (1), and P. Whitson (1) during Expeditions 13–16 between September 5th, 2006 and October 22nd, 2007. The highlights of each operation are highlighted below:

1. September 5th, 2006 (GMT 2006-248), VG1-1, J. Williams, Nominal Science Run
   - Successful completion of all science objectives for first half of crew procedures
   - Completed two complete CW vane rotations
   - Clearly identified critical wetting angles to better than anticipated precision
   - Data suggests third global critical wetting condition (later called bulk shift)

   - Successful completion of revised science run to determine equilibrium configurations in Quadrant 1 (Q1)
• Positive identification of global asymmetric interface and associated critical vane angle
• Identification of container asymmetry and impact on interface


• Successful completion of revised science run to determine equilibrium configurations in Q4
• Positive identification of global asymmetric interface and associated critical vane angle
• Identification of container asymmetry and impact on interface (global shift requires > 15min.)
• Verification of critical global shift angle outside of gap wetting envelope

4. April 6th, 2007 (GMT 2007-096), VG2-1, S. Williams, Voluntary Science (360° CW dry and wet tests)

• Successful completion of nominal science run for CW vane rotations for dry and wet tests
• Positive identification of critical wetting and dewetting angles and hysteresis
• Global asymmetric wetting not observed
• Preliminary symmetry of wetting conditions observed


• Successful completion of all revised science run operation and objectives
• Identified critical angles with high precision
• Mapped critical de/wetting hysteresis


• De/wetting angles in Q1 and Q2 including hysteresis
• Extra Science run relocating fluid to lid, identified new meta/stable interface configuration for all vane angles
• Drain procedure reveals unstable film on ellipse walls following a rupture event initiated at the drain exit port


• Demonstration of three new interface configurations: filament, asymmetric right (vane at 90°), asymmetric left (vane at 0°)
1.4.3 Static Wetting Configurations

The vane dial angle is converted to the absolute acute interior angle $\alpha$ between the vane and the major axis of the ellipse as shown in Figure 1.11. Thus, $\alpha$ in the various quadrants is determined from the vane angle $\phi$: For $0 < \phi < 90^\circ$, $\alpha = \phi$, for $90^\circ < \phi < 180^\circ$, $\alpha = 180^\circ - \phi$, for $180^\circ < \phi < 270^\circ$, $\alpha = \phi - 180^\circ$, and for $270^\circ < \phi < 360^\circ$, $\alpha = 360^\circ - \phi$.

The quadrant (Q1 through Q4) where the particular wetting occurs is also of concern and tabulated.

Each vane angle produces sub- and/or supercritical wetting conditions for the two vane gaps as shown in Figures 1.12 (VG1 and VG2). Supercritical conditions are characterized by spontaneous corner wetting. In addition to vane gap wetting and dewetting a third wetting regime is observed where the fluid shifts from one side of the vane to the other ($\phi = 53^\circ$, Figure 1.12(a)). A detailed theoretical analysis of this phenomenon has been completed and is presented elsewhere [8]. Experiment repeatability is high ($\pm 1^\circ$), but static interfaces are not always established at angles sufficiently close to the critical angles leading to a range within which the ‘critical angle’ is certainly crossed.

Figure 1.12(a) presents several key interfaces for a $0^\circ$ to $180^\circ$ sweep for VG1. The sequence begins with subcritical equilibrium surfaces at $0^\circ$ and $36^\circ$. Small-gap wetting (SGW) is observed at $43^\circ$ and a complete bulk shift (BS) at $53^\circ$ where the fluid completely migrates to the left side of the vane. Notice that a bulk shift occurs before large-gap wetting (LGW) which takes place at $59.5^\circ$. Small-gap wetting (SGW) and large gap wetting (LGW) along with a complete bulk shift persist at $90^\circ$. Large gap dewetting (LGD) occurs at $127.5^\circ$ followed by a reverse bulk shift (BSR) at $134.5^\circ$, and small gap dewetting (SGD) at $150.5^\circ$. The original but reflected configuration of $0^\circ$ returns at $180^\circ$.

VG1 critical wetting and dewetting angles $\alpha$ are reported in Table 1.2 for the four quadrants. The data are arranged in order of occurrence: for increasing $\alpha$: small gap wetting, bulk shift, large gap wetting, and for decreasing $\alpha$: large gap dewetting, reverse bulk shift, and small gap dewetting. When considering all uncertainties these trends are common in all quadrants except in Quadrant 4 where the bulk shift clearly occurs before the small gap wetting. This result signals the certain presence of slight container asymmetries which have been quantified and will be published subsequently. This phenomena was uniquely
(a) Equilibrium interfaces for VG1 for vane dial angles: 0°, 36°, 43°, 53°, 59.5°, 90°, 127.5°, 134.5°, 150.5°, 180° (from top left to bottom right).

(b) Equilibrium interfaces for VG2 for vane dial angles: 0°, 45°, 50°, 58°, 72°, 76.5°, 90°, 120°, 135°, 180° (from top left to bottom right).

Figure 1.12: Equilibrium interfaces for VG1 and VG2 for vane angles between 0° and 180°.
Table 1.2: Critical wetting conditions for VG1: small gap wetting (SGW), bulk shift (BS), large gap wetting (LGW), large gap wetting (LGD), bulk shift reversal (BSR), small gap dewetting (SGD).

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGW</td>
<td>40.0° ± 3.0°</td>
<td>43.3° ± 2.3°</td>
<td>42.5° ± 2.0°</td>
<td>47.3° ± 2.3°</td>
<td>42.94°</td>
</tr>
<tr>
<td>BS</td>
<td>48.0° ± 5.0°</td>
<td>46.3° ± 0.8°</td>
<td>47.5° ± 2.5°</td>
<td>42.5° ± 2.5°</td>
<td>-</td>
</tr>
<tr>
<td>LGW</td>
<td>51.8° ± 0.8°</td>
<td>47.3° ± 2.3°</td>
<td>56.0° ± 3.0°</td>
<td>50.8° ± 3.8°</td>
<td>51.29°</td>
</tr>
<tr>
<td>LGD</td>
<td>52.8° ± 1.3°</td>
<td>48.0° ± 2.0°</td>
<td>58.3° ± 6.8°</td>
<td>53.3° ± 4.3°</td>
<td>51.29°</td>
</tr>
<tr>
<td>BSR</td>
<td>43.8° ± 7.8°</td>
<td>47.0° ± 2.0°</td>
<td>48.3° ± 1.8°</td>
<td>42.3° ± 2.3°</td>
<td>-</td>
</tr>
<tr>
<td>SGD</td>
<td>41.8° ± 5.8°</td>
<td>41.0° ± 0.5°</td>
<td>43.0° ± 2.0°</td>
<td>45.8° ± 0.8°</td>
<td>42.94°</td>
</tr>
</tbody>
</table>

Table 1.3: Critical wetting conditions for VG2: small-gap wetting (SGW), large gap wetting (LGW), large gap dewetting (LGD), small gap dewetting (SGD).

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGW</td>
<td>57.8° ± 2.8°</td>
<td>53.5° ± 3.5°</td>
<td>57.0° ± 4.0°</td>
<td>55.0° ± 3.0°</td>
<td>53.47°</td>
</tr>
<tr>
<td>LGW</td>
<td>67.5° ± 5.5°</td>
<td>67.5° ± 5.0°</td>
<td>71.3° ± 5.3°</td>
<td>68.3° ± 6.8°</td>
<td>62.29°</td>
</tr>
<tr>
<td>LGD</td>
<td>53.8° ± 8.3°</td>
<td>55.0° ± 8.0°</td>
<td>58.3° ± 8.3°</td>
<td>60.0° ± 10.0°</td>
<td>62.29°</td>
</tr>
<tr>
<td>SGD</td>
<td>43.0° ± 5.0°</td>
<td>45.8° ± 7.8°</td>
<td>45.5° ± 5.5°</td>
<td>43.8° ± 8.3°</td>
<td>53.47°</td>
</tr>
</tbody>
</table>

exploited providing a third dynamic wetting problem could be investigated for a potentially crucial critical wetting condition. Despite the presence of known vane alinement asymmetries, subsequent numerical computations confirm that the bulk shift can occur even for perfectly symmetric containers. These results are perhaps surprising and to be addressed in greater detail in a forthcoming article where both advantages and cautions for such strong dependence of fluid position on such slight changes or asymmetries in container geometry is addressed. Comparisons of experimental and theoretical interfaces are provided in Figure 1.13 for VG1. Theoretical critical angles are listed in Table 1.2. Only SGW and LGW are predicted for the ideally symmetric configurations analyzed.

Figure 1.12(b) provides several key interfaces for a 0° to 180° sweep for VG2. Static subcritical interfaces at 0° and 45° are shown before stick-slip small gap wetting is initiated at 50° and completed by 58°. Large gap wetting begins at 72° and is complete by 76.5°. No bulk shift is observed. Partial large-gap dewetting occurs at 120° and is complete by 135°, where small-gap dewetting begins. Small gap dewetting is complete by 180°. Table 1.3 lists the distilled critical wetting angles in the various quadrants for VG2. Tolerances and asymmetries in VG2 are similar to VG1 but symmetry and order in wetting and dewetting angles are consistent in all quadrants. The hysteresis in wetting behaviors is clear from the table entries. The experimental data is compared with numerical predictions in Figure 1.14 for VG2. Theoretically predicted [8] critical angles are listed in Table 1.3 where applicable.
Figure 1.13: VG1 experiment and computations for vane angles: $0^\circ/0^\circ$, $30^\circ/30^\circ$, $43^\circ/45^\circ$, $59.5^\circ/60^\circ$, $90^\circ/90^\circ$, $125.5^\circ/125^\circ$, $131^\circ/130^\circ$, $139.5^\circ/140^\circ$, $150.5^\circ/150^\circ$, and $180^\circ/180^\circ$ (Experiment/Surface Evolver).

Figure 1.14: VG1 experiment and computations for vane angles: $0^\circ/0^\circ$, $45^\circ/45^\circ$, $50^\circ/51^\circ$, $58^\circ/57^\circ$, $72^\circ/72^\circ$, $76.5^\circ/78^\circ$, $90^\circ/90^\circ$, $120^\circ/120^\circ$, $135^\circ/135^\circ$, and $180^\circ/180^\circ$ (Experiment/Surface Evolver).
1.5 Interior Corner Flow (ICF)

The CFE Interior Corner Flow (ICF) experiments investigate bubble displacement as a result of secondary imbibition in tapered polygonal conduits. The ICF1 vessel has a geometric cross-section of a 30°-75°-75° isosceles triangle that tapers uniformly (geometrically similar triangles) as shown in Figure 1.15(a). The height of the triangular cross-section at the base is 40.0mm and at the top is 26.0mm over a height of 127.0mm—all faces tilt at 3.155°. The test fluid is 10ml of 5cs Silicone oil. ICF2 is a rectangular cross-section that tapers on two faces to a line as shown in Figure 1.15(b). The base rectangle measures 40.0mm wide by 10.0mm deep. The two faces tilt at 8.95° over a height of 127.0mm. The test fluid is 9.02ml of 2cs Silicone oil.

The basic operation of the experiment is as follows: the fluid is injected into the tapered test chamber from the reservoir. During injection, the fluid immediately wicks along the corners toward the vertex. A transition in the flow takes place once the liquid reaches the vertex. This secondary imbibition appears like a bubble migration where the ullage or ‘bubble’ migrates toward the base, an example of which is shown in Figure 1.16 for ICF2. The leading and trailing menisci are labeled in the figure as $z_2$ and $z_1$, respectively. The bubble migration continues until the leading interface reaches the end of the conduit, the flow ceasing shortly thereafter. The experiment may be ‘reset’ to the initial state by manipulating the valves and reservoir piston or by using a centrifuge method to return the fluid to the base of the container. Either method permits the experiment to be re-run indefinitely. The four variations of the experiment are referred to as Dry, Wet, Open Loop, and Bubbly tests and defined below:

**Dry:** These tests are characterized by little to no liquid film on the interior surfaces during the flow. This situation occurs during the first run of the experiment since the interior surfaces are initially completely dry. However, during repeat tests, a thin prewetting
film is present but the fluid behaves essentially identically to the initially dry test. Thus, all such tests are classified as ‘Dry’. These test conditions are achieved when using the valves and reservoir piston to reset the experiment.

**Wet:** When the fluid is manually returned to the base of the tapered section using a centrifuge method, significant liquid films remain on the interior walls that drain slowly. The presence of these thick films increases capillary flow rates. Such tests are classified as ‘Wet’.

**Open Loop:** For these tests the valves are opened permitting a parallel counter clockwise flow between the base and vertex through a bypass conduit. The ‘Open Loop’ tests are considered a subset of the Wet condition due to the moderately thick films established before each test.

**Bubbly:** The fourth event type is called ‘Bubbly’ flow which is a repeat of previous tests but with numerous bubbles in the fluid. A variety of bubble sizes are created by vigorously shaking the container, resetting the fluid to the base, and then allowing the flow to proceed passively. These tests are also a subset of the Wet condition due to the presence of thick films. The flow with entrained bubbles demonstrates the passive phase separation capability of such geometries and is used for theory development.

### 1.5.1 ICF Flight Operations Summary

CFE ICF was performed 4 times aboard ISS by astronauts M. Lopez-Alegria (1) and S. Williams (3) on Expeditions 14 and 15 between August 28th, 2004 and November 16th, 2007. The highlights of each operation are outlined below:

1. March 10th, 2007 (GMT 2007-069), ICF1-1, M. Lopez-Alegria, Nominal Science Run
   - Successful completion of all science objectives for first half of crew procedures
   - Completed dry fill and two wet fill tests
   - Low liquid volume limiting experiment duration observed
2. April 7th, 2007 (GMT 2007-097), ICF1-2, S. Williams, Voluntary Science (all nominal operations)
   - Successful completion of all revised science run operation and objectives
   - Demonstration of centrifugal method to rapidly redeploys liquid
   - Provision of critical data for global fluid reorientation
   - Demonstration of high Loop test flow rates
   - Demonstration of passive bubble separations

3. April 29th, 2007 (GMT 2007-119), ICF2-1, S. Williams, Voluntary Science (Complete nominal operations: Dry, Wet, Open Loop and Bubble tests)
   - Demonstration of centrifugal method to rapidly redeploy liquid
   - Variety of large bubble migration/ separation tests resulting from lateral excitations
   - Variety of small bubble migration/ separation tests resulting from vigorous axial excitations
   - Demonstrated clear ability of corner flows to filter, separate, and coalesce bubbly two-phase systems passively
   - Coarsening was also observed for most cases involving multiple bubbles and long flow times

   - Additional Wet and Bubbly tests
   - Small numbers of large bubble interactions observed (smaller bubbles overtake and merge with larger bubbles)

1.5.2 ICF1 Results Summary

A low volume of low viscosity fluid in the vessel permitted only limited duration data collection for the leading interface \(z_2\) before it reached the base of the container. Even for the trailing meniscus \(z_1\), less than 20 seconds of ‘clean’ data could be obtained for the trailing interface before base effects became dominant. This trend is evident in Figure 1.17(a) which plots the full duration for the trailing interface \(z_1\). Figure 1.17(b) presents the first 20s where nearly linear trends are observed. The characteristic time scale computed from the theoretical model developed during the flight of the ICF experiments is \(\sim 680\) assuming a virtual vertex [9], whereas the total experimental flow time is less than 40s. Thus, the data in effect represent only a snapshot of the intended idealized flow rather than a long-time characterization. However, for the ‘snapshot’ in Figure 1.17(b), the data is linear and can be thought of as a local derivative of the long-term behavior.

From Figure 1.17(b) it is immediately obvious that the results vary depending on the test type. In general, the Open Loop tests produce the highest flow rates followed by Wet and then Dry conditions. The flow rates are somewhat sporadic between event types; however, the Open Loop, Wet, and Dry cases produce average dimensional trailing meniscus velocities.
of 1.37, 1.06, and 0.85 mm/s, respectively. The linear trailing meniscus velocities for the various tests are non-dimensionalized (by way of an asymptotic theoretical analysis [9] to be published in greater detail elsewhere) and listed in Table 1.4. For the fluid properties and geometry of ICF1 the analytic dimensionless velocity is 1.52. The Open Loop, Wet, and Dry average dimensionless velocities are 2.33, 2.09, and 1.64, respectively. The most favorable agreement with the present theory is fortunately with the most applicable Dry tests yielding an average error of 7.3%. A complete set of comparisons can be found in Table 1.4 which includes dimensional and non-dimensional linear fit coefficients as well as statistical $R^2$ values and % error calculations with respect to the dimensionless analytic estimate.
1.5.3 ICF2 Results Summary

Unlike the underfilled ICF1 vessel, the ICF2 tests produced long-duration flow events lasting up to 7 minutes for trailing $z_1$ meniscus and nearly 4 minutes for leading $z_2$ meniscus. Figure 1.19 presents both $z_1$ and $z_2$ on a single plot with the conduit drawn at left to scale. As with ICF1, Dry, Wet, Open Loop, and Bubbly test are conducted. Approximately three distinct rates are obvious with Wet and Dry test behaving similarly, with Bubbly tests flowing faster and the Open Loop tests even faster. The Bubbly flows progress at a rate slightly greater than the Wet/Dry rate due to bubble coalescence which has been since addressed theoretically and will be addressed in a subsequent publication. An expanded scale of the leading and trailing interfaces can be found in Figure 1.20(a) for $z_1$ and Figure 1.20(b) for $z_2$.

The initial Dry run produces a curve fit of $z_1 = 6.32 \, t^{0.40}$ whereas Wet fits are $z_1 = 6.21 \, t^{0.40}$ and $z_1 = 7.22 \, t^{0.38}$. The rates are very similar, but if the two Wet rates are averaged they are slightly higher than the Dry rate, which is expected. The single Bubbly flow produces a curve fit of $z_1 = 5.18 \, t^{0.44}$ and a rate which is always slightly higher than the Dry and Wet rates. During the bubble flows, bubbles are forced into the corner with only the smallest bubbles ($< 0.7 \text{mm diameter}$) passing without coalescing. The Open Loop power-law curve fits reveal higher rates, $z_1 = 13.91 \, t^{0.30}$ and $z_1 = 16.00 \, t^{0.27}$, than the other test types. The leading meniscus $z_2$ is shown in Figure 1.20(b) on an expanded scale. The curves are linear over the larger time scale, with $R^2$ values very near 1 when fit with linear regressions. Trends for $z_2$ are similar to those reported for $z_1$, with the hierarchy of migration rates being the same.

In preliminary summary of the CFE ICF experiments, it appears that the geometric impact of ICF-like tapered polygonal sectioned containers can be reasonably and explicitly predicted [10]. This implies that systems can be designed to provide desired pumping...
Table 1.4: Dimensional and dimensionless linear fit coefficient with $R^2$ statistics for ICF1 including % error with the theoretical dimensionless coefficient of 1.52.

<table>
<thead>
<tr>
<th>Data Name</th>
<th>Dim'l Slope (mm/s)</th>
<th>Dim'less Slope</th>
<th>% Error</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0724-0805 Dry 1</td>
<td>0.86</td>
<td>1.66</td>
<td>9.20%</td>
<td>0.9913</td>
</tr>
<tr>
<td>4045-4135 Dry 2</td>
<td>0.89</td>
<td>1.72</td>
<td>13.2%</td>
<td>0.9945</td>
</tr>
<tr>
<td>6125-5215 Dry 3</td>
<td>0.80</td>
<td>1.55</td>
<td>2.00%</td>
<td>0.9825</td>
</tr>
<tr>
<td>0651-0751 Wet 4</td>
<td>1.28</td>
<td>2.47</td>
<td>62.5%</td>
<td>0.9952</td>
</tr>
<tr>
<td>1442-1612 Wet 5</td>
<td>0.91</td>
<td>1.77</td>
<td>16.5%</td>
<td>0.9944</td>
</tr>
<tr>
<td>2026-2136 Wet 6</td>
<td>1.20</td>
<td>2.31</td>
<td>52.0%</td>
<td>0.9964</td>
</tr>
<tr>
<td>3375-3858 Wet 7</td>
<td>1.22</td>
<td>2.37</td>
<td>56.0%</td>
<td>0.9922</td>
</tr>
<tr>
<td>4427-4548 Wet 8</td>
<td>1.05</td>
<td>2.03</td>
<td>33.6%</td>
<td>0.9941</td>
</tr>
<tr>
<td>4800-4910 Wet 9</td>
<td>1.00</td>
<td>2.17</td>
<td>42.8%</td>
<td>0.9844</td>
</tr>
<tr>
<td>5525-5636 Open Loop 10</td>
<td>1.12</td>
<td>1.94</td>
<td>27.6%</td>
<td>0.9954</td>
</tr>
<tr>
<td>5831-5942 Open Loop 11</td>
<td>1.61</td>
<td>3.12</td>
<td>105%</td>
<td>0.9958</td>
</tr>
<tr>
<td>8727-8858 Wet 13</td>
<td>0.79</td>
<td>1.53</td>
<td>0.66%</td>
<td>0.9889</td>
</tr>
</tbody>
</table>

Figure 1.19: ICF2 data for $z_1$ and $z_2$ for Dry, Wet, Open Loop, and Bubbly flows with the conduit geometry drawn to scale at left.
Figure 1.20: ICF-2 data representing the $z_1$ interface under various experimental conditions.

rates for a variety of applications including low speed bubbly flow separations. For such calculations the desired flow rate would be used as an input and the container geometry would be ‘derived’. Ground-based applications for such a method are also relevant to microfluidics phenomena.

1.6 Conclusion

The fact that such simple experiments can yield enough quantitative data to support fundamental and applied numerical and theoretical investigations argues well in support of continued efforts by space entities to pursue simple experiments benefitting from crew interest and interaction. Arguably more important, intricate, and automated experiments are of higher priority, but such small experiments can fit flexibly into time lines and even be conducted during the crew’s free time if desired (up to 50% of CFE was conducted in this manner). At least three journal articles are expected from the CFE work and several
of the tools developed to analyze the flows have been employed in advanced life support systems [11]. Several follow-on CFE-like experiments have been proposed to and are under development by NASA. The experiments are called CFE-2 and consist of refurbished CFE hardware as well as new builds. The experiments themselves focus on critical geometric wetting in systems with a wide disparity in capillary length scales using the CFE VG approach, and a family of weakly 3-D capillary conduits capable of passive phase separations relevant to liquid processing on spacecraft—akin to CFE ICF. The new hardware exploits design guides developed during this investigation.
Chapter 2

CFE Contact Line Details

Summary. The Contact Line (CL) Capillary Flow Experiments are part of the suite of low-g experiments flown onboard the International Space Station to observe the impacts of various conditions at the moving contact line for fluid interfaces in circular cylindrical containers. An ample CL review aboard ISS was presented in 1 and more may be found in [3], as well as in Appendix 7, but additional non-overlapping details are collected here that might prove of use to subsequent researchers interested in using either the raw or digitally reduced data. The chapter provides a minor review of the CL experiment hardware before discussing details of specific tests, data reduction methods, results, and more in depth comparisons of the experiments and the sample numerical benchmark investigation.

2.0.1 Hardware Review

CL-1 and CL-2 are identical in all respects except for surface coating, contact angle, Pinning lip location, and maximum fluid volume. A single container is composed of four chambers, with two serving as reservoirs and two as test chambers as shown in Figure 2.1. The reservoirs store the liquid when the experiment is not being operated. Figure 2.2 along with Table 2.1 identifies the critical dimensions.

The test chambers are composed of circular cylinders with ellipsoidal lids. The height of the cylinders from the base of the container to the top (excluding the lid) is 146.0mm. The

<table>
<thead>
<tr>
<th>Physical Dimensions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinning Lip Width, $w_{pl}$ (mm)</td>
<td>$7.6 \pm 0.1$</td>
</tr>
<tr>
<td>Cylinder Height, $H_c$ (mm)</td>
<td>$146.0 \pm 0.1$</td>
</tr>
<tr>
<td>Cylinder Diameter, $D_c$ (mm)</td>
<td>$38.10 \pm 0.05$</td>
</tr>
<tr>
<td>Pinning Lip Diameter, $D_{pl}$ (mm)</td>
<td>$43.7 \pm 0.1$</td>
</tr>
<tr>
<td>Acrylic Refractive Index, $N_{acr}$</td>
<td>1.491</td>
</tr>
<tr>
<td>$\theta = 48.7^\circ$ (CL1)</td>
<td></td>
</tr>
<tr>
<td>Base to Pinning Lip, $h_{pl}$ (mm)</td>
<td>$36.9 \pm 0.1$</td>
</tr>
<tr>
<td>Maximum Fluid Volume (mL)</td>
<td>39.04</td>
</tr>
<tr>
<td>$\theta = 0^\circ$ (CL2)</td>
<td></td>
</tr>
<tr>
<td>Base to Pinning Lip, $h_{pl}$ (mm)</td>
<td>$50.8 \pm 0.1$</td>
</tr>
<tr>
<td>Maximum Fluid Volume (mL)</td>
<td>43.44</td>
</tr>
</tbody>
</table>
Figure 2.1: A solid model (left) and image (right) of the CL2 vessel.

Figure 2.2: CL schematic indicating significant physical dimensions (drawn to scale for CL2).
The diameter of both cylinders is 38.1mm with the Pinning lip diameter measuring 43.7mm. The location of the Pinning lip $h_{pl}$ differs between CL1 and CL2 where the distances are 36.9 and 50.8mm, respectively. Maximum fluid volumes are 39.04mL for CL1 and 43.44mL for CL2.

Chemical coatings are applied to the test chambers in an effort to produce partial wetting in CL1 and enhance liquid control in CL2. The entire interior surface of CL1 is rinse coated with FC-724\textsuperscript{1}, a transparent fluoro-polymer surface coating manufactured by 3M Corporation. CL2 is intended to be perfectly wetting ($\theta = 0^\circ$) and only select surfaces are coated in an attempt to better control the liquid during operation. Coating is applied to CL2 above the Pinning lip, including the ellipsoidal cap and inside the groove of the Pinning edge itself. Its application above the Pinning lip promotes a passive return of the liquid as successfully demonstrated during the flight. Coating inside the Pinning lip deters liquid from flooding it. The coated surfaces are identified in Figure 2.3 for CL1 and CL2.

The equilibrium contact angle for Silicone oil on an FC-724 coated surface is determined by measuring the advancing and receding contact angles using a tilted FC-724 coated glass capillary tube \cite{1}. Using the advancing and receding contact angles of $\theta_{\text{rec}} = 47.3^\circ \pm 2^\circ$ and $\theta_{\text{adv}} = 52.2^\circ \pm 2^\circ$ the equilibrium angle of $\theta_{eq} = 48.7^\circ \pm 2^\circ$ is calculated \cite{2}, which is similar to that of certain aqueous systems. All internal surfaces of CL1 are rinse coated, thus the expected equilibrium contact angle is 48.7° and is reported as such when referring to the experiment. Empirical measurements suggest that a lower contact angle is actually produced and is discussed in Section 2.5. Several key surfaces of CL2 are not coated and exhibit a perfectly wetting condition $\theta = 0^\circ$, which is similar to that of many liquid fuels and propellant for spacecraft. These contact angle values along with general fluid properties are listed in Table 2.1.

Contact angle measurements could also be made during the flight tests. For example, the contact angle is measured in each event using a simple method of measuring the meniscus diameter and distance between the contact line and lowest point of the meniscus (at the centerline). If $D_c$ is the cylinder diameter and $h_m$ is the meniscus height, then the contact angle is calculated from

$$\theta = \sin^{-1}\left(\frac{D_c - 2h_m}{D_c}\right),$$ \hspace{1cm} (2.1)

Optical distortion does not affect the measurements due to the locations at which they are taken.

2.1 Various CL Procedures

As stated, the CL experiments are hand-operated, requiring disturbances to be imparted manually by the astronaut. Disturbances are applied to the containers followed by a quiet time where the fluid is allowed to passively settle.

2.1.1 Setup Procedure

Once the experiment is set up on the MWA (as shown in Figure 1.1), the fluid in the reservoirs must be dispensed into the test chambers. This is achieved by opening a valve

\textsuperscript{1}3M has replaced Fluorad coating FC-724 with Novec\textsuperscript{TM} Electronic Coating EGC-1700.
and turning the fill knobs counter-clockwise, which displaces a piston, pushing the fluid into the test chambers (reference Figure 2.1). The fill knob can be turned clockwise, reversing the piston, returning the fluid back into the reservoirs. Not only is this the method of placing fluid into the test chambers, but also of adjusting the fill level. The fluid depth $\kappa$ is the measure of fill level and is defined as the distance from the centerline of the interface to the bottom of the test cylinder (see Figure 2.2). Though the fill level can be modified by operating the fill knobs, it also changes passively as fluid is thrown up the cylinder walls after large disturbances. This is most pronounced in the Smooth cylinder of CL2 and is discussed in greater detail in Section 2.7.3. In general, all of the fluid in the reservoirs is pushed into the test chambers unless depth effects are being investigated. Fluid depth changes were also employed during CL1 tests and will be discussed on connection with a CL1 wetting anomaly in Section 2.1.3.

2.1.2 Interface Depinning and Recovery

As disturbance amplitudes increase, the Pinning surface may destabilize, the Pinning lip may ‘flood’, and the fluid fill the Pinning lip groove—effectively eliminating the ‘Pinned’ contact line boundary condition. The result is a condition very similar to the Smooth cylinder with the fluid behaving similarly in disturbance waveform, frequency, and damping rate. Flooding of the Pinning lip is loosely referred to as depinning. It is always the case for CL2 that depinning leads to the flooding condition. Figure 2.4 represents an image sequence of two Push disturbances where the Pinning lip is flooded after two events.

The experiment is designed to investigate the effects of Smooth and Pinning boundary conditions when subjected to an identical disturbance. With the Pinning lip flooded this is not possible, as both interfaces behave as if they were in Smooth cylinders; this creates twice as much data for investigating an effectively Smooth boundary condition, but detracts from the primary objective. For this reason, a procedure for clearing the liquid from the Pinning lip was develop by several astronauts on orbit (in order M. Fincke, W. McArthur, NASA/CR—2009-215586, 33
J. Williams) and was perfected by astronaut Jeff Williams. The final procedure involves partially draining the Pinning Cylinder, removing the CL vessel from the MWA, and providing a combination of impulsive and centrifugal forces great enough to dislodge the liquid from the pinning edge and drive it to the base of the container. The centrifugal force is created by moving the vessel back and forth in a radial fashion. The impulsive force is created by hitting the container. Combined, the motion is much like the playing of a tambourine. Depinning events occurred many times for the CL2 vessel and only once during the last operation of CL1 by Peggy Whitson. Clearing the Pinning lip was significantly easier for CL2 due to the favorable wetting gradient and lower contact angle. It was found that CL1 required considerable centrifugal and lateral force to reset the experiment, so much in fact, that the force exerted by the astronaut resulted in physical damage to CL1 vessel. Interestingly, in both CL experiments the Pinning lip surface was coated (θ ∼ 48.7°). For CL2 a discontinuous wetting gradient occurs between the Pinning lip and the surface below it where θ = 0°. The result is that the liquid desires to be below the Pinning lip where the contact angle is lower making it is easier to clear the liquid. For CL1 all internal surfaces are coated and no gradient exists in the Pinning cylinder, resulting in only partial success in clearing the Pinning lip, due to the large forces required.

2.1.3 Wetting Anomaly in CL1 Smooth Cylinder

Despite application of the coating in a clean room environment, the wetting characteristics of the CL1 Smooth cylinder exhibited unexpected behavior requiring changes to the in-flight procedures. CL1 is designed to be a partially wetting experiment with all internal surfaces coated with FC-724. However, the Smooth cylinder appeared to exhibit nonuniform wetting properties along the walls near the base of the container only (ref. Fig. 1.10).

With the maximum volume of liquid in the test chamber the interface assumed an
Figure 2.5: The upper plot represents the measured contact angle $\theta$ as a function of fluid depth $\kappa$, while the lower plot indicates the difference in measured contact angle $\Delta \theta$ in a single event due to asymmetry.

asymmetric configuration. After several perturbations of the cylinder, the interface settled to a nearly symmetric orientation where $\theta \approx 10^\circ$–16°. The fill level was then dropped slightly and a new symmetric contact angle of $\approx 36^\circ$ could be determined. Following two perturbations of the cylinder, the interface became asymmetric again taking on values that varied circumferentially between 16° and 33°. The liquid level was finally dropped to a point where $\theta = 4^\circ$, similar to a perfectly wetting (or uncoated) condition. Figure 2.5 indicates this trend where the fluid depth versus the measured contact angle is plotted. The ‘Min’ and ‘Max’ values account for the asymmetry that occurs during specific events, with the lower plot presenting the difference. Significant asymmetries occur near depths of 30.5mm and 27.2mm while symmetric interfaces occur at 29.6mm and below 22mm. The Smooth cylinder for CL1 was dropped to a fill level below 22mm for more than 72% of the events so that a consistent and symmetric interfaces were established. The cause of the wetting anomaly is not exactly known; however, a rough surface due to local crazing (observed pre- and post-flight), a poorly applied coating, or aging during the extended storage ($\sim 2$ years) of the vessel may all be factors. The Pinning cylinder did not produce any wetting anomaly and was stored for the same length of time as the Smooth cylinder. In addition, the coating above the maximum fill level seemed to function properly. The most likely causes of the wetting anomaly seem to be either due to manufacture or improper application of the coating.

Discovery of the wetting anomaly during flight experiments required a special procedure to create both Pinning and Smooth boundary conditions at the prescribed contact angle. The Pinning cylinder was used to create both boundary conditions by changing the depth of the fluid. The Pinning condition is created as usual by filling the cylinder with
Fluid to the Pinning lip, while a ‘Smooth condition’ is created in the Pinning cylinder by withdrawing liquid dropping the contact line below the Pinning lip as shown in Figure 2.6. Such conditions are referred to in the datasheets as ‘Pinned’ when filled and ‘Below Pin’ when the interface is dropped below the Pinning lip. There are at least two disadvantages caused by the procedure. The first is the introduction of a depth effect due to the change in interface height location. This was more pronounced in lateral/slosh disturbances (e.g. Push), but not of consequence for Axial disturbances as discussed in Section 2.5.1. The second disadvantage is that simultaneous responses to identical disturbances for Pinning and Smooth conditions could not be studied. Nonetheless, a large amount of data could be collected such that several similar disturbances were imparted that can be adequately compared, as is done in Section 2.5.

2.2 Data Processing and Preparation

The most generally useful data for follow-on investigations by independent researchers is the CFE CL video library available for download at http://cfe.pdx.edu. This data can be analysed in any manner desired by the user. However, for the data reduced in this effort a certain procedure was developed and followed. For example, the flight video for CL was cut, formatted, organized, optically corrected, and digitized for preliminary analysis. Formatting the video is the same process across all CFE tests and is detailed in Section 7.1. The basic process involves the conversion: MPEG-2 \(\rightarrow\) MPEG-1 \(\rightarrow\) 24-bit uncompressed AVI. Documenting, classifying, and organizing over 400 events requires a strict methodology that was outlined in Section 1.3.6 with further details provided here.

2.2.1 Scale Factor Details

CL requires the astronaut to visually align the vessel perpendicular to the camera. This is of course not always possible, especially during the manually imparted disturbances. For this reason a more dynamic scale factor is employed. To account for certain but small out-of-plane motion, three points are used and a ‘scale factor plane’ is created, both before and after the imparted disturbance. In general, the mathematical plane is derived by measuring
the diameter of the cylinder in three different locations. In some cases the distance from the bottom of the Pinning cylinder to the bottom of the Pinning lip (distance \( h_{pl} \), see Figure 2.2) is used if the Pinning cylinder is partially out of view and a measurement of the diameter cannot be obtained. Though rare, this generally occurs during lateral motion where the vessel is moved partially out of the camera field of view. Figure 2.7 depicts typical measurement locations and nomenclature. The endpoints of each line are recorded and the midpoint and length are calculated. The line length is used to calculate a local scale factor in the vicinity of the line. The line \( L_{01} \) endpoints are denoted as \((x_0, y_0)\) and \((x_1, y_1)\) with midpoint

\[
P_{01} = \left( \frac{x_0 + x_1}{2}, \frac{y_0 + y_1}{2} \right) = (x_{01}, y_{01}),
\]

and line length

\[
L_{01} = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2}.
\]

\( L_{01} \) is used to calculate the scale factor at point \( P_{01} \), where

\[
SF_{01} = \frac{\ell}{L_{01}}.
\]

The parameter \( \ell \) represents the true length of the object being measured (typically cylinder diameter). \( SF_{01} \) is determined in units of mm/pixel. Point \((P_{01}, SF_{01})\) is calculated with two additional points to construct a scale factor plane. Points \((P_{23}, SF_{23})\) and \((P_{45}, SF_{45})\) are calculated in the same manner as the ‘01’ line. The scale factor plane is described by

\[
SF = a \, x + b \, y + c
\]
where \( a \), \( b \), and \( c \) are found by solving the system

\[
\begin{align*}
\text{SF}_{01} &= a \ x_{01} + b \ y_{01} + c \quad (2.6) \\
\text{SF}_{23} &= a \ x_{23} + b \ y_{23} + c \quad (2.7) \\
\text{SF}_{45} &= a \ x_{45} + b \ y_{45} + c. \quad (2.8)
\end{align*}
\]

Simultaneous solution of the system yields coefficients

\[
\begin{align*}
a &= \frac{-\text{SF}_{23} y_{01} + \text{SF}_{45} y_{01} + \text{SF}_{01} y_{23} - \text{SF}_{45} y_{23} - \text{SF}_{01} y_{45} + \text{SF}_{23} y_{45}}{-x_{23} y_{01} + x_{45} y_{01} + x_{01} y_{23} - x_{45} y_{23} - x_{01} y_{45} + x_{23} y_{45}} \quad (2.9) \\
b &= \frac{\text{SF}_{23} x_{01} - \text{SF}_{45} x_{01} - \text{SF}_{01} x_{23} + \text{SF}_{45} x_{23} + \text{SF}_{01} x_{45} - \text{SF}_{23} x_{45}}{-x_{23} y_{01} + x_{45} y_{01} + x_{01} y_{23} - x_{45} y_{23} - x_{01} y_{45} + x_{23} y_{45}} \quad (2.10) \\
c &= \frac{\text{SF}_{01} (x_{23} y_{45} - x_{45} y_{23}) + \text{SF}_{23} (x_{45} y_{01} - x_{01} y_{45}) + \text{SF}_{45} (x_{01} y_{23} - x_{23} y_{01})}{-x_{23} y_{01} + x_{45} y_{01} + x_{01} y_{23} - x_{45} y_{23} - x_{01} y_{45} + x_{23} y_{45}}, \quad (2.11)
\end{align*}
\]

which are used in turn to determine the scale factor plane given by Equation (2.5). The plane is constructed twice per event: once before the input disturbance, and once after the input is complete. This corrects the scale factor after the input, which may have moved out of the original plane. Every data point recorded in pixels is scaled over the entire plane using Eq. 2.5. Scale factor values determined in this way range between 0.18mm/pixel and 0.25mm/pixel with an average value of 0.20mm/pixel for the wide variety of experiments performed. Tracking is accurate to ±0.5 pixels, thus oscillations are tracked with between 90\(\mu\)m and 125\(\mu\)m resolution (standard deviation of ±100\(\mu\)m resolution). Differences in scale factor are attributed to the field of view and zoom of the camera, which are variably established by the astronaut during set-up.

The scale factor plane is used to determine the out-of-plane motion. The plane can be thought of as being flush with the front face of the vessel. If multiple planes are constructed at different times, then rotation and translation of the vessel can be computed. Significant out of plane translation is not a significant factor in any of the events analyzed (except Swirl) as the vessel is constrained by a setscrew fastened in a slot. Rotation, however, is a possible factor and is computed by finding the angle between the two scale factor planes,

\[
\vartheta = \cos^{-1} \left( \frac{\text{SF}_1 \cdot \text{SF}_2}{||\text{SF}_1|| \ ||\text{SF}_2||} \right) \quad (2.12)
\]

which is the angle of rotation between vectors \( \text{SF}_1 \) and \( \text{SF}_2 \) representing two scale factor planes calculated using Equation (2.6). Push, Slide/Slosh, Multi-Slide, and Swirl mode disturbances have the potential to rotate, while Axial mode rotation is not possible. Scale factor coefficients are reported twice for every event and can be used to compute the rotation angle before and after the input. Spot checks of the data have indicated that the rotation angle before and after the input is, in general, negligible.

\subsection*{2.2.2 Digitization Techniques}

Before digitizing, the video is converted to a suitable format through a series of steps outlined in Section 7.1 including the NASA-developed Spotlight image analysis tool [5]. Spotlight
uses an Area of Interest (AOI) tracking method where image processing is performed on a specified area and a tracking technique is applied. In general, automated ‘Threshold’ tracking is preferred. When this method fails manual tracking is used.

For each event, an input disturbance, Smooth and Pinning cylinder dynamic interface response\(^2\) are tracked with a small overlap (generally less than 10 frames or 0.3s) between the end of the input and beginning of the response. The video frame rate is 29.97fps resulting in a time step of \(\approx 0.03\)s.

2.2.3 Tracking Method—Axial Mode

Axial mode input and fluid response are the simplest to track. Rotation and translation of the vessel during input is not a concern as the container is rigidly mounted to the MWA. The input is tracked along a straight line on a feature that is fixed to the CL vessel with the choice of location often an issue of favorable lighting. Example tracking locations include: the bottom of cylinder, the setscrew, any of four white bracket stickers affixed to face of vessel, or other locations. All tracking locations and methods are documented in each event’s datasheet and can be recreated by the user.

The response for both Smooth and Pinning cylinders is tracked at the center of the cylinder/interface as represented by the \(x\)-locations of \(P_{01}\) and \(P_{23}\) in Figure 2.7. When tracking Axial events, the \(x\)-location is fixed along a line and the AOI is free to translate in the \(y\)-direction as shown in Figure 2.8. The location is denoted by \(D_{1/2}\), a distance one-half the diameter from the cylinder wall. Because the image coordinate system is oriented with the origin in the upper left corner of the image and with the positive \(y\)-direction directed ‘downward’, the data collected is reflected about the \(x\)-axis.

2.2.4 Tracking Method—Lateral Modes

Push, Slide/Slosh, and Multi-Slide disturbances are composed of a lateral or side-to-side motion in the \(x\)-direction. Both disturbance input and fluid response are tracked in time

\(^2\)The disturbance is commonly referred to as ‘input’ while the fluid passive oscillation is simply ‘response’ with terminology borrowed from signal processing.
using automatic threshold tracking methods if lighting conditions are satisfactory, or manual methods if automatic tracking fails. More complex tracking and processing techniques are possible, but generally not needed. Figure 2.9 depicts Threshold tracking of a Multi-Slide response in the Pinning cylinder. The tracking location for lateral modes is chosen as a fixed height 1/4 diameter from either wall. This produces the best compromise between response amplitude and ease of tracking. The 1/4 diameter optical location, denoted $D_{1/4}$, is chosen before the input disturbance by measuring 1/4 the diameter from either wall and finding the $y$-position at which the interface is intersected. The interface may be tracked on either the left or right side of the interface, depending on lighting conditions, but must be consistent between the Pinning and Smooth cylinders per event. All of the data is obtained at ‘optical’ locations and not the ‘real’ locations. A ray trace analysis to correct optical distortions is discussed below. Tracking methods for all events are documented in each datasheet with sufficient information such that the reader can reconstruct the tracking methodology if desired.

### 2.3 Ray Trace Optical Correction

The data reduction for CL requires tracking a location on the interface, which can be distorted by mismatched refractive indices between the test fluid and acrylic container. Axial modes are unaffected by such distortion since they are tracked at the centerline where distortions are negligible. However lateral interface motions must be corrected. Figure 2.10 depicts the geometry under analysis where $(x/R)_d$ is the distorted location and $(x/R)_r$ is the real location. The light is assumed to be parallel to the observer but defracts at the Si oil/cylinder wall interface. The incident angle normal to the circular arc is

$$
\theta_a = \sin^{-1}\left(\frac{x}{R}\right)_d,
$$

which is also the normal angle $\theta_n$. As the light hits the arc it is refracted by angle

$$
\theta_b = \sin^{-1}\left[\frac{N_{acr}}{N_{sil}} \left(\frac{x}{R}\right)_d\right].
$$
Figure 2.10: Ray trace schematic for optical correction of CL.

The refracted light is offset by distance $\delta$ depending on the distance the light travels and the angle $\theta_b$,

$$
\delta = \left[1 - \left(\frac{x}{R_d}\right)^2\right]^{1/2} \tan(\theta_b - \theta_a),
$$

which includes the distorted or apparent location $(x/R)_d$. The distance $\delta$ is essentially the correction to the distorted point,

$$
\left(\frac{x}{R}\right)_r = \left(\frac{x}{R}\right)_d + \delta.
$$

Using the optical properties for Si oil and acrylic (Table 2.1) where the distorted location is corrected by adding a distance $\delta$. For lateral disturbances the percent correction is nearly constant ranging between 6.8% and 8.9%. The maximum error occurs when $(x/R)_d \approx 0.91$, which is mapped to the real point $(x/R)_r \approx 1$. Any values beyond $(x/R)_d \approx 0.91$ are erroneous as the ray of light is refracted out of view. The percent error correction is calculated from

$$
\% \text{ Error} = \frac{(x/R)_d - (x/R)_r}{(x/R)_r} \times 100\%.
$$

As the refraction angle increases, the transit length decreases, and the error is nearly constant until very near the walls as shown in Figure 2.11. All figures presented in this report are distortion-corrected, but the CL datasheets are always tracked at the apparent or distorted locations and must be corrected by the user.

### 2.4 Data Analysis and Presentation

Following digitization, the data can be analyzed for any number of characteristics. The most obvious quantities are the frequency and damping rate of the fluid response in the linear regime, defined as the regime where interface oscillation amplitudes are $< 0.1R$ ($\approx 2\text{mm}$). Frequency is calculated by first finding the average period in a specified time interval, and then inverting it to find the average frequency, $f = 1/P$. The average period is calculated
by counting peaks in the linear regime and dividing by the time duration to obtain an average period. The method is increasingly accurate as the number of periods increase. CL1 average frequencies contain less scatter (> 15 peaks) whereas CL2 exhibits more (< 4 peaks).

The interface response data is always zeroed with the depth after the fluid has settled. In other words, the depth after the input disturbance and passive fluid response is used as the zero elevation. The idea is that after the disturbance has been imparted, the fluid should return to the original level. The fluid in the Pinning cylinder is not thrown onto the walls if the contact line is Pinned. However, if the Pinning lip is flooded it generally returns to the bulk due to the favorable wetting gradient (discussed in Section 2.7.3). This is less true for the CL2 Smooth cylinder, as residual wetting fluid films reside on the walls and can accumulate over time. In this way, large disturbances have the potential to change the fluid level in the Smooth cylinder. There is generally not a significant change in fluid depth before and after the input disturbance as documented in every datasheet.

The damping rate $\xi$ is the coefficient in the exponential decay function $e^{-\xi t}$, which is the assumed peak-to-peak decay rate in the linear regime. Calculation of the damping rate is sensitive to the ‘zero’ location. The damping rate is calculated using absolute values and an exponential fit calculated from the peak data points. Two points are chosen for the calculation, with the first being near the beginning of the linear regime and the second being near the end of the response. If the two peak data points are represented as $(x_1, y_1)$ and $(x_2, y_2)$ then the damping rate is

$$\xi = \ln \frac{y_1}{y_2} \frac{x_1 - x_2}{x_1 - x_2},$$

which is reported for several experiments in Section 2.6.1. The video processing protocol
Figure 2.12: Axial mode input disturbance (top) and coupled passive fluid response for CL2 (bottom) where the coordinate system is corrected—up is positive and down is negative.

was reviewed in Section 1.3.6 with further details given in Section 7.1.

2.5 Representative Results

One objective of the experiments is to observe the difference in response due to the two extremes in boundary conditions. Representative results are presented for Smooth and Pinning boundary conditions for both CL1 and CL2 using differing modes and amplitudes. In addition, numerical results are calculated using the OpenFoam CFD software presented for comparisons. Four comparisons are presented for Axial and Push modes for CL1 and CL2. The Axial mode for CL2 is investigated first with a typical example shown in Figure 2.12. In this case the input disturbance consists of a little more than one full period, which is not always the case, but is generally observed for larger amplitude disturbances. For small amplitude disturbances the Pinning and Smooth fluid responses are similar. As the input amplitude increases, the discrepancy in the Pinning and Smooth responses becomes more pronounced. The lower plot in Figure 2.12 is typical, showing how the Smooth cylinder settles more quickly than the Pinning case due to increased damping in the contact line.
region. This trend is common to all disturbance modes.

Figure 2.13 presents a Push mode disturbance with corresponding fluid response. It is clear that the damping rate of the disturbance is less than that of the Axial mode, which is true for all lateral mode disturbances including Slide and Multi-Slide. Another clear observation is that the response frequency is roughly half that of Axial modes.

As discussed above, the experimental procedure for CL1 is modified due to a wetting anomaly in the Smooth cylinder. For this reason a direct comparison between simultaneous Pinning and Smooth cylinders is not possible for a single disturbance. Instead, similar inputs are sought for disturbances to the Pinning cylinder when the liquid is at the Pinning lip (the pinned condition) and when the liquid is below the Pinning lip (the smooth contact line boundary condition, but in the Pinning cylinder), refer to Figure 2.6. The liquid depth changes in such tests reveal a negligible effect on Axial modes and only a slight effect for Push modes.

Figure 2.14 compares Pinning and Smooth boundary conditions for CL1 Axial modes. The input disturbances are of a similar form and amplitude. The frequency for both CL1 Smooth and Pinning is much higher than CL2 and the damping rate is much lower for CL1.
Both trends are due solely to differences in contact angle. Figure 2.15 depicts Push mode results for CL1 with input disturbances that are nearly identical. The differences in Pinning and Smooth responses are obvious. In the Smooth case the contact line moves along the wall maintaining a large contact angle. This motion apparently dissipates significant energy as can be seen in the plot where the difference between the first and second peak is over 600%. The Pinning response shows a different profile and slightly higher frequency, but the linear damping rate is nearly identical.

2.5.1 Liquid Depth Effect: Frequency

In certain tests the liquid depth is manually varied by changing the volume of liquid in the test chambers. In other instances liquid accumulates in an annular film on the cylinder wall above the bulk meniscus essentially removing liquid from the bulk and lowering the overall interface height. This occurs almost exclusively in the CL2 Smooth cylinder where the uncoated perfectly wetting surfaces allow the liquid to ‘migrate up’ the walls following large disturbances. The CL2 Pinning cylinder is coated above the Pinning lip and liquid rarely moves above it; if it does, it passively returns to the bulk. A slight decrease in liquid depth is still possible when the Pinning lip is flooded, as it removes some liquid from the

Figure 2.14: CL1 Axial mode input disturbance (top) and passive fluid response (bottom).
Figure 2.15: CL1 Push mode input disturbance (top) and passive fluid response (bottom).

bulk. Depth is varied systematically for CL1 data by adjusting the fill level.

Sample depth effects will be shown for linear perturbations defined as having peaks less than $0.1R \sim 2\text{mm}$. For the measurement to follow, frequency and fluid depth are determined with uncertainties $f \pm 0.01s$ and $\kappa \pm 0.05\text{mm}$, respectively.

### 2.5.2 CL1 Depth Effect

Depth effects for CL1 are reported here for Push and Axial input disturbances. Significant depth effect data was not collected for other disturbance modes (Slide, Multi-Slide, Swirl). Table 2.2 and Figure 2.16 provide CL1 Push mode data and reveal the change in frequency as a function of depth. The figure and table include Pinning and Smooth conditions with the assumption that in the linear regime they behave similarly. A linear curve yields $f = 0.0071\kappa + 1.10$ with $R^2$ value of 0.996. A 15% change in linear frequency is observed between maximum and minimum fill levels. At the shallow end, the exact range of applicability can not be determined from the experiments for CL1, but, as will be seen, the linear fit persists for CL2 to depths of less than 5mm ($R_{cyl} = 19.05\text{mm}$). It is clear the linear relationship will not apply at either deep or shallow depth limits. Axial mode disturbances are less sensitive to liquid depth as Table 2.3 and Figure 2.17 indicate.
2.5.3 CL2 Depth Effect

Depth effects for CL2 are reported here for all disturbance modes with significant depth ranges for Slide and Multi-Slide disturbances. In addition, coupled disturbances across all lateral/slosh modes are presented. In this context the term ‘coupled’ means that the reported Pinned and Smooth frequencies are determined simultaneously from the same disturbance events. ‘Decoupling’ disturbances are reported when the Pinning lip is flooded and the Pinned and Smooth response are not directly compared in a single event. (It was found that events where the Pinning lip is flooded could be treated as having a Smooth boundary condition, a result which is telling of conditions at the contact line for low contact

Table 2.3: CL1 Axial mode depth effect statistics for Figure 2.17.

<table>
<thead>
<tr>
<th>$\kappa_{avg}$ (mm)</th>
<th>$\sigma\kappa$ (mm)</th>
<th>$f_{avg}$ (Hz)</th>
<th>$\sigma_f$ (Hz)</th>
<th>$N = \kappa_1-\kappa_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.80</td>
<td>0.50</td>
<td>2.53</td>
<td>0.03</td>
<td>22  30.70–32.80</td>
</tr>
<tr>
<td>26.20</td>
<td>0.00</td>
<td>2.53</td>
<td>0.05</td>
<td>2   26.20–26.20</td>
</tr>
<tr>
<td>22.30</td>
<td>0.40</td>
<td>2.50</td>
<td>0.02</td>
<td>15  21.80–23.00</td>
</tr>
</tbody>
</table>
angle. Again, thin viscous film damping for low contact angle fluids masks the specific damping contribution tied to the moving contact line.)

The first comparisons shown here are for lateral/slosh mode disturbances including: Push, Slide, and Multi-Slide for coupled Pinning and Smooth response frequencies. By comparing the coupled disturbances one can determine the difference in the linear frequency as a result of the boundary condition. Figure 2.18 presents all coupled modes, while Figure 2.19 presents a sub-selected range of the data. A quick observation of Figure 2.18 reveals the roughly linear relationship between frequency and depth for the Smooth Multi-Slide case. Slide mode frequency also varies with depth, while Push mode depths do not span a large enough depth range to draw significant conclusions. Figure 2.19 reveals a difference in linear frequency between Pinning and Smooth boundary conditions. Recall that the data represented in the figure is coupled, further strengthening the argument that there is a difference in linear frequency for the two boundary conditions. The difference increases with disturbance type, for Push 4%, Slide 8%, and Multi-Slide 18%, all calculated for depths greater than 30mm and similar to the depth of the Pinning cylinder. Similar to Figure 2.17, Figure 2.20 indicates a 10% difference between Pinning and Smooth boundary condition frequencies. Push modes suffer from insufficient data to deduce a trend as shown in Figure 2.21. Larger depth range data are collected for both Slide and Multi-Slide tests where power and linear trends are reported. Figure 2.22 portrays a roughly linear trend between 31mm and 10mm before becoming nonlinear below 10mm. A 3-parameter power-law regression is applied with a best fit equation of $f = 0.072 + 0.24\kappa^{0.13}$. Multi-Slide responses exhibit a linear behavior between 5mm and 33mm and are fit by $f = 0.002\kappa + 0.36$. The data and trendline are presented in Figure 2.23.
Figure 2.18: CL2 coupled lateral modes, $f$ vs. $\kappa$.

Figure 2.19: CL2 coupled lateral/slosh modes (magnified region of Fig. 2.18), $f$ vs. $\kappa$. 

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Figure 2.20: CL2 Axial mode, $f$ vs. $\kappa$.

Figure 2.21: CL2 Push mode, $f$ vs. $\kappa$. 
Figure 2.22: CL2 Slide mode, $f$ vs. $\kappa$.

Figure 2.23: CL2 Multi-Slide mode, $f$ vs. $\kappa$. 
Table 2.4: CL1 statistics for the linear frequency in the Pinning cylinder.

<table>
<thead>
<tr>
<th>Input Mode</th>
<th>B.C.</th>
<th>θ</th>
<th>$f_{avg}$ (Hz)</th>
<th>St.dev. (Hz)</th>
<th>N</th>
<th>$\kappa_1-\kappa_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>Pinned</td>
<td>51°</td>
<td>2.75</td>
<td>0.04</td>
<td>14</td>
<td>32.90–34.70</td>
</tr>
<tr>
<td>Axial</td>
<td>Smooth</td>
<td>41°</td>
<td>2.51</td>
<td>0.02</td>
<td>17</td>
<td>21.80–26.20</td>
</tr>
<tr>
<td>Axial</td>
<td>Pinned</td>
<td>44°</td>
<td>2.53</td>
<td>0.03</td>
<td>22</td>
<td>30.70–32.80</td>
</tr>
<tr>
<td>Push</td>
<td>Smooth</td>
<td>41°</td>
<td>1.25</td>
<td>0.02</td>
<td>23</td>
<td>18.90–26.50</td>
</tr>
<tr>
<td>Push</td>
<td>Pinned</td>
<td>44°</td>
<td>1.32</td>
<td>0.01</td>
<td>14</td>
<td>29.50–32.30</td>
</tr>
<tr>
<td>Multi-Slide</td>
<td>Smooth</td>
<td>41°</td>
<td>1.24</td>
<td>0.02</td>
<td>14</td>
<td>18.90–20.30</td>
</tr>
</tbody>
</table>

Table 2.5: CL1 statistics for the linear frequency in the Smooth cylinder exhibiting the wetting anomaly.

<table>
<thead>
<tr>
<th>Input Mode</th>
<th>BC</th>
<th>θ</th>
<th>Avg. (Hz)</th>
<th>Stdev (Hz)</th>
<th>N</th>
<th>$\kappa_1-\kappa_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>Smooth</td>
<td>29°</td>
<td>1.97</td>
<td>0.02</td>
<td>5</td>
<td>24.35–25.20</td>
</tr>
<tr>
<td>Axial</td>
<td>Smooth</td>
<td>16°</td>
<td>1.58</td>
<td>0.01</td>
<td>5</td>
<td>21.30–21.80</td>
</tr>
<tr>
<td>Axial</td>
<td>Smooth</td>
<td>4°</td>
<td>1.04</td>
<td>0.03</td>
<td>19</td>
<td>12.15–12.70</td>
</tr>
<tr>
<td>Push</td>
<td>Smooth</td>
<td>4°</td>
<td>0.46</td>
<td>0.01</td>
<td>35</td>
<td>11.70–13.70</td>
</tr>
<tr>
<td>Multi-Slide</td>
<td>Smooth</td>
<td>4°</td>
<td>0.46</td>
<td>0.02</td>
<td>13</td>
<td>12.50–13.40</td>
</tr>
</tbody>
</table>

2.5.4 Linear Frequency Summary

Depth effect statistical data is presented in Table 2.4 for the CL1 Pinning cylinder, Table 2.5 for the CL1 Smooth cylinder, and Table 2.6 for CL2 containing both Smooth and Pinning results. The Smooth cylinder of CL1 which suffered the wetting anomaly discussed in Section 2.1.3 provided results for several effective contact angles as shown in Table 2.5. Most of the disturbances are Axial and reflect change in frequency with contact angle, and, to a lesser degree, depth. Recall that the Axial mode frequency was not particularly sensitive to depth as shown in Figure 2.17. The depth affects measured are rarely significant ($\lesssim 10\%$) unless a depth of less than 5mm, in which cases differences of up to 25% are reported. Multi-Slide mode trends (5mm–30mm) are very similar.

2.6 Further Numerical Benchmark Comparisons

As introduced in Chapter 1, blind numerical predictions were made with the OpenFoam CFD package in an effort to demonstrate the use of the CFE CL database for code benchmarking where the specific numerical implementation of the moving contact line boundary condition is central to the computational flow phenomena. Details of our numerical approach can be found in [3] with the highlights presented below. It is important to note that the benchmark process was not ‘closed’ in that the requisite second round of computations using improved boundary conditions was not carried out in keeping with the ‘blind’ demonstration. It is certain that a second effort would produce results of increased accuracy.

For the comparisons to follow, all optical distortions are corrected in both numerical predictions and experimental data with numerical values taken at the apparent tracking...
Table 2.6: CL2 statistics for the linear frequency where a * indicates significant depth ranges.

<table>
<thead>
<tr>
<th>Input Mode</th>
<th>BC</th>
<th>Avg. (Hz)</th>
<th>Stdev (Hz)</th>
<th>$N$</th>
<th>$\kappa_1-\kappa_2$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>Smooth</td>
<td>0.99</td>
<td>0.07</td>
<td>32</td>
<td>19.50–30.50*</td>
</tr>
<tr>
<td>Axial</td>
<td>Pinned</td>
<td>1.10</td>
<td>0.05</td>
<td>16</td>
<td>28.30–32.30</td>
</tr>
<tr>
<td>Push</td>
<td>Smooth</td>
<td>0.46</td>
<td>0.03</td>
<td>72</td>
<td>17.70–33.20*</td>
</tr>
<tr>
<td>Push</td>
<td>Pinned</td>
<td>0.50</td>
<td>0.03</td>
<td>22</td>
<td>31.30–34.40</td>
</tr>
<tr>
<td>Slide</td>
<td>Smooth</td>
<td>0.41</td>
<td>0.05</td>
<td>103</td>
<td>1.40–31.20**</td>
</tr>
<tr>
<td>Slide</td>
<td>Pinned</td>
<td>0.50</td>
<td>0.02</td>
<td>29</td>
<td>31.20–34.00</td>
</tr>
<tr>
<td>Multi-Slide</td>
<td>Smooth</td>
<td>0.42</td>
<td>0.03</td>
<td>48</td>
<td>5.50–32.80**</td>
</tr>
<tr>
<td>Multi-Slide</td>
<td>Pinned</td>
<td>0.51</td>
<td>0.01</td>
<td>40</td>
<td>30.90–34.90</td>
</tr>
</tbody>
</table>

location. The ray trace used to correct the optics is detailed in Section 2.3. Similar numerical modeling and experimentation for perfectly wetting Axial mode disturbances have been investigated [12]. Numerical results and experimental comparisons are presented here for Axial and Push mode disturbances with Smooth and Pinning boundary conditions. Numerical computations are carried out for CL1 with $\theta = 50^\circ$, despite the theoretically determined value of $\theta = 48.7 \pm 2^\circ$ [2] and experimental measurements between $41^\circ$ and $44^\circ$ ($\pm 3^\circ$).

In the comparisons certain numerical data points are represented by triangles while experimental points are circles. Several key parameters are chosen for comparison including linear damping rate $\xi$, frequency $f$, number of peaks $N$ used to calculate frequency, amplitude ratio $\lambda$, maximum experimental peak-to-peak amplitude $A_{exp}$, and dynamic Bond number $Bo$; all of which are documented for CL1 in Table 2.7. The damping rate $\xi$ is the coefficient in the exponential decay $e^{-\xi t}$. The amplitude ratio $\lambda$ is the maximum experimental versus numerical peak amplitude ratio in the linear (subscript $l$) and nonlinear (subscript $nl$) regions. Recall that the linear region is defined as an amplitude of $\sim 0.1R$ ($\sim 2mm$). The maximum peak-to-peak amplitude $A_{exp}$ is the maximum peak from which the next minimum peak is subtracted and used to provide an measure of dynamic interface deflection. Figure 2.24 depicts the parameters under investigation for a generic decaying sinusoid.

### 2.6.1 CL1 Numerical Comparison

CL1 is compared first for the Pinned Axial mode case shown in Figure 2.25. It is apparent by inspection that the initial amplitude and damping rate of the numerical results are less than the experiment; however, frequency is correctly predicted. The Smooth Axial mode comparison is shown in Figure 2.26. In this case the contact line is able to translate, adding a degree of freedom which the numerical calculations that employ fixed contact angle boundary conditions at the contact line are unable to recreate. However, the damping rate is modeled correctly in the linear region. Push modes for both Pinning and Smooth boundary conditions are presented in Figures 2.27 and 2.28, respectively. The Pinning solution captures both damping rate and frequency well, while the Smooth solution misses frequency, damping rate, and amplitude ratios.
Figure 2.24: Example plot describing nomenclature used in the numerical (solid) and experimental (dashed) comparisons.

The comparisons for CL1 are summarized in Table 2.7 and discussed in detail below.

- Numerical predictions of the frequency are within 2% for the Pinned Axial response (Figure 2.25), which is the best agreement for any of the CL1 cases. However, damping is under-predicted by 55%. Amplitudes are poorly predicted, especially in the nonlinear region where the experimental amplitude is over 5 times greater than the numerical prediction.

- Smooth Axial (Figure 2.26) predictions do not fare as well in terms of frequency where a 33% under-prediction is reported. Damping rate is within 4% of the experiment and the linear amplitude ratio is at best 0.65 for CL1.

- Pinned Push mode (Figure 2.27) calculations are in good agreement with only an 11% error in frequency and are similar for damping rates. Amplitude ratios vary between 1.85 to 2.68, but overall characteristics and shape are well-predicted.

- Smooth Push mode (Figure 2.28) computations produced the widest discrepancies > 50% for frequency and damping rate. Frequency was significantly under-predicted while damping rate was over-predicted. Surprisingly, the nonlinear amplitude ratio was well predicted, which happened to be the best of all CL1 cases. Overall the combination of high contact angle and free slip boundary condition proved difficult for the numerical solution, indicating the already obvious need for a refined moving
Figure 2.25: CL1 Axial mode input (top) and experimental (○) Pinned response with numerical (▲) comparison (event 4124).

Table 2.7: Summary of CL1 numerical and experimental comparison.

<table>
<thead>
<tr>
<th></th>
<th>Axial</th>
<th>Push</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pinned</td>
<td>Smooth</td>
<td>Pinned</td>
</tr>
<tr>
<td>$f_{exp}$</td>
<td>2.55</td>
<td>2.50</td>
<td>1.31</td>
</tr>
<tr>
<td>$f_{num}$</td>
<td>2.50</td>
<td>1.66</td>
<td>1.17</td>
</tr>
<tr>
<td>$\xi_{exp}$</td>
<td>0.67 (10)</td>
<td>0.52 (10)</td>
<td>0.15 (10)</td>
</tr>
<tr>
<td>$\xi_{num}$</td>
<td>0.30 (5)</td>
<td>0.50 (5)</td>
<td>0.15 (5)</td>
</tr>
<tr>
<td>$N_{exp}$</td>
<td>20</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>$N_{num}$</td>
<td>20</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>$\lambda_{l}$</td>
<td>3.58</td>
<td>0.65</td>
<td>2.68</td>
</tr>
<tr>
<td>$\lambda_{nl}$</td>
<td>5.65</td>
<td>-</td>
<td>1.85</td>
</tr>
<tr>
<td>$A_{exp}$</td>
<td>4.50</td>
<td>3.10</td>
<td>16.20</td>
</tr>
<tr>
<td>$B_{0max}$</td>
<td>1.9</td>
<td>3.2</td>
<td>3.1</td>
</tr>
</tbody>
</table>
contact line boundary condition. This challenge was certainly appreciated a priori. A next logical step would be to repeat the computations with a more physically inspired boundary condition tuned to reproduce the data.

2.6.2 CL2 Numerical Comparison

CL2 ($\theta = 0^\circ$) is calculated for coupled cases, meaning the Smooth and Pinned responses are simultaneous, the result of a single input disturbance. CL2 results are summarized in Table 2.8 with some details listed below.

- The Pinning Axial mode (Figure 2.29) fluid response is predicted well where frequency is within 2% of the experiment and damping rate is within 6%. Amplitude ratios indicate small under predictions in the nonlinear region and over-predictions in the linear region.

- The Smooth Axial case (Figure 2.29) is also well predicted in all respects including frequency (2%), damping rate (4%), and amplitude ratio (0.84). These results are
Figure 2.27: CL1 Push mode input (top) and experimental (●) Pinned response with numerical (▲) comparison (event 5665).

Table 2.8: Summary of CL2 numerical and experimental comparisons.

<table>
<thead>
<tr>
<th></th>
<th>Axial</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Push</td>
<td>Pinned</td>
<td>Smooth</td>
<td>Pinned</td>
<td>Smooth</td>
<td>Error</td>
<td>Error</td>
<td>Error</td>
</tr>
<tr>
<td>$f_{exp}$</td>
<td>1.13</td>
<td>1.05</td>
<td>0.48</td>
<td>0.48</td>
<td>±1% Hz</td>
<td>±1% Hz</td>
<td>± (% err.)</td>
<td>± (% err.)</td>
</tr>
<tr>
<td>$f_{num}$</td>
<td>1.11</td>
<td>1.07</td>
<td>0.45</td>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\xi_{exp}$</td>
<td>1.11 (4)</td>
<td>1.00 (-)</td>
<td>0.62 (4)</td>
<td>0.70 (8)</td>
<td>± (% err.)</td>
<td>± (% err.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\xi_{num}$</td>
<td>1.04 (3)</td>
<td>1.04 (-)</td>
<td>0.30 (3)</td>
<td>0.73 (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{exp}$</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{num}$</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda_l$</td>
<td>0.60</td>
<td>-</td>
<td>0.65</td>
<td>4.10</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda_{nl}$</td>
<td>1.45</td>
<td>0.84</td>
<td>0.85</td>
<td>1.60</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{exp}$</td>
<td>9.80</td>
<td>5.50</td>
<td>10.00</td>
<td>7.4</td>
<td>±0.05mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Bo_{max}$</td>
<td>13.4</td>
<td>13.4</td>
<td>2.0</td>
<td>2.0</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
excellent because these are commonly occurring conditions.

- Pinned Push response (Figure 2.30) frequency is predicted within 6% of the experiment, but the damping rate is > 50% below the experimental result with numerical oscillations lasting much longer than expected. Amplitudes are calculated lower than the experiment at values in the nonlinear region and become over-predicting in the linear region.

- The Smooth Push response (Figure 2.30) predicts frequency perfectly and damping rate is within 2%. Amplitudes in the nonlinear region are well predicted while the linear region is off by a factor of 4.

Several important observations from the comparisons are provided below:

- Overall, the perfectly wetting case (CL2) is modeled most accurately for both the Pinning and Smooth boundary conditions.

- Axial and Push modes for perfectly wetting (CL2) are modeled well with similar accuracy.
Figure 2.29: CL2 Axial mode input (top) with experimental (●) Smooth (middle) and Pinned response numerical (▲) comparisons (event 878).
Figure 2.30: CL2 Push mode input (top) with experimental (●) Smooth (middle) and Pinned response numerical (▲) comparisons (event 2814).
• High contact angle (CL1) Push mode with free slip ('Smooth') boundary conditions is the worst predicted of all the comparisons. The model is not able to capture the contact line correctly, resulting in large errors for high contact angle (CL1) Smooth boundary conditions.

• In general, Pinned boundary conditions are more accurately predicted as the boundary condition is most suited to the modeling boundary condition of a fixed contact line.

2.7 Extra Science

As mentioned in 1, extra science refers to experimental data that was obtained in addition to the primary science objectives. Numerous extra science events/experiments were conducted and recorded on video including: liquid jetting, droplet impact and satellite rebound dynamics, air entrainment caused by Axial disturbances, ‘hourglass’ interface formation and draining, Pinning due to a wetting gradient, Pinned interface stability, and more. In this section a few extra science topics are discussed with the purpose of demonstrating the wide range of phenomena that may be examined from the simple CL experiments. Any or all may be studied to greater depth by the reader using the CFE video database (http://cfe.pdx.edu).

2.7.1 Axial Mode Droplet Ejection

If the Axial disturbance amplitude is large, destabilization of the interface may occur resulting in droplet ejection or liquid jetting. Several parameters affect whether ejections occur, including disturbance amplitude, frequency, and waveform. Figure 2.31 represents the displacement and velocity for Axial mode disturbances that are subcritical, critical, and supercritical. The event labeled ‘Below’ does not cause a droplet to eject. The ‘Critical’ event ejects a droplet with nearly no inertia—the ejected drop hovers over the bulk meniscus. The event labeled ‘Above’ produces jetting with significant ejected droplet momentum and is characterized as being above the critical condition (supercritical). All of the events are for Smooth contact line boundary conditions. Ejection or near ejection occurs at approximately 0.95s. The disturbance motion is characterized by a single depression of the MWA followed by its release and rebound.

The displacement frequency for the all of the disturbances is $\sim 2.50\text{Hz}$ which is 2.5 times the fundamental Axial frequency. The velocity plot gives an idea of how waveform plays a role. The primary peaks are $-80\text{mm/s}$ and $84\text{mm/s}$ for the critical event, $-62\text{mm/s}$ and $56\text{mm/s}$ for the subcritical event, and $-67\text{mm/s}$ and $74\text{mm/s}$ for the supercritical event. The symmetry of the signal seems to be important, where net momentum in the upward direction promotes ejection and net downward momentum inhibits ejection. Adequate velocity or Bond number is not sufficient to cause ejection as Figure 2.32 indicates. The critical event produces a larger Bond number than the supercritical event, indicating that a lesser Bond number produces droplets if the waveform has a significant upward component. The data represented in this section provides a glimpse of Axial ejection dynamics, with the full database providing additional data.
Figure 2.31: CL2 displacement and velocity plot depicting input disturbances that are below, at, and above the threshold that causes droplet ejection. (Drop ejection occurs at \( t = 0.95 \text{s} \).)

### 2.7.2 Depinning Investigation

Large Axial mode disturbances produce jetting dynamics while large lateral mode disturbances generally cause depinning. A depinning event occurs in the Pinning cylinder when the input acceleration is sufficiently large to cause the contact line to break free of the Pinning lip. An example of a depinning event was shown in Figure 2.4 while an input acceleration plot is shown in Figure 2.33 for a Multi-Slide disturbance. The interface moves in the opposite direction of the container when accelerating, thus depinning occurs on the right hand side of the Pinning lip in the figure as the disturbance velocity changes direction. Complete depinning occurs at 4.56s due to an acceleration of \(-99.45 \text{mm/s}^2 (\text{Bo}_d \sim 1.7)\), while critical depinning occurs at 3.39s and \(-130.08 \text{mm/s}^2 (\text{Bo}_d \sim 2.2)\). Greater accelerations are reported at 1.79s and 4.13s, yet depinning does not occur, indicating acceleration alone is not sufficient to explain dynamic depinning. Frequencies for depinning are approximately twice the passive response frequency \((f \gtrsim 1 \text{Hz for Multi-Slide events})\). Additional
Figure 2.32: CL2 dynamic Bond number as a function of time for Axial events comparing droplet ejection dynamics.

Figure 2.33: CL2 Multi-Slide input acceleration causing depinning, where the dashed line indicates partial depinning and the dash-dotted line represents full depinning (cf 2.4.)
depinning phenomena could be studied for CL. More controlled investigations have been conducted ([13] and others), but the CL dataset adds large capillary length as a parameter in addition to low-g equilibrium initial conditions.

### 2.7.3 Volume Changes During the Experiments

As discussed previously, the Smooth cylinder is not coated while the Pinning cylinder is coated above the Pinning lip (see Section 2.0.1). Figure 2.34 presents the difference in fluid depth before and after the input disturbance $\Delta \kappa$ versus the input displacement amplitude $\xi$ for Slide events. The Pinning data includes dry events where the Pinning lip is intact, and wet events where the Pinning lip is flooded. It is clear that as the disturbances become large, the liquid depth changes significantly for the Smooth cylinder while the Pinning cylinder is largely unchanged. The coating above the Pinning lip discourages fluid from accumulating on the walls and promotes a return to the bulk even for the flooded cases. The Smooth cylinder is not coated and thus fluid films ‘thrown up’ onto the walls remain there for a much longer time. This can also be thought of as a local axial wall pumping phenomenon resulting from lateral oscillations. Over time the films drain back into the bulk liquid lowering $\Delta \kappa$ further than what is indicated in Figure 2.34.

### 2.7.4 Axial Mode Frequency and Contact Angle

The wetting anomaly tests in the CL1 Smooth cylinder, the depth change tests in the CL1 Pinning cylinder, and the CL2 tests provide dynamics for a variety contact angles for Axial mode disturbances. Data is gathered from Tables 2.4, 2.5, and 2.6, along with other data obtained from the CL database [14] and presented in Figure 2.35. Surprisingly, the axial
mode frequency appears linear with a fit $f = 0.036 \theta + 0.968$ with $R^2 = 0.994$ and over a $50^\circ$ range in $\theta$.

2.8 Other Experimental Considerations

Each disturbance event is considered a miniature experiment where unique low-g phenomena can be studied. It is clear there is little repeatability in such manually imparted disturbances. However, it is also clear that each input can be quantified to a high degree, that each individual disturbance is imparted simultaneously and essentially identically to a given Smooth and Pinning Cylinder pair, and that with numerous disturbances a broad data set of a variety of fluid responses can be observed. In part due to the lack of total control of these experiments, an assortment of experiment anomalies occurred of which the reader should be aware if further analyses are carried out. This is not an exhaustive representation of all peculiarities witnessed in the experiments, and many more are sure to be discovered by anyone interested in analyzing the data.

One such example pertains to the Pinning cylinder in CL2 and CL1 where the contact angle varies with fill level. When bubbles are entrained in the bulk they displace liquid; thus, when the cylinder is fully filled and bubbles are present, the interface is displaced higher than designed for creating a ‘larger’ than intended contact angle. The fill level is adjusted in a manner that creates ‘effective’ contact angles. Nonetheless, fill level (fluid depth) has the ability to modify the contact angle in the Pinning cylinder (this is especially true for CL1). For this reason the effective contact angle in the Pinning cylinder must be measured for each event (refer Section 2.1.3).

As described previously, the Pinning lip may become flooded following large amplitude disturbance. During the first two operations of CL2, the effects of a flooded Pinning lip

Figure 2.35: CL Axial mode frequencies at varying contact angles, $f$ (Hz) vs. $\theta$ (degrees).
were not entirely known and many of the disturbance events were conducted in the flooded
condition. As reported, this condition behaves nearly identically to the Smooth cylinder
data and is easily identifiable in the CFE database movies.

2.9 Directions

Independent study by other researchers is strongly encouraged. An attempt is made here to
inspire future work. Such studies might use the statistical data already digitized, but entirely
independent studies can be conducted using only the video database. The simple Contact
Line experiments produced a wealth of information with only a portion presented here.
Primary investigations focused on frequency across several axial and lateral disturbance
modes, depth effects on frequency, and numerical comparisons. Sample extra science is
reported to give the reader an idea of additional phenomena that may be investigated using
the database. The complete database, updates, and additional information can be found at
Chapter 3

CFE Vane Gap Wetting Analysis

Summary. The Vane Gap Capillary Flow Experiments are part of a suite of low-g experiments flown onboard the International Space Station to observe critical wetting phenomena in ‘large length scale’ capillary systems. The Vane Gap geometry consists of a right cylinder with elliptic cross-section and a single central vane that does not contact the container walls. The vane is slightly asymmetric so that two gaps between the vane and container wall are not of the same size. In this study, we identify the critical wetting conditions of this geometry using the Concus-Finn method for both perfectly and partially wetting fluids as a function of container asymmetry. In a cylindrical container in zero-g, single-valued finite height equilibrium capillary surfaces fail to exist if a critical wetting condition is satisfied. This nonexistence results in significant redistribution of the fluids in the container. It will be shown that there could be three critical geometric wetting conditions that include one in each gap region and one for a global shift of bulk fluid which, among the three, is the most significant.

3.1 Introduction and Background

Experiments aboard the International Space Station (ISS) provide a clear picture of the extent to which liquid behavior aboard spacecraft can be controlled by wetting and container geometry. The experiments are referred to as the ‘Vane-Gap’ (VG) experiments and are part of a more general set of simple handheld Capillary Flow Experiments\[15\](CFE) designed and developed at the NASA’s Glenn Research Center for conduct on ISS. The CFE-VG experiments clearly illustrate the sensitivity of a capillary fluid surface to container shape and how small changes to said shape may result in global shifts of the fluids within the container. Understanding such behaviors is key to the passive management of liquids aboard spacecraft and in certain cases permits us the ability to move large quantities (potentially tons!) of liquid by a simple choice of container shape. In other words, in the absence of significant gravity the container geometry can act as a pump to position the fluid in a desirable location within the container (i.e. liquid fuel over the fuel exit port).

The CFE-VG experiments are the latest of a line of experiments performed in low-g environments and sponsored in part by NASA to observe critical corner wetting phenomena in ‘large length scale’ capillary systems[16, 17, 18]. Mathematicians Concus and Finn[19] were perhaps first to construct the mathematical foundations of the critical interior corner wetting condition that, if satisfied, spontaneously draws the liquid into and along the corner to an impressive extent, and at known rates[20]. Such critical wetting conditions dictate the design of systems seeking to exploit the passive pumping capacity of the interior corner.
geometry. Critical wetting conditions also dictate how to design a system in which the goal is to maintain liquid in one location.

Adding geometric complexity introduces significant complexity to the critical geometric wetting criteria. For example, an intricate geometric wetting condition arises for interior corners that do not actually contact. Such conditions arise in certain large propellant tanks where a gap is formed between a vane and the tank wall, as studied by Chen and Collicott[21]. The CFE-Vane Gap experiments are devised to investigate such phenomena and provide a benchmark to both confirm and guide methods of design for systems of increased complexity.

An image of a Vane Gap test unit is shown in Figure 3.2 with a schematic view shown in Figure 3.3. The test unit employs a right cylinder with elliptic cross-section and a single central vane that does not contact the container walls. The vane pivots 360° clockwise (CW) and counter-clockwise (CCW) varying the angle between the vane and the wall and consequently the size of the vane-wall gaps. The vane is also slightly asymmetric so that two gaps can be tested for each container. Two wetting conditions are studied between two Vane Gap containers (VG-1 with γ = 0° and VG-2 with γ = 55°).

Example images of CFE VG-1 from the ISS operations are presented in Figure 3.4 along with Surface Evolver [22] computations for the same vane angles. The images show a selection of several equilibrium interface configurations following prescribed clockwise vane movements in quadrant 1 which is depicted in the figure. The vane angle α is defined as the acute angle between the vane and the major axis of the ellipse. At a critical vane angle the fluid wicks up along the small gap and corners forming a slender column over the entire extent of the vane. The fluid also wicks up the large gap corner with a further increase of the vane angle. Note that in between the small and large gap wetting there is another critical wetting condition resulting in a bulk shift of fluid from right to left side of the vane as shown in the 4th and 5th image in the top row of Figure 3.4. This bulk shift is significant because of the amount of fluid involved. It is observed that the bulk shift takes place between the
Figure 3.2: VG1 test vessel.

Figure 3.3: VG1 3D schematic view.
Figure 3.4: Equilibrium configurations in CFE-VG-1 for various critical vane wetting angles during $90^\circ$ clockwise vane rotation. From top left to right vane angles are 0, 30, 44, 60, and $90^\circ$, respectively. *Surface Evolver* computations of the same vane angles are shown in the bottom row.

Table 3.1: Experimentally determined critical wetting conditions($\alpha$) for CFE VG-1. SGW: small gap wicking; SGD: small gap dewetting; LGW: large gap wicking; LGD: large gap dewetting; BS: bulk shift; BSR: bulk shift reversal. All values in degrees.

<table>
<thead>
<tr>
<th>Quad.</th>
<th>SGW ±</th>
<th>SGD ±</th>
<th>LGW ±</th>
<th>LGD ±</th>
<th>BS ±</th>
<th>BSR ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.5 ± 1.5</td>
<td>40.0 ± 0.5</td>
<td>56.0 ± 1.0</td>
<td>54.0 ± 2.0</td>
<td>47.5 ± 2.5</td>
<td>39.0 ± 1.0</td>
</tr>
<tr>
<td>2</td>
<td>44.5 ± 1.0</td>
<td>41.0 ± 1.5</td>
<td>53.5 ± 1.5</td>
<td>51.5 ± 1.5</td>
<td>46.25 ± 0.7</td>
<td>44.0 ± 1.0</td>
</tr>
<tr>
<td>3</td>
<td>42.0 ± 2.0</td>
<td>40.0 ± 0.5</td>
<td>51.0 ± 1.0</td>
<td>49.0 ± 0.5</td>
<td>47.5 ± 2.5</td>
<td>45.5 ± 0.5</td>
</tr>
<tr>
<td>4</td>
<td>46.5 ± 1.5</td>
<td>44.7 ± 0.5</td>
<td>48.5 ± 0.5</td>
<td>48.7 ± 1.2</td>
<td>42.5 ± 2.5</td>
<td>40.5 ± 0.5</td>
</tr>
</tbody>
</table>

small and large gap wicking when the small gap is in quadrant 1-3. However, for the small gap in quadrant 4 it is found that the bulk shift takes place before the wicking in the two gaps takes place, as shown in Figure 3.5, in which it can be seen that the fluid shifts from left to right. The critical vane angles for the small gap in different quadrants are listed in Table 3.1. The data shows that there is asymmetry present in the geometry.

It is interesting to note that the bulk shift is not observed in the preliminary *Surface Evolver* computations as shown in the bottom row of Figure 3.4. The computations assume perfect geometry which is apparently not true with the experiment vessels where finite tolerance of fabrication, however small, is present. This suggests that tiny asymmetries in fabrication result in significant differences in the behavior of the fluid interfaces.

Critical vane angles for CFE VG-2 are listed in Table 3.2. For the VG-2 only small
and large gap wickings are observed throughout the entire range of the vane angle. Note that a vane angle range is provided in each quadrant for wetting and de-wetting cases. The range is substantially larger as compared to that of CFE VG-1. It is believed that this is caused by contact angle hysteresis. In the experiments, it is observed that the movement of the meniscus tip in the gap is relatively slow and ‘stick-slip’. It often resumes advancing when the vane angle is increased. In addition, due to the contact angle difference, the cross-sectional area of the wetting liquid column in the gap region is smaller than that of CFE VG-1. A sample image is shown in Figure 3.6.

The critical vane angles for both the wetting and de-wetting are provided in Table 3.1 and 3.2. De-wetting takes place when the vane is rotated from the position aligning with the short axis towards that aligning with the long axis of the ellipse. The critical vane angle for the de-wetting is lower than that for the wetting. It is believed that this is caused by the contact angle hysteresis due to the pinning edges of the vane.

In the remainder of this paper, the various critical wetting conditions are identified theoretically following the established Concus-Finn method of analysis[23]. Each condition results in a significant redistribution of the fluid in the container, either covering the base, or along a particular wall leaving a portion of the base uncovered. In addition to the vane angle and fluid wetting properties (for ideal sharp corners) the critical geometric wetting conditions for the Vane Gap vessels depend on the specific vane gap, vane thickness, ellipse size and shape as shown by analysis. The results are then compared to experiments. Exploiting such phenomena, fluids may be positioned as desired by simply and slightly changing the geometry of container. Conversely, knowledge of such critical geometric wetting behavior might avoid mishaps. For example, a slight but uncontrolled container asymmetry might lead to a highly unfavorable shift in fluid preventing or limiting system function. As a result, the ISS CFE-Vane Gap experiments help provide a means for specifying container tolerance.
Figure 3.6: Equilibrium configuration with fluids wicking up in the small gap in quadrant 1 in CFE VG-2, $\alpha = 62^\circ$.

Table 3.2: Experimentally determined critical wetting conditions ($\alpha$) for CFE VG-2.

<table>
<thead>
<tr>
<th>Quad.</th>
<th>SGW</th>
<th>SGD</th>
<th>LGW</th>
<th>LGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$53^\circ - 62^\circ$</td>
<td>$44^\circ - 37.5^\circ$</td>
<td>$69^\circ - 79^\circ$</td>
<td>$60^\circ - 50^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$52^\circ - 59.5^\circ$</td>
<td>$48^\circ - 38^\circ$</td>
<td>$70^\circ - 75^\circ$</td>
<td>$60^\circ - 52^\circ$</td>
</tr>
<tr>
<td>3</td>
<td>$56^\circ - 61^\circ$</td>
<td>$48^\circ - 41^\circ$</td>
<td>$66^\circ - 75^\circ$</td>
<td>$54^\circ - 46^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>$47^\circ - 58^\circ$</td>
<td>$50^\circ - 37^\circ$</td>
<td>$66^\circ - 73^\circ$</td>
<td>$58^\circ - 48^\circ$</td>
</tr>
</tbody>
</table>

3.2 Analysis

3.2.1 Concus-Finn Method

The analytic method described below identifies the existence of equilibrium surfaces in any cylindrical container. To avoid confusion, the equilibrium surface refers to a finite-height single-valued fluid surface that covers the base of the container, see Figure 3.7. Note that there is only one simply connected contact line on each simply connected solid wall boundary for such equilibrium fluid configurations. This type of equilibrium surface is called a simple surface. In a generic cylindrical container as shown in Figure 3.7, such equilibrium simple surfaces in general exist in terrestrial conditions where gravity overwhelms capillary forces. In zero gravity, however, the existence of such a surface can not always be guaranteed. Nevertheless, a surface ‘non-existence’ is desirable in many applications as it provides a passive means to transport and/or locate fluids. The non-existence of a simple surface means that there is always a curvature gradient along the free surface such that part of the interface rises to infinity while the bulk surface remains one of constant mean curvature given that there is enough liquid to cover the base of the container. Such a situation is not likely to take place in practice. In reality, what happens is that the fluid wicks along part of the container wall with relatively high curvature until it either reaches the top of the container or part of the base of the container is exposed. Of course, the fluid surface will ultimately possess some equilibrium shape in a container of finite size. Such equilibrium surfaces are
Figure 3.7: A generic cylindrical container and a simple equilibrium surface.

different from simple surfaces and are called complex surfaces. In general, complex surfaces may either have multiple disconnected contact lines on every simply connected solid wall or have portions of contact lines pinned along edges of the boundary walls. Essentially, the Concus-Finn method predicts the transition from a simple surface to a complex one in a cylindrical container of finite extent.

In zero gravity, simple equilibrium capillary surfaces in a cylindrical container are described by the Young-Laplace-Gauss equation

\[ \nabla \cdot \mathbf{T}_u = 2H = \frac{\Sigma}{\Omega} \cos \gamma , \]  

(3.1)

where

\[ \mathbf{T}_u = \frac{\nabla u}{\sqrt{1 + |\nabla u|^2}} , \]  

(3.2)

and with contact angle boundary condition

\[ \nu \cdot \mathbf{T}_u = \cos \gamma \]  

(3.3)

on the container walls where \( \nu \) is the exterior normal vector of the wall. Note that the mean curvature of equilibrium surfaces is determined by the area \( \Omega \) and perimeter \( \Sigma \) of the container cross-section along with the contact angle \( \gamma \), as shown in Eq.(3.1).

A necessary condition for the existence of a simple surface in a cylindrical container is established by Concus and Finn. The derivation of the condition is only outlined here. A complete presentation can be found in Finn[24] and references contained therein. For a general cross section shown in Figure 3.8, \( \Omega \) represents both the entire domain and its area and \( \Sigma \) represents the entire boundary of \( \Omega \) and its length. In the domain \( \Omega \) one can draw arcs \( \Gamma \) of radius

\[ R_{\gamma} = \frac{\Omega}{(\Sigma \cos \gamma)} \]  

(3.4)
that meet the boundary $\Sigma$ at contact angle $\gamma$. Note that the angle that $\Gamma$ meets at a corner $\Lambda$ can be greater than or equal to $\gamma$. The angle of the corner $\Lambda$ measured inside of $\Omega$ is greater than 180° and is called a reentrant corner. The angle at which $\Gamma$ meets $\Lambda$ is dictated by Gibbs’s inequality

$$\gamma \leq \beta \leq \pi - \eta + \gamma,$$

(3.5)

where $\gamma$ is the equilibrium contact angle, $\beta$ is the angle at which the free surface meets the edge of the corner measured within fluid ‘a’, and $\eta$ is the angle of the corner at the edge (measured in the solid) as depicted in Figure 3.9. A rigorous description of Gibbs’s inequality can also be found in Finn[24].

Single or multiple arcs $\Gamma$ and part of boundary $\Sigma^* \subset \Sigma$ bound a subdomain $\Omega^* \subset \Omega$. A necessary condition for the existence of a simple equilibrium capillary surface on $\Omega$ is

$$\Phi(\Gamma) = \Gamma - (\cos \gamma)\Sigma^* + \left(\frac{\Sigma \cos \gamma}{\Omega}\right) \Omega^* > 0$$

(3.6)

for every $\Omega^*$ configuration as shown in Figure 3.8. In general, there are a finite number of
admissible \{Γ; γ\} configurations for a given domain such that it is possible to evaluate the value of Φ on every Ω*.

### 3.2.2 C-singular Solution

A natural question following the non-existence of the simple equilibrium surface is what will happen to the fluid surface. Finn and Neel[25] point out that there is a solution surface in a singular sense, called a Cylindrically singular solution, referred to as C-singular solution. Typically, there is a subdomain Ω₀ as shown in Figure 3.10 over which the free surface has constant mean curvature; the surface meets the solid wall at contact angle γ, while it becomes asymptotically a vertical cylindrical surface when approaching an arc Γ₀ with radius of curvature R₀. In other words, the surface rises to infinity for any approach to Γ₀ from within Ω₀. Over the subdomain Ω − Ω₀, the interface rises to infinity. Arc Γ₀ serves as a barrier between the subdomain Ω₀ over which the simple surface exists and the subdomain Ω − Ω₀ over which the simple surface fails to exist. Note that when Φ = 0, the radius of curvature R₀ = Rγ. However, for cases where Φ < 0 the radius of curvature R₀ > Rγ and R₀ is determined by integrating the Young-Laplace-Gauss equation

\[
\nabla \cdot T u = 2H₀
\]

over Ω₀ and applying divergence theorem to obtain

\[
Γ₀ + (\cos γ)Σ₀ − 2H₀Ω₀ = 0.
\]

Solving Eq.(3.8) gives rise to R₀.

### 3.2.3 Analysis: Perfectly Wetting Case (CFE VG-1)

For the perfectly wetting case where the contact angle is zero, it can be shown that there are at least five Ω∗ configurations as shown in Figure 3.11. For each configuration two or more arcs Γ are necessary with various portions of the solid boundary to enclose subdomains Ω∗ and evaluate Φ. Note that the four corners of the vane are all reentrant as sketched in
Figure 3.8. Based on the vane angle, arc $\Gamma$ either meets the vane surface at contact angle $\gamma$, or it can meet the vane corner at any angle within the range specified by Eq.(3.5). Arc $\Gamma$ in the former case is called regular while the latter is called irregular. With the vane centerline aligned with the center of the ellipse and when all arcs $\Gamma$ are regular, $\Gamma_a$ and $\Gamma_c$, and $\Gamma_b$ and $\Gamma_d$ are antisymmetric about the axes of the ellipse. Otherwise, for certain vane angles, $\Gamma_a$ and $\Gamma_c$ are not antisymmetric (i.e. not the same) and must be determined independently; $\Gamma_b$ is regular for the entire range of the vane angle so $\Gamma_d$ does not need to be identified independently. Furthermore, when both $\Gamma_a$ and $\Gamma_c$ are regular, it can be shown that $\Phi$ has the same value for cases 4 and 5.

$\Phi$ values as a function of the vane angle $\alpha$ are computed and plotted in Figure 3.12. In general, $\Phi$ decreases with increasing $\alpha$; $\Phi$ for the small gap is lower than that of all the other cases crossing through zero first. The $\Phi$ values for case 4 and 5 are slightly different from each other (indistinguishable on plot) over certain vane angles when either one or both of $\Gamma_a$ and $\Gamma_c$ are irregular. It is found that $\Phi_1 = 0$ at $\alpha = 42.94^\circ$. Once $\Phi_1 = 0$ in the small gap region a simple equilibrium surface fails to exist in the container and fluid wicks up the small gap. This is in agreement with the experiment where the critical vane angle $41.5^\circ \leq \alpha_{cr} \leq 46.5^\circ$, see SGW, Table 3.1.

$\Phi_1 < 0$ for further increases of the vane angle $\alpha$ and C-singular solutions for the free surface persist. As mentioned above, arcs $\Gamma_0$ can be identified that separate the small gap region from the rest of the domain in the sense that the surface rises to infinity over the small gap region while remaining a simple surface of constant mean curvature in the rest of the domain. With further increases of the vane angle $\alpha$, the question remains whether there is always a simple solution over the rest of the problem domain. Since $\Gamma_0$ serves as a barrier between the small gap region and the rest of the domain it is necessary to subtract the small gap region $\Omega_1$ from the entire domain $\Omega$ in order to analyze the rest of the domain.
Figure 3.12: \( \Phi \) for various \( \Gamma \) configurations as a function of vane angle \( \alpha \) for VG-1; \( \Phi_1-\Phi_5 \) are the values of \( \Phi \) for cases 1-5 in figure 3.11 respectively.

The approach employed here is as follows. For each vane angle \( \alpha \) one needs to first locate \( \Gamma_0 \) whose radius \( R_0 \) satisfies Eq.(3.8) as shown in Figure 3.13a. Subsequently, the small gap region included on the convex side of the arcs \( \Gamma_{0a} \) and \( \Gamma_{0b} \) is subtracted giving rise to a new modified domain shown in Figure 3.13b. In the new domain, one draws arc \( \Gamma \) wherever possible. Note that for \( \Gamma \) the radius \( R_\gamma = R_0 \). Accordingly, there are at least three \( \Omega^* \) configurations as shown in Figure 3.13c-e.

\( \Phi \) values for each configuration are computed and shown in Figure 3.14. Note that \( \Phi_d = \Phi_e \) and that both are smaller than \( \Phi_c \). \( \Phi \) in all configurations passes through zero at the same vane angle \( \alpha = 51.29^\circ \). \( \Phi = 0 \) for all configurations which we prove as follows. Using the notation in Figure 3.15, when \( \Phi_c = 0 \), one has

\[
\Phi_c = \Gamma_c + \Gamma_d - \Sigma_2^* + \frac{\Omega_2^*}{R_0} = 0. \tag{3.9}
\]

The two C-singular solutions \( \Gamma_{0a} \) and \( \Gamma_{0b} \) satisfy Eq.(3.8) which can be written as

\[
\Gamma_{0a} + \Gamma_{0b} + (\Sigma_2^* + \Sigma_3 + \Sigma_4) - \frac{\Omega_2^* + \Omega_3 + \Omega_4}{R_0} = 0, \tag{3.10}
\]

which, with \( \Gamma_{0a} = \Gamma_c, \Gamma_{0b} = \Gamma_d, \Sigma_3 = \Sigma_4, \Omega_3 = \Omega_4 \), and subtracting Eq.(3.9) from Eq.(3.10)
Figure 3.13: Arcs $\Gamma$ configurations in the modified problem domain. a. C-singular solutions $\Gamma_{0a}$ and $\Gamma_{0b}$; b. Modified domain with small gap region subtracted; c. Large gap region; d. Modified right bulk region; e. Modified left bulk region.

yields

\[
(\Sigma^*_2 + \Sigma_3) - \frac{\Omega^*_2 + \Omega_3}{R_0} = 0,
\]

and since $\Gamma_{0b} = \Gamma_d$,

\[
\Gamma_d - (\Gamma_{0b} + \Sigma^*_2 + \Sigma_3) + \frac{\Omega^*_2 + \Omega_3}{R_0} = \Phi_d = \Phi_e = 0.
\]

Note that this is only possible when $\Phi_d = \Phi_e$, which is true when both $\Gamma_{0a}$ and $\Gamma_c$ are regular. This shows that multiple C-singular solutions co-exist at the present vane angle. It is not definite which solution takes place in such a situation. However, it shows that the bulk shift can not take place any sooner than wicking in the large gap region. Interestingly, experiments show that the bulk shift takes place at vane angles below $50^\circ$, which is several degrees lower than the critical vane angle $\alpha_{cr} = 51.29^\circ$ identified in Figure 3.14. It will be shown that the most possible cause for this is container asymmetries.

To compare the analytical and experimental results critical vane angles in different quadrants for the small gap, large gap, and bulk shift are listed in Table 3.1. A comparison of theoretical predictions and the experimental results is shown in Figure 3.16, which reveals that the critical vane angle differs from quadrant to quadrant. The bulk shift takes place between the small gap and large gap wetting when the small gap is in quadrant 1, 2, and 3, while it takes place before either gap wetting when the small gap is in quadrant 4. The difference is apparently caused by the asymmetry in the geometry currently presumed within the specified tolerance of fabrication. The asymmetry could mean that the gap size is not exact or the vane is somehow misaligned such that the vane center-line does not exactly pass through the center of the ellipse. The experiment also shows that the bulk shift always takes place at the same side of the vane for both clockwise and counter-clockwise operation.
Figure 3.14: $\Phi$ for the three $\Gamma$ configurations in the modified domain in VG-1.

Figure 3.15: Problem domain with C-singular solutions in the small gap region.
Figure 3.16: Comparison between analytic predictions and experiment results for CFE VG-1. □, Small gap; ◇, Large gap.

Figure 3.17: A definition of vane thickness and length about the center of the ellipse.
of the vane, which further suggests that there are geometric asymmetries. It is also remotely possible that asymmetry of the ellipse contributes to the difference observed. A detailed inspection of the test cell is not possible at present. However, a preliminary investigation of the gap size and misalignment of the vane is carried out analytically below.

It can be shown that if there is any misalignment of the vane then $\Phi_d \neq \Phi_e$ such that $\Phi$ of the three configurations in Figure 3.13 will not pass through zero simultaneously. For example, the experiment data shows that in quadrant 1 the bulk shift takes place at $\alpha = 47.5^\circ$ with $2.5^\circ$ uncertainty. Quantities $\lambda \equiv \epsilon_t/\epsilon_1$ and $\Pi \equiv L_2/L_1$ are defined from $\epsilon_t$, $\epsilon_1$, $L_1$, and $L_2$ shown in Figure 3.17. Note that $L_1$ is the length of the vane on the small gap side. Given by design that $L_1 = 16.091$ mm and $L_2 = 15.253$ mm, $\Pi = 0.948$. It can be shown that at $\alpha = 48^\circ$ in quadrant 1 in order for the bulk shift to take place one should have $\lambda = 1.277$ if $\Pi$ is held constant as shown in Figure 3.18.

It is necessary to point out that what happens in quadrant 4 is very interesting because the bulk shift takes place first at $\alpha = 42.5^\circ$. A detailed analysis shows that in order for this to happen, it is necessary to have $\lambda = 0.541$ while $\Pi$ is held constant. The effect of $\Pi$ is found to be negligible. Once there is a bulk shift, corresponding C-singular solutions exist. Note that even though there are C-singular solutions and the fluid on one side of the vane

Figure 3.18: $\Phi$ of three configurations in modified domain at different $\lambda$ for $\alpha = 48^\circ$. 

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would rise to infinity, the free surface on this side of the vane still has certain constant mean curvature. This means that it is still possible to analyze this part of the free surface for the critical wetting condition. The modified domain is shown in Figure 3.19b. In a sense, this is the opposite of what happens when the small gap wetting first takes place as previously discussed, see Figure 3.13. The critical wetting in the gap regions can be analyzed in the modified domain as shown in Figure 3.19c and d. By keeping $\lambda = 0.541$, it is found that $\Pi = 0.971$ in order for the wetting to take place in the small gap region at $\alpha = 46.5^\circ$. This gives the offset of the vane rotation center relative to the ellipse center. Based on this offset, for the other quadrants, the critical vane angles are computed and compared in Figure 3.20. Agreement in quadrant 2 and 3 is not as good as that in quadrant 1 and 4. Obviously the determination of the vane rotation center is not the only explanation. Further analysis and/or test cell measurements are necessary to fully identify the cause.

Note that once there is wicking in both the small and large gaps, the C-singular solutions in the two regions have the same radius of curvature. The free surface between the two C-singular solutions has constant mean curvature which is actually greater than the curvature of the free surface on the other side of the vane. As a result, the bulk shift co-exists with the wicking in the two gap regions. This also implies that the arcs $\Gamma$ on the two sides of each gap actually have different radii of curvature. This is different from cases where there is no misalignment of the vane for which the radii of curvature should always be same.

### 3.2.4 Analysis: Partially Wetting Case (CFE VG-2)

CFE VG-2 test cell examines a partially wetting case. The interior surface is coated such that the effective contact angle of the test fluid is around $55^\circ$. Except for the thickness of the vane which is twice that of the vane in the CFE VG-1 test cell, all other dimensions are the same for VG-1 and VG-2.

The critical wetting conditions are found in the same manner as that for the perfectly
wetting case. It can be shown that for any given vane angle arcs $\Gamma$ of both regular and irregular types exist. However, only the irregular type yields critical wetting conditions where the functional $\Phi$ vanishes at certain vane angles $\alpha$. It is found that the small gap wetting takes place at $\alpha = 53.47^\circ$ whereas the large gap wetting takes place at $\alpha = 62.29^\circ$, which compares suitably with the experimentally determined angles $47^\circ \leq \alpha_{cr} \leq 62^\circ$ and $66^\circ \leq \alpha_{cr} \leq 79^\circ$, respectively. The experimental results are listed in Table 3.2. A comparison between the analysis and the experiment is shown in Figure 3.21. The difference between the average experimental value and the prediction is 4.8% for the small gap wetting while it is 14.2% for the large gap wetting. It is speculated that both geometric asymmetry and contact angle hysteresis could play a role causing the difference and this shall be clarified once detailed measurements of the test cells is available. A bulk shift is not observed in the experiment which can be shown to be possible only when there is substantial misalignment of the vane.
3.3 Chapter Summary

Critical capillary wetting phenomena can be observed in many situations. It has important applications in fuel systems, fluids handling, and material processing in the liquid state on spacecraft. To fully understand it provides important and useful means to perform operations more efficiently. In this work a Vane Gap geometry is studied as part of the Capillary Flow Experiments conducted onboard the International Space Station. This geometric configuration features typical critical wetting phenomena that can be analyzed using the Concus-Finn method. The geometry is relatively simple while the phenomena observed through experiments and its analysis is rich.

In general, it is observed that there are three wetting configurations for the perfectly wetting fluid in CFE VG-1 test cell. Those are the small gap wetting, the large gap wetting, and the bulk shift. Among the three the bulk shift is most significant because of the amount of the liquid involved. Analysis shows that the bulk shift is not likely to happen if there is perfect symmetry. It also shows that fractions of a millimeter of misalignment of the vane can cause the bulk shift to take place revealing the geometric sensitivity of the critical
wetting. In contrast, only the small gap wetting and large gap wetting are observed for the partially wetting fluid in CFE VG-2 test cell. Bulk shift is unlikely unless there is substantial vane misalignment or the contact angle is small enough with relatively small misalignment.
Chapter 4

CFE-ICF Model Background: Weakly 3-D Capillary Flows

Summary. Spontaneous capillary flows in containers of increasing complexity are currently under investigation to determine important transients for low-g propellant management. Significant progress has been made for complex containers that are cylindrical, but many practical systems involve geometries that are tapered. For example, the taper of an irregular polygonal cross section provides particular design advantages by preferentially locating the liquid where desired and by providing a passive means for fluid phase separation. Passive capillary flow in such containers is termed imbibition and cannot be studied easily on the ground for large, significantly 3-D geometries. For certain flows the governing equations are known but have not been solved analytically to date due to a lack of experimental data identifying the appropriate boundary conditions for the flow. The experimental results of the CFE-ICF test vessels as well as drop tower tests support the analysis of imbibition in tapered polygonal sections, and, in particular, a variety of regular \( n \)-gonal pyramids. The theory can be used to aid in the design and analysis of capillary devices such as 3-D vane networks for bubble-free collection and positioning of fuels for satellites, an important problem concerning propellant and/or cryogenic liquid management aboard spacecraft.

4.1 Introduction

Capillary-driven flows along the interior corners of containers have been studied in detail and a selection of geometries and flow scenarios were recently reviewed [26]. Many such flows are applicable to fluids management aboard spacecraft. For example, a typical flow is shown in Figure 1 where a right cylinder of polygonal section is partially filled with a wetting fluid and released in a drop tower. The fluid is drawn along the corners by capillary forces in the low-g environment and advances at a rate proportional to \( t^{1/2} \). The fluid rapidly establishes a constant height (a.k.a. constant pressure) at a specific location in the container as denoted by \( H \) in the figure. This fixed height serves as an essential boundary condition for the analysis of the flow and leads to the predicted \( t^{1/2} \) behavior. \( H \) may be determined a priori for a large family of cylindrical vessels [27][28].

In general, for slender fluid columns, the lubrication approximation may be applied to quantify the nonlinear diffusive flows that occur in corners under favorable wetting conditions. In conditions where a certain container possesses a slight taper the flows are observed to transition between various regimes. For example, in Figure 2 the edges of a polygonal sectioned container taper uniformly at an angle characterized by \( \psi \). For such ‘pyramidal’ containers whose edges meet at a vertex or virtual vertex, the cross-sectional area is pro-
Figure 4.1: Spontaneous capillary rise (imbibition) in an equilateral triangular container during a drop tower experiment. Vertex on right observed in profile. The constant height (pressure) location rapidly achieved by fluid is identified by $H$.

Portional to $z^2 \tan^2 \psi$ as identified in Figure 2a. Provided wetting conditions are favorable and fluid content is ample, a visco-capillary dominated fluid introduced to the base of the container will wick to the vertex of the container at a rate $t^{1/2}$ (Figure 2b-c). However, once the fluid arrives there, new boundary conditions arise that change the transient response of the fluid which continues to wick at an altered rate toward the vertex. The flow of liquid toward the vertex effectively displaces the ‘ullage’ away from the vertex and toward the ‘base’ of the container as shown in Figures 2d-e. The pressure gradient for the global flow is maintained by the varying curvature of the bulk meniscus as sketched in Figures 2d-e and to be discussed in further detail in context with Figure 3a. The individual capillary driven corner flows represent local flows that contribute to the migration of the bulk menisci that define the ullage.

The relevance of such flows is obvious for fuels and fluids handling and the quantitative dependence on specific container geometry adds significant design capability to engineers optimizing flow channels for a variety of passive fluids positioning and phase separation tasks in spacecraft fluids systems. In this work, a zeroth order solution is reported for what we define here as ‘weakly 3-D’ capillary driven flow—the flow process that characterizes the migration of the ullage depicted in Figure 2c-e. Higher order solutions will be reported in a subsequent publication.

4.2 Model and Equation Formulation

A simplified analysis of the flow is possible by employing a number of modeling assumptions at local and global levels. These are first listed below before they are applied in the mathematical development. Similar approaches have been employed to analyze capillary
4.2.1 Global Assumptions

1. An ullage in a tapered container is represented schematically in Figure 3a. For small taper angles the container axis coordinate $z$ may be approximated by corner axis coordinate $z'$ such that $z' = z + O(\psi)$. This assumption requires $\psi << 1$.

2. Referring to Figure 3a, provided the volume of the ullage is large compared to the volume of the ullage contained solely within the regions of bulk meniscus curvature ($R_1$ and $R_2$), the ullage may be modeled as one with flat ends as shown in Figure 3b. It can be shown that this assumption is valid for the most part provided the taper angle is small, $\psi << 1$. Further support for this assumption will be provided herein. The leading and trailing bulk menisci are identified at positions 2 and 1 as shown on Figure 3a and represented by $z_2$ and $z_1$ in Figure 3b, respectively.
Figure 4.3: Schematic of capillary flow in a tapered conduit: a) Ullage shown with effective radii of curvature at leading (2) and trailing (1) bulk menisci, b) simplified ullage illustrated as modeled herein.

3. The local radius of curvature and thus the pressure in the liquid at the leading and trailing bulk menisci may be determined by the method of de Lazzer et al. [27][28][32]. This assumption permits the clean and closed-form calculation of the constant height boundary condition $h_1(z_1)$ and $h_2(z_2)$ required for solution of the local problem and allows the bulk meniscus leading and trailing locations to be modeled by $z_2(t)$ and $z_1(t)$. Fortunately, this assumption also requires the same constraint as assumption #1, $\psi << 1$. Experimental support for this assumption applied to tapered geometries is provided by way of simple drop tower tests to be highlighted in summary.

4. Not necessarily in general, but for the purposes of the present analysis a further restriction is made to tapered section types where, at any section along the ullage, the total cross flow area $A$ of the spreading fluid is small compared to the container cross-section area $A_s$. Thus, $A/A_s << 1$ and represents a low liquid saturation at any section across the ullage. As will be discussed in context with Figure 4, $A/A_s \equiv \beta << 1$ is maintained for a large number of polygonal container types such as $n$-side regular polygonal sections, rectangular sections, and general sections where $\alpha_i$ interior corner half angles are typically larger than $30^\circ$. Sections with highly acute interior angles do not necessarily meet this criterion and require a higher order analysis.

The local flow problem concerns the capillary driven interior corner flow from the leading bulk meniscus region of the ullage at $z_2$ to the trailing region at $z_1$, Figures 3 and 4. The local flow is represented schematically in Figure 5 and might be effectively modeled provided several conditions are satisfied.

4.2.2 Local Assumptions

5. The liquid columns that flow along the corners are assumed slender. This assumption requires that $\epsilon^2 << 1$, where $\epsilon = h_2/(z_2 - z_1)$ is the slenderness ratio. This assumption allows the lubrication approximation to describe the corner flow.
6. For slender columns, streamwise curvature of the interface in the \( z \)-direction can be ignored provided \( \epsilon^2 f \ll 1 \) where \( f \) is a cross-stream geometric curvature function to be defined (\( R = f_i H_i \)). This assumption is frequently satisfied by the previous assumption \( \epsilon^2 \ll 1 \) and, with the lubrication approximation, reduces the Navier-Stokes and mass conservation equations to a single transient 1-D nonlinear diffusion equation for the interface height \( h(z,t) \) along the corner. (Note that \( h_{i1} = h_i(z_1,t) \) and \( h_{i2} = h_i(z_2,t) \).)

7. Inertia in the corner flows is assumed negligible. This assumption is frequently satisfied by the slender column assumption \( \epsilon^2 \ll 1 \) as well.

8. The influence of gravity on the flow is presently neglected.

### 4.2.3 Dimensional Equations

A. Local Mass Balance and Flow Profile. The dimensional equation for the local flow along the \( i \)th of \( m \) wetted corners in a container of \( n \) interior corners derives from the Navier Stokes equation and a local mass balance for each corner; namely,

\[
\frac{\partial A_i}{\partial t} = -\frac{\partial \dot{Q}_i}{\partial z},
\]

(4.1)

where \( \dot{Q}_i = A_i \langle w_i \rangle \) is the \( i \)th corner volumetric flow rate and \( \langle w_i \rangle \) is the average corner flow velocity through flow area \( A_i \). As shown elsewhere [33][34], Eq. (4.1) may be expressed dimensionally in terms of local fluid height \( h_i \),

\[
\frac{\partial h_i^2}{\partial t} = \frac{\sigma F_i}{\mu} \frac{\sin^2 \alpha_i}{f_i} \frac{\partial}{\partial z} \left( h_i^2 \frac{\partial h_i}{\partial z} \right),
\]

(4.2)
subject at least to boundary conditions at the trailing and leading bulk menisci locations $h_i(z_1) = h_{i1}$ and $h_i(z_2) = h_{i2}$. In Eq. (4.2), $\sigma$ is the fluid surface tension, $\mu$ is the dynamic viscosity, and $F_{ii}$ is a numerical dimensionless resistance coefficient which can in many practical circumstances be treated as a constant $1/8 \leq F_{ii}(\alpha, \theta) \leq 1/6$ (see refs. [34] and [35]). In Eq. (4.2) the geometric surface curvature function $f_i$ is given by

$$f_i = \frac{\sin \alpha_i}{\cos \theta - \sin \alpha_i}, \quad (4.3)$$

where $\theta$ is the contact angle and $a_i$ is the particular corner half angle. Again, subscript $i$ denotes the $i$th of $m$ wetted corners in a container with $n$ interior corners.

When possible, solutions to Eq. (4.2) and associated boundary and initial conditions may be used in turn to compute the total flow rate at bulk menisci locations 1 and 2 using

$$\dot{Q}_1 = \sum_{i=1}^{m} A_i \langle w_i \rangle = \sum_{i=1}^{m} F_{Ai} h_{i1}^2 \sigma F_{ii} \sin^2 \alpha_i \frac{\partial h_{i1}}{\partial z}, \quad (4.4)$$
and
\[
\dot{Q}_2 = \sum_{i=1}^{m} A_i \langle w_i \rangle = \sum_{i=1}^{m} F_{Ai} h_i^2 \frac{\sigma F_i \sin^2 \alpha_i}{\mu f_i} \frac{\partial h_i}{\partial z},
\]
(4.5)

where \( F_{Ai} \) is a dimensionless \( i \)th wetted corner geometric flow area function defined such that
\[
A_i = F_{Ai} h_i^2
\]
with
\[
F_{Ai} = f_i^2 \left( \frac{\cos \theta \sin \delta_i}{\sin \alpha_i} - \delta_i \right),
\]
(4.6)

where \( \delta_i = \pi/2 - \alpha_i \) is the surface curvature angle (refer to Figure 5c). The total local volumetric flow rates determined from eqs. (4.4) and (4.5) may be substituted into a global mass balance and solved for the transient position of the ullage identified by \( z_1(t) \) and \( z_2(t) \) which are further defined below.

B. Global Mass Balance. Under the global assumptions #1, #2, and #3, dimensional global mass balance equations may be written at both bulk meniscus locations 1 and 2 (ref. Figure 4a), such that
\[
\dot{Q}_1 = \frac{d}{dt} (V_s - V) \bigg|_{z_1} = (A_s - A) \frac{dz}{dt} \bigg|_{z_1}
\]
(4.7)

and
\[
\dot{Q}_2 = \frac{d}{dt} (V_s - V) \bigg|_{z_2} = (A_s - A) \frac{dz}{dt} \bigg|_{z_2},
\]
(4.8)

where, in general,
\[
V_s = \int_{z_1}^{z_2} A_s d\tilde{z} \quad \text{and} \quad V = \int_{z_1}^{z_2} A d\tilde{z}.
\]
(4.9)

Areas \( A_s = A_s(z) \) and \( A = A(z(t)) \) are the respective local cross-sectional areas of the container and liquid as sketched in Figure 4b. For pyramidal containers, conduits, and pores whose edges converge to a single vertex or virtual vertex,
\[
A_s = F_{As} z^2,
\]
(4.10)

where \( F_{As} \) is a dimensionless geometric function for the section inclusive of characteristic taper angle \( \psi \). Concerning the total area of liquid in the section at time \( t \),
\[
A = A(z, t) = \sum_{i=1}^{m} A_i = \sum_{i=1}^{m} F_{Ai} h_i^2.
\]
(4.11)

The height of the fluid along the \( i \)th corner is described by \( h_i(z, t) \) as depicted in Figure 5. In general, \( A(z, t) \) is unknown because \( h_i \) for each wetted corner is unknown. However, at bulk menisci locations 1 and 2, \( h_i \) may be evaluated via global assumption #3 where the bulk radius of curvature is known by
\[
R = \frac{P_s \cos \theta}{2\Sigma} \left[ 1 - \left( 1 - \frac{4\Sigma A_s}{P_s^2 \cos^2 \theta} \right)^{1/2} \right],
\]
(4.12)
where \( P_s \) is the section perimeter and \( \Sigma \) is the normalized flow area at fixed \( z \) defined by

\[
\Sigma \equiv \frac{A}{R^2} = \sum_{i=1}^{m} \frac{A_i}{R^2} = \sum_{i=1}^{m} \frac{F_{Ai}}{f_i^2}.
\]

(4.13)

For pyramidal containers the section perimeter is proportional to \( z \), or \( P_s \equiv F_{Ps} z \). Thus, noting \( A_s = F_{As} z^2 \) from Eq. (4.10), Eq. (4.12) becomes

\[
R = \frac{F_{Ps} \, z \cos \theta}{2\Sigma} \left[ 1 - \left( 1 - \frac{4\Sigma \, F_{As}}{F_{Ps}^2 \cos^2 \theta} \right)^{1/2} \right] \equiv F_R z
\]

(4.14)

The bulk radius \( R \) is related to \( h \) in the bulk region by

\[
R_1 \equiv f_i h_{i1} \quad \text{and} \quad R_2 \equiv f_i h_{i2}
\]

(4.15)

from which

\[
h_{i1} = \frac{F_R}{f_i} z_1 \quad \text{and} \quad h_{i2} = \frac{F_R}{f_i} z_2
\]

(4.16)

Thus, at menisci locations \( z_1 \) and \( z_2 \), \( A \) from Eq. (4.11) may be determined by combining eqs. (4.14) and (4.16) such that

\[
A(z_1) = \sum_{i=1}^{m} F_{Ai} \left( \frac{F_R}{f_i} \right)^2 z_1^2 \equiv z_1^2 \sum_{i=1}^{m} F_{Ai}
\]

(4.17)

and

\[
A(z_2) = \sum_{i=1}^{m} F_{Ai} \left( \frac{F_R}{f_i} \right)^2 z_2^2 \equiv z_2^2 \sum_{i=1}^{m} F_{Ai}.
\]

(4.18)

Substitution of eqs. (4.10), (4.17), and (4.18) into (4.7) and (4.8) yields

\[
\dot{Q}_1 = \left( F_{As} - \sum_{i=1}^{m} F_{Af_i} \right) z_1^2 \frac{dz_1}{dt} \quad \text{and}
\]

(4.19)

\[
\dot{Q}_2 = \left( F_{As} - \sum_{i=1}^{m} F_{Af_i} \right) z_2^2 \frac{dz_2}{dt},
\]

(4.20)

subject to initial conditions \( z_1(t=0) = 0 \) and \( z_2(t=0) = z_{2ini} \).

C. Volume Constraint. Lastly, under global assumption \#2, for a fixed ullage volume \( V_u \), \( z_1 \) and \( z_2 \) are related by the dimensional volume constraint

\[
V_u = \int_{z_1}^{z_2} (A_s - A) \, dz = \int_{z_1}^{z_2} F_{As} \, z^2 \, dz - \sum_{i=1}^{m} F_{Ai} \int_{z_1}^{z_2} h_i^2 \, dz,
\]

(4.21)

the first term on the right hand side of which may be integrated to give

\[
V_u = \frac{F_{As}}{3} \left( z_2^3 - z_1^3 \right) - \sum_{i=1}^{m} F_{Ai} \int_{z_1}^{z_2} h_i^2 \, dz.
\]

(4.22)
4.2.4 Scales and Nondimensional Equations

The governing system of equations represented dimensionally by eqs. (4.2), (4.19), (4.20), and (4.22) is nondimensionalized by the following scales:

\[ z \sim L \]  
\[ h_i \sim \frac{F_R L}{f_i} \]  
\[ \dot{Q} \sim \sum_{i=1}^{m} W_i A_i \sim L^2 \sum_{i=1}^{m} W_i F_{Afi} \]  
\[ W_i = \frac{h_{iL} \sigma F_{ii} \sin^2 \alpha_i}{L \mu f_i} \]  

and

\[ L \equiv \left( \frac{3V_u}{F_{As}} \right)^{1/3} \]  

The characteristic initial ullage length \( L \) is the initial \( z \)-coordinate dimension of the ullage in the absence of any fluid in the corners as depicted in Figure 2a. Scales for characteristic heights \( h_i \), flow areas \( A_i \), and the global volumetric flow rate \( \dot{Q} \) are evaluated at \( z \sim L \). \( W_i \) is the \( i \)th corner velocity scale also evaluated at \( z \sim L \). The global mass balance Eq. (4.8) at \( z = z_2 \) is used to compute the global flow time scale

\[ t_s \sim \frac{A_{sL} L}{\dot{Q}} \sim \frac{A_{sL} L}{\sum_{i=1}^{m} W_i A_i} = \frac{F_{As} L}{\sum_{i=1}^{m} W_i F_{Afi}} \]  

where \( A_{sL} \equiv A_s(z = L) \). Employing these scales the resulting nondimensional system is the following:

**A. The \( i \)th corner flow local mass balance (Eq. 2):**

\[ \beta_i \frac{\partial h_i^2}{\partial t^*} = \frac{\partial}{\partial z^*} \left( h_i^2 \frac{\partial h_i^*}{\partial z^*} \right) \]  

subject to \( h_i^*(z_1^*) = z_1^* \) and \( h_i^*(z_2^*) = z_2^* \), from which evaluated at \( z_1^* \) (eqs. 4 and 5)

\[ \dot{Q}_1^*(z_1^*) = \frac{\sum_{i=1}^{m} W_i F_{Afi} h_i^2 \partial h_i^*/\partial z^*}{\sum_{i=1}^{m} W_i F_{Afi}} \]  

and evaluated at \( z_2^* \)

\[ \dot{Q}_2^*(z_2^*) = \frac{\sum_{i=1}^{m} W_i F_{Afi} h_i^2 \partial h_i^*/\partial z^*}{\sum_{i=1}^{m} W_i F_{Afi}} \]  

**B. The global bulk meniscus mass balance (eqs. 19 and 20):**

\[ \dot{Q}_1^* = (1 - \beta) \ z_1^2 \frac{dz_1^*}{dt^*} \]
subject to $z_1^*(0) = 0$ and

$$\dot{Q}_2^* = (1 - \beta) z_2^* \frac{dz_2^*}{dt}$$

subject to $z_2^*(0) = z_{2 ini}^*$. Parameters $\beta$ and $\beta_i$ are closely related and defined by

$$\beta \equiv \sum_{i=1}^{m} \frac{F_{Afi}}{F_{As}}$$

and

$$\beta_i \equiv \sum_{i=1}^{m} \frac{W_i F_{Afi}}{W_i F_{As}}.$$ 

C. The volume constraint (Eq. 22):

$$1 = z_2^{s3} - z_1^{s3} - 3 \sum_{i=1}^{m} \left( \frac{F_{Afi}}{F_{As}} \int_{z_i^*}^{z_2^*} h_i^* dz^* \right).$$

With $h_i^*(z^*,0)$, $z_1^*(0)$, and $z_{2 ini}^*(0)$ known, eqs. (4.29)-(4.33), and the volume constraint Eq. (4.36) represent a coupled integro-differential system of $m + 5$ nonlinear equations for $m$ local dependent variables $h_i^*(z^*,t^*)$ and the four global dependent variables: $\dot{Q}_1^*(z_1^*), \dot{Q}_2^*(z_2^*), z_1^*(t^*)$, $z_2^*(t^*)$. Numerical solution to the system is possible and will be pursued at a later date. At present however, it is sufficient to observe that $\beta$ and $\beta_i$ appear as parameters, which under certain limiting values allow approximate analytical solutions to the system.\(^1\)

4.2.5 Limiting Cases

Below are listed 4 limiting cases addressed here for an arbitrary $i$th corner (note that $\beta_i$ can be less than or greater than $\beta$):

1. $\beta \sim \beta_i \sim O(1)$: This scenario implies that the global and local time scales are of similar order and the system of equations is strongly coupled requiring a fully numerical approach.

2. $\beta_i >> 1, \beta << 1$: In this case, Eq. (4.29) becomes singular at $O(1)$ (cannot satisfy all boundary conditions) and reveals that $h_i^*$ is either a constant or not a function of $t$. Either way the result is no $i$th corner flow at $O(1)$ and thus no contribution of the $i$th corner to the ullage migration. This scenario is met for corners where the Concus-Finn wetting condition $\theta \leq \pi/2 - \alpha_i$ is only marginally satisfied and characteristic velocities approach 0, Eq. (4.26), while other wetting corners contribute significantly to the global flow.

3. $\beta << 1$ and $\beta_i << 1$: As viewed in Eq. (4.34), this is the condition of small liquid flow area compared to container section area. The implication is that the average corner

\(^1\)Alternate scalings are possible for the $m$ local flow equations, Eq. 4.29. For example, an average or maximum velocity scale may used to normalize both sides of the $m$ local flow equations along with the global time scale. Such a scaling is preferred because it renders all $m$ local corner flows $O(1)$ or less. Nonetheless, the $\beta_i$ scaling is employed below only to be removed during subsequent developments.
flow time scale \( \sim O(\beta) \) as well as all individual corner flow time scales \( \sim O(\beta_i) \) are much shorter than the global flow time scale \( \sim O(1) \), and that the local corner flows Eq. (4.29) may be treated as quasi-steady and solved with time dependent boundary conditions. The system of equations is thus significantly decoupled at zeroth order under this constraint.

4. \( \beta = \beta_i \ll 1 \): A subset of case 3 above, this significantly simplifying condition requires a container section such that \( W_i = constant \) for all \( m \) wetted corners. A sketch of several container section-types that meet this ‘equi-\( W_i \)’ criterion is provided in Figure 6. For brevity in this presentation, it is this condition that will be pursued analytically.

### 4.3 \( O(1) \) Solution for Sections where \( \beta = \beta_i \ll 1 \)

For ‘equi-\( W_i \)’ sections the velocity scale \( W_i = W \) is identical for all wetted corners and \( \beta = \beta_i \). Furthermore, when \( \beta \ll 1 \), the expansions

\[
h^* = h^*_0 + \beta h^*_1 + O(\beta^2),
\]

\[
z^*_1 = z^*_1 + \beta z^*_1 + O(\beta^2),
\]

and

\[
z^*_2 = z^*_2 + \beta z^*_2 + O(\beta^2)
\]

serve as nave approximations of the dependent variables of the problem. Employing eqs. (4.37)-(4.39), the \( O(1) \) system reduces to the \( i \)th corner flow local evolution equation

\[
0 = \frac{\partial}{\partial z^*} \left( h^*_{i0} \frac{\partial h^*_{i0}}{\partial z^*} \right)
\]

subject to \( h^*_{i0}(z^*_1) = z^*_1 \) and \( h^*_{i0}(z^*_2) = z^*_2 \), from which the global flow rates may be computed using

\[
\dot{Q}^*_1 = h^*_{i0} \frac{\partial h^*_{i0}}{\partial z^*} \bigg|_{z^*_1}
\]

\[
\text{and} \quad \dot{Q}^*_2 = h^*_{i0} \frac{\partial h^*_{i0}}{\partial z^*} \bigg|_{z^*_2}.
\]
For the time being, the volume constraint remains Eq. (4.36), while the global bulk meniscus mass balance eqs. (4.32) and (4.33) reduce to

$$\dot{Q}_1^* = z_{10}^* \frac{d z_{10}^*}{dt^*}$$

subject to $z_1^*(0) = 0$ and

$$\dot{Q}_2^* = z_{20}^* \frac{d z_{20}^*}{dt^*}$$

subject to $z_{20}^*(0) = 1$.

Solving Eq. (4.40) yields

$$h_{10}^* = \left[ z_{20}^* + \left( \frac{z_{20}^* - z_{10}^*}{z_{20}^* - z_{20}^*} \right) (z^* - z_{20}^*) \right]^{1/3}.$$  

(4.44)

Substituting Eq. (4.44) into the volume constraint Eq. (4.36) reveals that the summation-integral term on the right hand side is $\sim O(\beta)$ and may be ignored at $O(1)$. Thus, Eq. (4.36) reduces conveniently to

$$1 = z_{20}^* - z_{10}^*$$

(4.45)

allowing $z_{20}^*$ to be determined explicitly in terms of $z_{10}^*$. This simplification is indeed fortunate, unique to pyramidally tapered sections (or sections where $A \sim z^2$ and $P_s \sim z$), and reduces Eq. (4.44) further to

$$h_{i0}^* = \left[ z_{20}^* + \left( \frac{z^* - z_{20}^*}{z_{20}^* - z_{10}^*} \right) \right]^{1/3}.$$  

(4.46)

From this solution the flow rate eqs. (4.41) are found to be redundant,

$$\dot{Q}_0^* = \dot{Q}_1^* = \dot{Q}_2^* = \frac{1}{3(z_{20}^* - z_{10}^*)}.$$  

(4.47)

Now employing eqs. (4.47) and (4.45), the global meniscus mass balance Eq. (4.42) may be solved for $z_{10}^*$ yielding the first order ordinary differential equation

$$\frac{1}{3((1 + z_{10}^*)^{1/3} - z_{10}^*)} = \frac{z_{20}^* d z_{10}^*}{dt^*}$$

(4.48)

subject to initial condition $z_{10}^*(0) = 0$. When integrated, Eq. (4.48) yields

$$t^* = \frac{3}{4} \left[ (1 + z_{10}^*)^{4/3} - z_{10}^4 - 1 \right],$$

(4.49)

and from Eq. (4.44)

$$t^* = \frac{3}{4} \left[ z_{20}^* - (z_{20}^* - 1)^{3/4} - 1 \right],$$

(4.50)

The implicit solutions for $t^*(z_{20}^*)$ and $t^*(z_{10}^*)$ are inverted and plotted in Figure 7. The asymptotic forms of the solutions are provided below and noted on the figure where applicable: At short times $t^* \ll 1$, eqs. (4.49), (4.45), and (4.47) may be represented by expansions

$$z_{10}^* \approx t^{1/3} + \frac{1}{4} t^{2/3} + \frac{3}{16} t^* + \frac{35}{192} t^{4/3} + O(t^{5/3}),$$

(4.51)
Figure 4.7: Ullage positions and from eqs. (49) and (53) for transient imbibition in ‘equi-\(W_i\)’ tapered pyramidal sections. One- and 4-term expansions to the O(1) solution for \(z^*_{10}\) from Eq. (50) are shown for comparison.

\[
z^*_{20} \approx 1 + \frac{1}{3} t^* + \frac{1}{4} t^{4/3} + O(t^{5/3}), \tag{4.52}
\]

and

\[
\dot{Q}_0^* \approx \frac{1}{3} + \frac{1}{3} t^{1/3} + \frac{5}{12} t^{2/3} + \frac{65}{144} t^* + \frac{31}{64} t^{4/3} + O(t^{5/3}) \tag{4.53}
\]

The expansions represent a reasonable description of the flow to \(\sim O(t^{5/3})\). However, significantly less error in the predicted values for \(z^*_{20}\) and \(\dot{Q}_0^*\) are obtained using exact expressions

\[
z^*_{20} = (1 + z^*_{10}^3)^{1/3} \tag{4.54}
\]

from Eq. (4.45), \(\dot{Q}_0^*\) from Eq. (4.47), and the four-term expansion for \(z^*_{10}\), Eq. (4.51). As shown in Figures 7 and 8, expansion errors from terms computed in this manner remain small \(\approx 5\%\), even for \(t^* \approx 1.0\). At long times \(t^* \gg 1\)

\[
z^*_{10} = z^*_{20} = t^* + \frac{3}{4} + O(t^{5/3}). \tag{4.55}
\]

The bulk menicus and therefore ullage velocities are determined from

\[
\frac{dz^*_{10}}{dt^*} = \frac{1}{3 z^*_{10}^2 (1 + z^*_{10}^3 - z^*_{10})} \tag{4.56}
\]

\[
\approx \frac{1}{3} t^{2/3} + \frac{1}{6} t^{1/3} + \frac{3}{16} + O(t^{1/3})
\]

and

\[
\frac{dz^*_{20}}{dt^*} = \frac{1}{3 z^*_{20} (z^*_{20} - (z^*_{20} - 1)^{1/3})} \tag{4.57}
\]
Figure 4.8: Dimensionless flow rate, $\dot{Q}_{10}$ from Eq. (47). Solution is compared to the four-term expanded solution for $z_{10}$, Eq. (50), substituted into (53) and (47).

\[
\approx \frac{1}{3} + \frac{1}{3} t^{*1/3} + \frac{5}{12} t^{*2/3} + O(t^*)
\]

and are plotted on Figure 9. The expanded forms below eqs. 4.56 and 4.56 include 3-term expansions for $t^* << 1$ which are also noted on Figure 9. Keeping more than 3 terms in the expansions does not improve the agreement. Note that the 4-term expanded solution for $z_1^*$ from Eq. (4.51) and Eq. (4.54) for $z_2^*$, when substituted into the exact expressions for these velocities, produce values that coincide (typically with errors < 1%) with the exact solution over the full domain of $t^*$. As observed in Figure 9, both velocities approach 1 as $t^* \to \infty$.

4.4 Discussion of Solution and Constraints

From the expanded eqs. (4.51) and (4.55) it is apparent that the trailing meniscus first progresses as $\sim t^{*1/3}$ and then later as $\sim t^*$, while the leading meniscus moves as $\sim t^*$ for the majority of the flow, eqs. (4.52) and (4.55). As observed from Eq. (4.47) and Figure 8, the flow rate across the ullage increases in inverse proportion to the ullage length. At $t^* \approx 1$, a ten-fold reduction in ullage length results in a ten-fold increase in flow rate across the ullage.

For $t^* \to \infty$, from Figure 7 the ullage appears to lose its slender nature in violation of the model and significant 3-D curvature effects are expected to dominate the flow which will eventually produce a stationary spherical bubble if the container is long enough. At the other end of the spectrum, for $t^* \to 0$, from Figure 9 the unbounded trailing meniscus velocity $dz_1^*/dt^*$ is unphysical and speaks to the fact that at such short times the global trailing meniscus time scale is of similar order to the local corner flow time scale also in violation of the model which assumes $\beta << 1$.

The solution of eqs. (4.49), (4.54), and (4.46) may be used in turn to provide more quantitative time regimes under which the modeling assumptions are valid. For example,
for pyramidal vessels it can be shown that the most pivotal global assumption #2 is satisfied provided

\[ 16\pi F_R^3 z_2^3 z_1^3 F_A s << 1, \]

which for fixed geometry obviously becomes increasingly difficult to satisfy as \( z_2^* \) increases in time. However, it may also be shown that \( F_R^2 / F_A s \sim \tan \psi \), and that this constraint is readily satisfied for \( z_2^* \sim O(4.1) \) provided \( \psi \) is small enough (global assumption #1).

The most pivotal local modeling assumption is the slender column assumption #5. Again, for pyramidal vessels, it can be shown that this constraint requires

\[ \epsilon^2 \sim \left( \frac{F_R}{f_i} \right)^2 \left( \frac{z_2^*}{z_2^* - z_1^*} \right)^2 << 1, \]

which for fixed geometry again becomes increasingly difficult to satisfy both as \( z_2^* \) increases in time and as \( z_2^* - z_1^* \) decreases in time. Nonetheless, it can be shown that \( F_R^2 / f_i^2 \sim \tan^2 \psi \) which readily maintains the constraint of Eq. (4.59) for \( z_2^* \sim O(4.1) \) for many practical problems provided \( \psi \) is small enough.

### 4.4.1 Impact of Geometry

The intricate dependence of the flow on container geometry can be interrogated by the present analysis. For example, redimensionalizing the flow rate for \( t^* << 1 \) for the equi-\( W_i \) pyramidal sections described above yield

\[ \dot{Q} = K_{geo} \frac{1}{3} (1 + t^{1/3}) \]
where

\[ K_{geo} \equiv m \sum_{i=1}^{m} F_{Ai} \left( \frac{F_{R} L}{f_{i}} \right)^{2} \left( \frac{F_{R} \sigma F_{ii} \sin^{2} \alpha_{i}}{f_{i} \mu} \right) = F_{geo} \left( \frac{L^{2} \sigma}{\mu} \right). \] (4.61)

\( K_{geo} \) is a dimensional flow rate coefficient separated into cross flow area and velocity scale components in Eq. (4.61). The length scale \( L \) appears in the cross flow area term only and stems from \( h \sim h_{2}(z_{2} = L) \propto L \). The velocity scale term may be broken down further into the slenderness ratio \( F_{R}/f_{i} \), the capillary velocity \( \sigma/\mu \), and the geometric ratio component of the capillary to viscous force, \( F_{ii} \sin^{2} \alpha_{i}/f_{i} \). Viscous effects are contained only within the velocity scale term in Eq. (4.61), where no length dimensions appear because the viscous length, also characterized by \( L \), is cancelled by the same capillary driving force length scale \( \sim L \). Thus, \( K_{geo} \) serves as the measure of the flow intensity at small times and provides a clear path for comparisons of like geometries or for optimizations given certain container, conduit, or pore dimensions. \( F_{geo} \) is a dimensionless geometric function that collects purely geometric quantities.

### 4.4.2 Application

To demonstrate the value and ease with which container, conduit, or pore geometries are compared, a brief analysis of equi-length, equi-volume, \( n \)-regular pyramidal containers is provided here. By fixing \( L, \psi \) can be varied such that all such containers possess the same volume and can be compared on this basis. Such a comparison is effectively one of comparing iso-porosity structures in which pore geometry is the sole distinguishing characteristic. A sketch of three \( n \)-sided regular pyramidal containers is provided in Figure 10. \( F_{geo} \) from Eq. (4.61) is

\[ F_{geo} = \frac{nF_{A}F_{i}F_{R}^{3} \sin^{2} \alpha}{f_{i}^{4}}, \] (4.62)

where

\[ \alpha = \frac{\pi(n-2)}{2n}. \] (4.63)

An overview of the terms appearing in Eq. (4.62) would include the fact that \( F_{A} \sim \tan \alpha, F_{i} \approx 1/7, \) and that for this container type,

\[ F_{As} = n \tan^{2} \psi \sin^{2} \alpha \tan(\pi/n) \] (4.64)

and

\[ F_{Ps} = 2n \tan \psi \sin \alpha \tan(\pi/2) \] (4.65)

from which \( F_{R} \) may be computed via Eq. (4.14). \( F_{geo}(10^{5}/F_{i}) \) is plotted against \( 1/n \) in Figure 11. For cases where \( n \gg 1 \), it can be shown that \( F_{A} \sim 4n/3\pi, F_{R} \sim (1/2) \tan \psi, \sin \alpha \sim 1, \) and \( f \sim 2n^{2}/\pi^{2} \). Thus, in this limit, with all assumptions for the analysis satisfied (i.e. \( \psi << 1 \)), it is found that \( F_{geo} \sim n^{-6} \) and in turn, \( \dot{Q} \sim n^{-6} \). In the limit \( n \to \infty, F_{geo} \to \pi^{7} \tan^{3} \psi/96n^{6} \). This power law dependence is reflected in the straight line fit on Figure 11. It is from such results that transport rates are readily observed to be strong functions of geometry. In this case for instance a change from a square \( (n = 4) \) conduit to an
Figure 4.10: Sketch of three constant volume, constant length, $n$-regular pyramidal containers. $\psi_n$ is varied to maintain volume constant between vessels.

Figure 4.11: For containers of Figure 11, $F_{geo}$ from Eq. (69) multiplied by constant $10^5/F_i$ and plotted against $3/n$, for $n = 3, 4, 5, ... 20$. The slope identified using the straight line shows $1/n^6$ dependence.

equilateral triangular one ($n = 3$) of identical volume and length produces a corresponding 5.6-fold increase in flow rate across the cell, $(4/3)^6$. A similar change from a hexagon to a triangle yields a 64-fold increase $(6/3)^6$.

4.5 Supportive Drop Tower and CFE-ICF ISS Experiments

Evidence supporting the flat bulk meniscus modeling assumption #3 applied to right cylindrical vessels is provided in earlier works on the subject [28][32][34]. Support for application of this assumption to the tapered containers investigated herein is provided in Figure 12 where 2.2s drop tower tests at NASA’s Glenn Research Center are conducted for the sudden
Figure 4.12: Select images from 2.2s drop tower test of a perfectly wetting 2cs Si Oil ($\sigma = 0.0187\text{N/m}$, $\mu = 0.00174\text{kg/ms}$, $\theta = 0^\circ$) in an inverted $\psi = 8^\circ$ tapered $75^\circ$-$30^\circ$-$75^\circ$ right isosceles pyramid at times 0, 0.23, 1, and 2s. The $30^\circ$ corner ($\alpha_i = 15^\circ$) is viewed in profile on the right hand side of the container (compare with Figure 1).

Figure 4.13: Advancing tip histories for drop tests performed at various initial fill levels $Z$ for the test cell of Figure 12 (the inset is approximately to scale). Linear predictions $\pm 5\%$ shown as continuous lines on plot lend further support for the application of the flat bulk meniscus assumption and the use of the de Lazzer et al.$^{2,3}$ method to compute bulk meniscus curvature as function of its axial location.
imbibition problem in a uniformly tapered right isosceles pyramid (compare with Figure 1). As shown in Figure 13 tests performed at several initial fill levels to determine the meniscus advance location are well predicted by current theory \( t^{1/2} \) which assumes that the method of de Lazzer et al. [27],[32] may be applied to compute the surface height boundary condition (bulk meniscus curvature) at the coordinate origin for the flow. Unfortunately, for these tests \( \psi \) is sufficiently small such that the predicted and measured slopes in Figure 14 do not vary significantly between tests. As a result, the experiments only provide 'support' for the use of the de Lazzer method to compute the constant height \( H(z) \) location for the flow. Proof of this claim awaits further experiments over a broader range of geometric parameters.

CFE-ICF data from ISS experiments outlined in Chapter 1 clearly confirm these trends and in some cases provide further evidence of quantitative agreement with experiments. However, test cell ICF2, which provides excellent data during the flight is not a pyramidal taper and does not lend itself to closed form solution (at present).

### 4.6 Chapter Summary

An analytic approach predicting liquid flow rates and/or ullage migration rates in partially filled containers, conduits, or pores that are slightly tapered is presented. Closed form solutions are offered for the special case of symmetric pyramidally-tapered sections where \( A_s \sim z^2 \). Solutions are also in hand for the special case of symmetric, tapered sections of high aspect ratio where \( A_s \sim z \) as well as other geometries and boundary conditions which will be reported elsewhere. The \( O(1) \) analytic solutions permit relatively easy comparisons and optimizations for various container shapes as demonstrated herein for pyramids of \( n \)-sided regular polygonal section. The method can be used as a tool to design specific capillary fluid elements for large length scale systems such as spacecraft fuel tanks, as well as to design microfluidic systems for terrestrial applications such as high performance porous wicks.
References


Chapter 5

Appendix: Abbreviated CFE Chronology and Accomplishments

5.1 Abbreviated Chronology

An abbreviated chronology of the CFE experiments development and performance is as follows:

- March, 2003: Authority to proceed with design and fabrication
- September, 2003: CL-2 Pre-Ship and Phase III Safety Reviews, Hardware Turnover (JSC)
- November, 2003: CL-2 Shipped to Russia
- January 29, 2004: CL-2 launched to ISS on Progress mission, 13P
- February 2, 2004: 1.5hr Crew Training, M. Fincke (JSC)
- September 18, 2004: 2nd Performance of CL-2 experiment by M. Fincke, Expedition-9, Saturday Science: Extra Science
- February 1, 2005: 1.5hr Crew Training, B. McArthur (JSC)
- February 2, 2005: 1.5hr Crew Training, J. Williams (JSC)
- February 9, 2005: CL-1/CL-2 Preship and Phase III Safety Reviews, Hardware Turnover (JSC)
- July 10, 2005: CFE-CL-1 (with CFE-VG and -ICF vessels, 2ea) launched to ISS aboard Shuttle STS-114
- August 30, 2006: 1st performance of CL-1 by J. Williams, Expedition-13, Nominal Science Operations
• September 5, 2006: 1st performance of CFE-VG-1 by J. Williams, Expedition-13, 1/2 of Nominal Operations

• September 21, 2006: Flight data tapes for CFE operation on ISS to date returned to Earth (including data for CFE-VG-1) aboard Shuttle flight STS-115 (received by PI team 12/2006)

• March 3, 2007: second performance of CFE-VG1-2, S. Williams, Increment 14, Saturday Science (Quadrant I tests, symmetry test)

• March 10, 2007: first performance of CFE-ICF1-1, M. Lopez-Alegria, Increment 14, Saturday Science (dry and 2 wet tests)

• March 26, 2007: third performance of CFE-VG1-3, S. Williams, Increment 14, Hard Schedule (Quadrant IV tests, symmetry test)

• April 6, 2007: first performance of CFE-VG2-1, S. Williams, Increment 14, Saturday Science (360° CW dry and wet tests)

• April 7, 2007: second performance of CFE-ICF1-2, S. Williams, Increment 14, Saturday Science (all operations including loop tests and bubble tests)

• April 23, 2007?: CFE-VG2-2, S. Williams, Increment 14, Saturday Science (360° CW for critical angles, the 360deg CCW for hysteresis)

• April 29, 2007: CFE-ICF2-1 S. Williams, Increment 14, Saturday Science (Complete nominal operations: dry, wet, loop and bubble tests)

• May 11, 2007: CFE-VG2-3, S. Williams, Increment 14, Saturday Science (180° CW and CCW, critical angle and hysteresis with fine increments)

• May 12, 2007: CFE-ICF2-2 S. Williams, Increment 14, Saturday Science (extra science Wet and Bubbly, reservoir and test chamber axial and lateral shakes to generate bubbles)

• June 2, 2007: CFE-VG2-4, S. Williams, Increment 14, Saturday Science (alternate interface experiments)

• July 14, 2007: CFE-VG1-4, C. Anderson, Increment 15, Saturday Science (Quadrant II test)


• Nov 16, 2007: CFE-CL1-2, P. Whitson, Increment 16, Voluntary Science, (pinned cylinder, slide depth effects)
5.2 Abbreviated Scientific Accomplishments

A more detailed list of scientific accomplishments during the various CFE operations on ISS is provided below. The progress points out some of the piecemeal development of certain methods and capabilities by the astronauts, e.g., centrifugal methods and the axial disturbance methods for CFE-CL, Quadrant tests for CFE-VG, etc.

1. CFE-CL-2-1 (Fincke): Nominal Science Run
   (a) Successful completion of all science objectives
   (b) Demonstration of centrifugal technique to reset experiment for certain repeat runs
   (c) Identified controlled method to impart axial mode disturbance using MWA
   (d) Noteworthy additional science: droplet ejection, drop-wall impacts and rebound, hourglass formation

2. CFE-CL-2-2 (Fincke): Extra Science
   (a) Repeat Push, Slide, and new data using Axial mode
   (b) Noteworthy additional science: Depth effects to Push disturbance

3. CFE-CL-2-3 (McArthur): Extra Science
   (a) Demonstrate augmented version of Fincke centrifuge method to fully clear pinning lip of liquid allowing for the indefinite repetition of the experiments
   (b) Repeat Push, Slide, and Axial mode (camera mounted to MWA)
   (c) Noteworthy additional science: more droplet/jet ejections, drop-wall impacts, and rebound

4. CFE-CL-2-4 (J. Williams): Extra Science
   (a) Perfection of McArthur’s augmented centrifuge method
   (b) Repeat Push, Slide, and Axial mode (camera mounted ISS rail)
   (c) Noteworthy additional science: significant droplet/jet ejections and manifold droplet-wall and free surface impacts and rebound events

5. CFE-CL-1-1 (J. Williams): Nominal Science Run
   (a) Successful completion of all science objectives
   (b) Noteworthy additional science: some depth effects

6. CFE-VG-1-1 (J. Williams): Nominal Science Run
   (a) Successful completion of all science objectives for first half of crew procedures
   (b) completed two complete CW vane rotations
   (c) Clearly identified critical wetting angles to better than anticipated precision (1)
(d) Data suggests third global critical wetting condition

7. CFE-VG-1-2 (S. Williams): Nominal (revised) Science Run
   (a) Successful completion of revised science run to determine equilibrium configurations in Quadrant I
   (b) Positive identification of global asymmetric interface and associated critical vane angle
   (c) Identification of container asymmetry and impact on interface

8. CFE-ICF-1-1 (M. Lopez-Alegria): Nominal Science Run of first half of procedures
   (a) Successful completion of all science objectives for first half of crew procedures
   (b) completed dry fill and two wet fill tests
   (c) Data clearly identified wetting regimes depending on container geometry

9. CFE-VG-1-3 (S. Williams): Nominal (revised) Science Run
   (a) Successful completion of revised science run to determine equilibrium configurations in Quadrant IV
   (b) Positive identification of global asymmetric interface and associated critical vane angle
   (c) Identification of container asymmetry and impact on interface (global shift requires ≈ 15min.)
   (d) Verification of critical global shift angle outside of gap wetting envelope
   (e) Completion of all science for VG1 vessel

10. CFE-VG-2-1, S. Williams, Increment 14, Saturday Science (360° CW dry and wet tests)
    (a) Successful completion of nominal science run for CW vane rotations for dry and wet tests
    (b) Positive identification of critical wetting and dewetting angles and hysteresis
    (c) Global asymmetric wetting not observed
    (d) Preliminary symmetry of wetting conditions observed

11. CFE-ICF-1-2, S. Williams, Increment 14, Saturday Science (all nominal operations)
    (a) Successful completion of all revised science run operation and objectives
    (b) Demonstration of centrifugal method to rapidly redeploy liquid
    (c) Provision of critical data for global fluid reorientation
    (d) Demonstration of high loop test flow rates
    (e) Demonstration of passive bubble separations
12. CFE-VG2-2, S. Williams, Increment 14, Saturday Science (360° CW for critical angles, 360° CCW)
   (a) Successful completion of all revised science run operation and objectives
   (b) Identified critical angles with high precision
   (c) Mapped critical de/wetting hysteresis

13. CFE-ICF2-1, S. Williams, Increment 14, Saturday Science (Complete nominal operations: dry, wet, loop and bubble tests)
   (a) Successful completion of all revised nominal operations for dry test, wet test (2ea), loop tests (3ea), and bubble tests (6ea)
   (b) Demonstration of centrifugal method to rapidly redeploy liquid
   (c) Provided variety of large bubble migration/separation test resulting from lateral excitations
   (d) Provided variety of small bubble migration/separation tests resulting from vigorous axial excitations
   (e) Demonstrated clear ability of corner flows to filter, separate, and coalesce bubbly two-phase systems passively

14. CFE-VG2-3, S. Williams, Increment 14, Saturday Science (180° CW and CCW, fine increment)
   (a) De/wetting angles in Quadrants I and II including hysteresis
   (b) Extra Science run relocating fluid to lid, identified new meta/stable interface configuration for all vane angles. Drain procedure reveals unstable film on ellipse walls following a rupture event initiated at the drain exit port.

15. CFE-ICF2-2, S. Williams, Increment 14, Saturday Science (extra science)
   (a) Additional Wet and Bubbly tests
   (b) Small numbers of large bubbles interactions observed (small bubbles ‘overtake’ and merge with larger bubbles)
   (c) Bubbles production in reservoir fails, bubble production in test vessel succeeds (later and axial shaking)

16. CFE-VG2-4, S. Williams, Increment 14, Saturday Science (Alternate Interface Experiments)
   (a) Demonstration of three new interface configurations: filament, asymmetric right (vane at 90°), asymmetric left (vane at 0°).
   (b) Interface stability to a variety of input disturbances.

17. CFE-VG1-4, C. Anderson, Increment 15, Saturday Science (Quadrant II test)
   (a) CCW 180° to 90°, CW 90° to 180°, and 180° to 90° quick turn.
(b) Accurate equilibrium data in Quadrant II
(c) Certain identification of critical vane wetting and bulk asymmetric wetting conditions.

18. CFE-VG1-5, P. Whitson, Increment 16, Voluntary Science (Quadrant III test)
   (a) CCW 180° to 270°, CW 270° to 180°, and 180° to 270° quick turn.
   (b) Accurate equilibrium data in Quadrant III
   (c) Certain identification of critical vane wetting and bulk asymmetric wetting conditions.

19. CFE-CL1-2, P. Whitson, Expedition 16, Voluntary Science (pinning cylinder, slide and depth effects)
   (a) Bubbles on fill, couldn’t remove, went ahead, first large axial disturbance broke pinning lip, 15 minute recovery. Subsequent disturbances de-pinned readily and subsequent de-pinning efforts ultimately lead to a break of the container (hit on ISS hand rail). (It was difficult to clear the pinning edge, apparently requiring a large acceleration level not possible to impart by hand.)
   (b) Nonetheless, a significant number of large amplitude pinned oscillations and destabilizations were recorded and will prove invaluable to the finalization of our CFE-CL database.
Chapter 6

Appendix: CFE-Related Dissemination Materials to Date (selection)

Journal Publications


Published Presentations


Other Publications and presentations; Reports, Brochures, etc. (selection)


Chapter 7
Appendix: Data Archive Conventions

7.1 Video Preparation Process

All of the experiments presented are captured on video and must be converted to a numerical representation in space and time. Such a process requires the original video to be conditioned and converted so that it is in a suitable format for analysis. Once in a compatible format, events must be digitized, which requires a technique unique to the experiment. The process of formatting the video is documented below and is applicable to all of the experiments presented.

CFE is conducted aboard ISS with video being captured on a 720x480 Sony DVCam. This video is of the highest quality and is termed ‘onboard’ or ‘flight’ video. Flight video is only accessible in its native form when the DV media makes it to earth, which can take several months from the date the experiment is performed. On orbit the video is also recorded to the Video Tape Recorder (VTR), which is located aboard ISS. Immediately following the experiment, video stored upon the VTR is sent to earth, digitally recorded, and copied to DVDs. In addition, ‘realtime’ video is sent to earth during the experiment, which is recorded while in orbit, and is available immediately after completion of the experiment. Down-linked realtime and VTR video are available shortly following the experiment; however, such video is of significantly lower quality than flight video. Media obtained from NASA is on DVD in MPEG-2 format, which must be converted to comply with the image analysis software. The freeware program Spotlight-8 is used to track events contained on video and can read uncompressed 24-bit AVI or Quicktime video. The objective of the video formatting is to render the video in a compatible 24-bit AVI format. This is achieved by the following conversion process: MPEG-2 $\rightarrow$ MPEG-1 $\rightarrow$ 24-bit AVI. Sony Vegas Video 6.0 with DVD Architect 3.0 is used to open the DVD VOB files (MPEG-2) contained on each DVD. Experimental events are selected from the DVD and rendered as high quality MPEG-1 videos. The MPEG-1 video is then imported into VirtualDub where it is converted to an uncompressed 24-bit AVI video, being a suitable format for Spotlight-8. When converting from a compressed MPEG-1 to an uncompressed AVI, the file size increases significantly, often becoming $\sim 120x$ greater, and requiring large amounts of disk space. To reduce disk space and increase portability, video is stored in MPEG-1 format until digitization is required. In addition, MPEG-1 video is portable, compact, useful for presentation, and easily converted to other formats. With the MPEG-1 video, one only needs VirtualDub to convert the MPEG-1 to a suitable AVI format and subsequently read into Spotlight-8 for digitizing. When converting between formats there is always a risk of quality loss; however, there is very little degradation in quality and no effect on digitization as a result of the
video formatting.

7.2 Naming Convention

The video files and resulting datasheets are named in a very specific manner with the objective of identifying the experiment, expedition, astronaut, DVD, and time.

Identification of Experiment Operation

1. Experiment (CL1, CL2, ICF1, ICF2)
2. Expedition (Exp##)
3. Date of Operation (##-##-##)

Identification of Video and Media

4. Video Origin (OB-Onboard, RT-Realtime, VTR-Video Tape Recorder)
5. Recording Media (DVCam, Hi8mm)
6. Content (Ops–Operations, Setup)

Identification of DVD

7. GMT Time of Experiment (##m##s–##m##s, if available)
8. Tape Number (T#, single digit, if available)
9. Tape ID (ID##–##, two digits, if available)
10. Astronaut Initials (MF, BM, JW, SW, CA, LA)

Event Location on DVD

11. DVD Chapter (Ch#, single digit if more than one chapter, otherwise excluded)
12. Time of Event (##m##s–##m##s)
13. Disturbance Type (CL only, A-Axial, P-Push, S-Slide, MS-Multi-Slide)

Examples are given for two experiments using the naming convention outlined above.

CL1_Exp13_08-30-06_OB_DVCam_Ops_T123_ID27-29_JW_Ch2_1108-1138_A

The name references the Contact Line-1 experiment performed by the Expedition 13 crew on August 30th, 2006. The video is from a physical onboard media captured with a Sony DVCam. The DVD is of experimental operations including tapes 1, 2, and 3 with ID numbers 27, 28, and 29. The operations were performed by astronaut Jeff Williams. Video from the DVD was cut from chapter 2 between the times 11:08 and 11:38 (mm:ss). The disturbance type is Axial.
The name references the Interior Corner Flow-1 experiment performed by the Expedition 15 crew on April 7th, 2007. The video is from a physical onboard media captured with a Sony DVCam. The DVD is of experimental operations with markings on the DVD identifying GMT times between 05:11–07:33. Note that ID and tape numbers were not found on this particular DVD. The operations were performed by astronaut Sunita Williams. Video from the DVD was cut between the times 06:51 and 07:51 (mm:ss).
Chapter 8

Appendix: Contact Line Sample Data Sheets

8.1 Datasheet Descriptions

Representative datasheets are presented with explanations of major features\(^1\). The right and bottom of all page images (except data pages) are numbered columns and rows. These are used for referencing only and are not part of the datasheets outside the Thesis. Each Excel datasheet contains several ‘tabs’ which are:

1. Notes & Dim (Notes and Dimensions)
2. Input & Response Notes
3. Input Data
4. Smooth Response Data
5. Pinned Response Data
6. Below Pin Response Data (CL-1 only, replaces 5.)
7. Input Plot
8. Smooth Response Plot
9. Pinned Response Plot
10. Below Pin Response Plot (CL-1 only, replaces 9.)
11. Comparison Plot

Datasheets are formatted and notated in a descriptive manner where most features are self-explanatory. The ‘Notes & Dim’ tab contains three pages of information separated into five different categories that are described below.

1. **Notes**: General notes are provided and may differ between CL-1 and CL-2. All of the information is heavily notated and self explanatory.

2. **Fluid Depth**: Measurements are taken before and after the input disturbance at the centerline of the interface. Depths are measured in pixels and converted to millimeters using the scale factors calculated at the representative points.

\(^{1}\) A feature is anything in a datasheet—though generally a phrase, number, character, object, or image.
3. **Physical Dimensions:** Measurements are taken before and after the input disturbance and used to calculate the scale factor plane described in Section 2.2.1. Three different locations are measured and related to known distances to obtain the local scale factors, which, when coupled with the midpoints, can be used to calculate the scale factor constants.

4. **Input/Response SF Constants:** Scale factor constants based on Equations 2.9–2.11 are reported before and after the input disturbance.

5. **Approximate Results:** A subset of results are calculated per event for the Pinning and Smooth cylinders. Result categories are subject to change and may include additional or different results in the future (e.g. damping rate). A value of ‘−1’ indicates the quantity cannot be measured accurately and is not reported.

Features highlighted in yellow (■) are generally input by the user between events while blue (■) indicates calculated results. In the tabs with rows of data the opposite is true, where blue indicates raw data used to calculate the results in yellow. Red (■) indicates a feature that causes significant changes to the experiment.

The second tab, labeled ‘Input & Response Notes’, is separated into four sections documenting how the input and response are tracked. The page is heavily notated with most features being self-explanatory. In some cases a ‘Labels’ section is present, and is used only to notate the plots in the datasheet. Finally, the first page of the input disturbance, Smooth and Pinning response data is presented for all of the example datasheets. The method of tracking is documented along with the filename and other output from Spotlight-8. The scale factor in the right-most column is calculated using the scale factor plane equation (see Equation 2.5)—utilizing the $x$ and $y$ coordinates. It should be noted that optical correction is not applied in any of the datasheets and must be post-processed by the user. Updated datasheets and additional information can be found at http://cfe.pdx.edu.
8.1.1 CL-1 Axial Mode Example Datasheet
General Notes/Physical Measurements

Notes

720x480 DV Converted to 640x480 square pixels.

"Left Cylinder" refers to the cylinder with the 'Smooth' boundary condition

"Right Cylinder" refers to the cylinder with the 'Pinning' boundary condition

The frame rate is (frames/s): 29.97

Disturbance Type: Axial

The pinning lip is: Dry

Fluid Depth

(Measured from meniscus to bottom of cylinder)

Fluid depths measured at frame: 0

<table>
<thead>
<tr>
<th>Rep. Point 1</th>
<th>Rep. Point 2</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>202.5</td>
<td>472.5</td>
<td>0.202798541</td>
</tr>
<tr>
<td>345.5</td>
<td>319.5</td>
<td>0.200156642</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (px)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>105</td>
</tr>
<tr>
<td>Pinning</td>
<td>159</td>
</tr>
<tr>
<td>Difference</td>
<td>54</td>
</tr>
</tbody>
</table>

Physical Dimensions:

Smooth Cylinder (Left)

Bottom of Cylinder P1

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>398</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bottom of Cylinder P2

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF0</th>
<th></th>
</tr>
</thead>
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<td>296</td>
<td>398</td>
<td>1.5</td>
<td>0.00802139</td>
<td>0.203743316</td>
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</tbody>
</table>

Difference

<table>
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<th>y -pixel</th>
<th>Actual</th>
<th>SF0</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>187</td>
<td>0</td>
<td>1.5</td>
<td>0.00793651</td>
<td>0.201587302</td>
</tr>
</tbody>
</table>

Midpoint (X0,Y0)

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF0</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>202.5</td>
<td>398</td>
<td>1.5</td>
<td>0.00793651</td>
<td>0.201587302</td>
</tr>
</tbody>
</table>

Pinning Cylinder (Right)

Bottom of Cylinder P1

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF1</th>
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</thead>
<tbody>
<tr>
<td>567</td>
<td>399</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bottom of Cylinder P2

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>399</td>
<td>1.5</td>
<td>0.00793651</td>
<td>0.201587302</td>
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</tbody>
</table>

Difference

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>189</td>
<td>0</td>
<td>1.5</td>
<td>0.00793651</td>
<td>0.201587302</td>
</tr>
</tbody>
</table>

Midpoint (X1,Y1)

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>472.5</td>
<td>399</td>
<td>1.5</td>
<td>0.00793651</td>
<td>0.201587302</td>
</tr>
</tbody>
</table>

Smooth Cylinder (Left)

Top of Cylinder P1

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>296</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Top of Cylinder P2

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF2</th>
<th></th>
</tr>
</thead>
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<td>105</td>
<td>160</td>
<td>1.5</td>
<td>0.0078534</td>
<td>0.19947644</td>
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</tbody>
</table>

Difference

<table>
<thead>
<tr>
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<th>y -pixel</th>
<th>Actual</th>
<th>SF2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>191</td>
<td>0</td>
<td>1.5</td>
<td>0.0078534</td>
<td>0.19947644</td>
</tr>
</tbody>
</table>

Midpoint (X2,Y2)

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>200.5</td>
<td>160</td>
<td>1.5</td>
<td>0.0078534</td>
<td>0.19947644</td>
</tr>
</tbody>
</table>

Average

<table>
<thead>
<tr>
<th>x -pixel</th>
<th>y -pixel</th>
<th>Actual</th>
<th>SF2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>0.0079371</td>
<td>0.201602352</td>
</tr>
</tbody>
</table>

1 2 3 4 5 6 7 8 9
## Input SF Constants

Scale Factor (SF) constants (in/px): 
-3.17003E-07  7.08493E-07  0.0078036  
Scale Factor (SF) constants (mm/px): 
-8.05189E-06  1.79957E-05  0.19821153  

## Fluid Depth

(Measured from meniscus to bottom of cylinder)

<table>
<thead>
<tr>
<th>Rep. Point 1</th>
<th>Rep. Point 2</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>201.5</td>
<td>473</td>
</tr>
<tr>
<td>y</td>
<td>352</td>
<td>327</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (px)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>108</td>
</tr>
<tr>
<td>Pinning</td>
<td>158</td>
</tr>
<tr>
<td>Difference</td>
<td>50</td>
</tr>
</tbody>
</table>

## Physical Dimensions:

### Smooth Cylinder (Left)

<table>
<thead>
<tr>
<th>Bottom of Cylinder P1</th>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom of Cylinder P2</td>
<td>295</td>
<td>406</td>
<td></td>
<td>0.0078036</td>
</tr>
<tr>
<td>Difference</td>
<td>187</td>
<td>0</td>
<td>1.5</td>
<td>0.00802139</td>
</tr>
<tr>
<td>Midpoint (X0,Y0)</td>
<td>201.5</td>
<td>406</td>
<td></td>
<td>0.201093782</td>
</tr>
</tbody>
</table>

### Pinning Cylinder (Right)

<table>
<thead>
<tr>
<th>Bottom of Cylinder P1</th>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom of Cylinder P2</td>
<td>567</td>
<td>406</td>
<td></td>
<td>0.0078036</td>
</tr>
<tr>
<td>Difference</td>
<td>188</td>
<td>0</td>
<td>1.5</td>
<td>0.00802139</td>
</tr>
<tr>
<td>Midpoint (X1,Y1)</td>
<td>473</td>
<td>406</td>
<td></td>
<td>0.201093782</td>
</tr>
</tbody>
</table>

### Smooth Cylinder (Left)

<table>
<thead>
<tr>
<th>Top of Cylinder P1</th>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Cylinder P2</td>
<td>104</td>
<td>138</td>
<td></td>
<td>0.0078036</td>
</tr>
<tr>
<td>Difference</td>
<td>192</td>
<td>0</td>
<td>1.5</td>
<td>0.00802139</td>
</tr>
<tr>
<td>Midpoint (X2,Y2)</td>
<td>200</td>
<td>138</td>
<td></td>
<td>0.201093782</td>
</tr>
</tbody>
</table>

Average 0.00793754 0.201613463

## Response SF Constants

Scale Factor (SF) constants (in/px): 
-1.57153E-07  7.80321E-07  0.00773625  
Scale Factor (SF) constants (mm/px): 
-3.99168E-06  1.98202E-05  0.19650065  

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
## Approximate Results

<table>
<thead>
<tr>
<th>Input Amplitude (mm)</th>
<th>3.13</th>
</tr>
</thead>
</table>

### Smooth Cylinder (Left)

<table>
<thead>
<tr>
<th>1st Period (s)</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of Smooth Response (s)</td>
<td>0.64</td>
</tr>
<tr>
<td>Frequency of Smooth Response (1/s)</td>
<td>1.56</td>
</tr>
<tr>
<td>Settling Time of Smooth Response (s)</td>
<td>7.10</td>
</tr>
</tbody>
</table>

### Pinning Cylinder (Right)

<table>
<thead>
<tr>
<th>1st Period (s)</th>
<th>0.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of Pinned Response (s)</td>
<td>0.39</td>
</tr>
<tr>
<td>Frequency of Pinned Response (1/s)</td>
<td>2.56</td>
</tr>
<tr>
<td>Settling Time of Pinned Response (s)</td>
<td>11.70</td>
</tr>
</tbody>
</table>

## Additional Notes

Enter Text....
**Input & Response Notes**

**Input Notes**

Tracking is started at frame: 0

The input data was tracked: at the bottom of the right cylinder.

**Response Notes**

Smooth Cylinder (Left)

The response with overlap starts at frame: 322

The center of the cylinder is at x-pixel location: 215 at frame 322

The meniscus was threshold tracked: Upward

Pinning Cylinder (Right)

The response with overlap starts at frame: 322

The center of the cylinder is at x-pixel location: 395 at frame 322

The meniscus was threshold tracked: Downward

**Additional Notes**

Enter Text….

**Labels**

Axial Input
Smooth Response-Axial (CA ~ 15 deg, Left) Smooth (CA ~ 15 deg, Left)
Pinned Response-Axial (CA = 44 deg, Right) Pinned (CA = 44 deg, Right)
Response Comparison-Axial
<table>
<thead>
<tr>
<th>Abs Frame</th>
<th>Filename</th>
<th>Rel Frame</th>
<th>x-px</th>
<th>y-px</th>
<th>Time (s)</th>
<th>y-Scaled (mm)</th>
<th>0'd y-Scaled (mm)</th>
<th>SF in/px</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CL1.....1108-1138...VDUB -&gt;</td>
<td>1</td>
<td>493</td>
<td>390</td>
<td>0.033</td>
<td>78.492</td>
<td>0.000</td>
<td>0.201</td>
</tr>
<tr>
<td>2</td>
<td>CL1.....1108-1138...VDUB -&gt;</td>
<td>2</td>
<td>493</td>
<td>390</td>
<td>0.067</td>
<td>78.492</td>
<td>0.000</td>
<td>0.201</td>
</tr>
<tr>
<td>3</td>
<td>CL1.....1108-1138...VDUB -&gt;</td>
<td>3</td>
<td>493</td>
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8.1.2  CL-1 Push Mode Example Datasheet
General Notes/Physical Measurements

Notes

720x480 DV Converted to 640x480 square pixels.

"Left Cylinder" refers to the cylinder with the 'Smooth' boundary condition

"Right Cylinder" refers to the cylinder with the 'Pinning' boundary condition

The frame rate is (frames/s): 29.97 Left Contact Angle (deg) 4

Disturbance Type: Push Left Interface Asymmetry No

The pinning lip is: Dry Right Contact Angle (deg) 41

Fluid Depth

(Measured from meniscus to bottom of cylinder)

Fluid depths measured at frame: 0

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<th>Rep. Point 2</th>
<th>SF</th>
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Physical Dimensions:

Smooth Cylinder (Left)

Bottom of Cylinder P1 126 426
Bottom of Cylinder P2 316 426
Difference 190 0 1.5 0.00789474 0.200526316
Midpoint (X0,Y0) 221 426

Pinning Cylinder (Right)

Bottom of Cylinder P1 587 428
Bottom of Cylinder P2 396 428
Difference 191 0 1.5 0.0078534 0.19947644
Midpoint (X1,Y1) 491.5 428

Smooth Cylinder (Left)

Top of Cylinder P1 123 189
Top of Cylinder P2 316 189
Difference 193 0 1.5 0.00777202 0.197409326
Midpoint (X2,Y2) 219.5 189

Average 0.00784005 0.199137361
**Input SF Constants**

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**Scale Factor (SF) constants (mm/px):**

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**The following information is taken after the response settles at frame:**

**Fluid Depth**

(Measured from meniscus to bottom of cylinder)

**Fluid depths measured at frame:**

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<th>SF</th>
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<td>378</td>
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<td>Difference</td>
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**Physical Dimensions:**

**Smooth Cylinder (Left)**

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<th>SF (mm/pixel)</th>
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**Pinning Cylinder (Right)**

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**Smooth Cylinder (Left)**

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<th>SF (mm/pixel)</th>
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**Average**

| 0.00786832 | 0.199855452 |

**Response SF Constants**

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### Approximate Results

**Input Amplitude (mm)**  
17.38072045

**Smooth Cylinder (Left)**
- **1st Period (s):** 2
- **Period of Smooth Response (s):** 2.26
- **Frequency of Smooth Response (1/s):** 0.442477876
- **Settling Time of Smooth Response (s):** 9.3

**Pinning Cylinder (Right)**
- **1st Period (s):** 1.3
- **Period of Pinned Response (s):** 0.81
- **Frequency of Pinned Response (1/s):** 1.234567901
- **Settling Time of Pinned Response (s):** 13.7

### Additional Notes

Enter Text….
**Input & Response Notes**

**Input Notes**

Tracking is started at frame: 0

The input data was tracked: at the left side of the pinning cylinder.

**Response Notes**

**Smooth Cylinder (Left)**

The response with overlap starts at frame: 70

The AOI is tracked at 1/4 the diameter from the: Left at frame 70

1/4 the diameter is at the point: (70, 349)

**Pinning Cylinder (Right)**

The response with overlap starts at frame: 70

The AOI is tracked at 1/4 the diameter from the: Left at frame 70

1/4 the diameter is at the point: (342, 316)

**Additional Notes**

**Labels**

Push Input
Smooth Response-Push (CA ~ 4 deg, Left) Smooth (CA ~ 4 deg, Left)
Below Pin Response-Push (CA = 41 deg, Right) Below Pin (CA = 41 deg, Right)
Response Comparison-Push
### Abs Frame | Filename | Rel Frame | x - px | y - px | Time (s) | x -Scaled (mm) | 0'd x -Scaled (mm) | SF in/px |
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8.1.3 CL-2 Axial Mode Example Datasheet
**General Notes/Physical Measurements**

**Notes**

720x480 DV Converted to 640x480 square pixels.

"Left Cylinder" refers to the 'Smooth' boundary condition

"Right Cylinder" refers to the 'Pinning' boundary condition

The frame rate is (frames/s):

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<th>Disturbance Type:</th>
<th>Axial</th>
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The pinning lip is:

**Fluid Depth**

(Measured from meniscus to bottom of cylinder)

| Fluid depths measured at frame: | 0 |

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<th>Rep. Point 2</th>
<th>SF</th>
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<td>y</td>
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<th>Depth (mm)</th>
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**Physical Dimensions:**

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<th>y -pixel</th>
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<th>SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
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<th>y -pixel</th>
<th>Actual</th>
<th>SF (in/pixel)</th>
<th>SF (mm/pixel)</th>
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| Average | 0.00748658 | 0.190159016 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
### Input SF Constants

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### Scale Factor (SF) constants (mm/px):

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The following information is taken after the response settles at frame:

**Fluid Depth**

(Measured from meniscus to bottom of cylinder)

<table>
<thead>
<tr>
<th>Rep. Point 1</th>
<th>Rep. Point 2</th>
<th>x</th>
<th>y</th>
<th>SF</th>
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<tbody>
<tr>
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<td>79</td>
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<td>280</td>
<td>396</td>
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### Physical Dimensions:

**Smooth Cylinder (Left)**

<table>
<thead>
<tr>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>Actual SF (mm/pixel)</th>
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</thead>
<tbody>
<tr>
<td>179.5</td>
<td>456</td>
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<td>0.192435513</td>
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### Pinning Cylinder (Right)

<table>
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<tr>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>Actual SF (mm/pixel)</th>
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</thead>
<tbody>
<tr>
<td>201</td>
<td>4</td>
<td>1.5</td>
<td>0.00746121 0.189514716</td>
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</table>

### Smooth Cylinder (Left)

<table>
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<tr>
<th>x-pixel</th>
<th>y-pixel</th>
<th>Actual SF (in/pixel)</th>
<th>Actual SF (mm/pixel)</th>
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</thead>
<tbody>
<tr>
<td>179.5</td>
<td>398</td>
<td>0.189534786</td>
<td>0.192435513</td>
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### Pinning Cylinder (Right)

<table>
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<th>Actual SF (mm/pixel)</th>
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### Smooth Cylinder (Left)

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<th>Actual SF (mm/pixel)</th>
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<td>171.5</td>
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<td>0.192435513</td>
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### Pinning Cylinder (Right)

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<th>Actual SF (mm/pixel)</th>
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<td>0.192435513</td>
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### Average

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<td>0.192435513</td>
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### Response SF Constants

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<td>0.00739113</td>
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**Smooth Cylinder (Left)**

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<th>Actual SF (mm/pixel)</th>
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**Pinning Cylinder (Right)**

<table>
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<th>Actual SF (mm/pixel)</th>
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**Average**

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<th>y-pixel</th>
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</thead>
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<tr>
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<td>4</td>
<td>1.5</td>
<td>0.00746121 0.189514716</td>
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**Approximate Results**

**Input Amplitude (mm)** 6.06

**Smooth Cylinder (Left)**

**Period** of Smooth Response (s): 1.03
**Frequency** of Smooth Response (1/s): 0.97
**Settling Time** of Smooth Response (s): 2.8

**Pinning Cylinder (Right)**

**Period** of Pinned Response (s): 0.95
**Frequency** of Pinned Response (1/s): 1.05
**Settling Time** of Pinned Response (s): 4.1

**Additional Notes**

---
### Input & Response Notes

#### Input Notes

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<th>Tracking is started at frame:</th>
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<td>The input data was tracked:</td>
<td>at the bottom of the left cylinder.</td>
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#### Response Notes

**Smooth Cylinder (Left)**

| The response with overlap starts at frame: | 49 |
| The center of the cylinder is at x-pixel location: | 180 at frame 269 |
| The meniscus was threshold tracked: | Downward |

**Pinning Cylinder (Right)**

| The response with overlap starts at frame: | 49 |
| The center of the cylinder is at x-pixel location: | 456 at frame 269 |
| The meniscus was threshold tracked: | Downward |

#### Additional Notes

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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#### Labels

- Axial Input
- Smooth Response-Axial
- Pinned Response-Axial
- Response Comparison-Axial
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<th>Filename</th>
<th>Rel Frame</th>
<th>y-px</th>
<th>Time (s)</th>
<th>y-Scaled (mm)</th>
<th>0'd y-Scaled (mm)</th>
<th>SF in/px</th>
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</tr>
<tr>
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<td>Filename</td>
<td>Rel Frame</td>
<td>x-px</td>
<td>y-px</td>
<td>Time (s)</td>
<td>y-Scaled (mm)</td>
<td>y'-Scaled (mm)</td>
</tr>
<tr>
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<td>0.192</td>
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<td>0.192</td>
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</table>
8.1.4 CL-2 Push Mode Example Datasheet
General Notes/Physical Measurements

Notes

720x480 DV Converted to 640x480 square pixels.

"Left Cylinder" refers to the 'Smooth' boundary condition

"Right Cylinder" refers to the 'Pinning' boundary condition

The frame rate is (frames/s): 29.97

Disturbance Type: Push

The pinning lip is: Wet

Fluid Depth

(Measured from meniscus to bottom of cylinder)

Fluid depths measured at frame:

<table>
<thead>
<tr>
<th>Rep. Point 1</th>
<th>Rep. Point 2</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td></td>
</tr>
<tr>
<td>286</td>
<td>330.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (px)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>135</td>
</tr>
<tr>
<td>Pinning</td>
<td>160</td>
</tr>
<tr>
<td>Difference</td>
<td>25</td>
</tr>
</tbody>
</table>

Physical Dimensions:

Smooth Cylinder (Left)

Bottom of Cylinder P1 184 398
Bottom of Cylinder P2 388 398
Difference 204 0 1.5 0.00735294 0.186764706
Midpoint (X0,Y0) 286 398

Pinning Cylinder (Right)

Bottom of Cylinder P1 467 400
Bottom of Pin P2 467 123
Difference 0 277 2 0.00722022 0.183393502
Midpoint (X1,Y1) 467 261.5

Smooth Cylinder (Left)

Top of Cylinder P1 182 82
Top of Cylinder P2 388 82
Difference 206 0 1.5 0.00728155 0.184951456
Midpoint (X2,Y2) 285 82

Average 0.0072849 0.185036555

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
</table>
Input SF Constants

Scale Factor (SF) constants (in/px):  
\[-5.61576E-07 \quad 2.27688E-07 \quad 0.00742293\]

Scale Factor (SF) constants (mm/px):  
\[-1.4264E-05 \quad 5.78327E-06 \quad 0.18854247\]

The following information is taken after the response settles at frame:  

Fluid Depth

(Measured from meniscus to bottom of cylinder)

Fluid depths measured at frame:

<table>
<thead>
<tr>
<th>Rep. Point 1</th>
<th>Rep. Point 2</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>Depth (px)</td>
</tr>
<tr>
<td>176.5</td>
<td>333.5</td>
<td>133</td>
</tr>
<tr>
<td>459.5</td>
<td>319</td>
<td>162</td>
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</table>

Physical Dimensions:

Smooth Cylinder (Left)

<table>
<thead>
<tr>
<th>Bottom of Cylinder P1</th>
<th>Bottom of Cylinder P2</th>
<th>Difference</th>
<th>Midpoint (X0,Y0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>74</td>
<td>400</td>
<td>279</td>
<td>400</td>
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</tbody>
</table>

Pinning Cylinder (Right)

<table>
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<th>Bottom of Cylinder P1</th>
<th>Bottom of Cylinder P2</th>
<th>Difference</th>
<th>Midpoint (X1,Y1)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>y</td>
<td>x</td>
<td>y</td>
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<tr>
<td>357</td>
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<td>562</td>
<td>401</td>
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Smooth Cylinder (Left)

<table>
<thead>
<tr>
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<th>Top of Cylinder P2</th>
<th>Difference</th>
<th>Midpoint (X2,Y2)</th>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>72</td>
<td>76</td>
<td>205</td>
<td>0</td>
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</table>

Average  
0.00731696 | 0.18585071

Response SF Constants

Scale Factor (SF) constants (in/px):  
\[-1.23039E-09 \quad 7.59499E-12 \quad 0.00731729\]

Scale Factor (SF) constants (mm/px):  
\[-3.12519E-08 \quad 1.92913E-10 \quad 0.1858591\]
### Approximate Results

<p>| | |</p>
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<table>
<thead>
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<th>Smooth Cylinder (Left)</th>
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<td><strong>Period</strong></td>
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<tr>
<td><strong>Frequency</strong></td>
<td>0.436681223</td>
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<tr>
<td><strong>Settling Time</strong></td>
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<table>
<thead>
<tr>
<th>Pinning Cylinder (Right)</th>
<th>Wet</th>
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<tr>
<td><strong>Frequency</strong></td>
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<tr>
<td><strong>Settling Time</strong></td>
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</table>

### Additional Notes

The right side of pinning cylinder is out of view prior to the input. Dimensions are taken along the left side from the bottom of cylinder to the bottom of pin.
Input & Response Notes

Input Notes

Tracking is started at frame: 0

The input data was tracked: at the bottom of the left cylinder.

Response Notes

Smooth Cylinder (Left)

The response with overlap starts at frame: 66

The AOI is tracked at 1/4 the diameter from the: Right at frame 386

1/4 the diameter is at the point: (227, 249)

Pinning Cylinder (Right)

The response with overlap starts at frame: 66

The AOI is tracked at 1/4 the diameter from the: Right at frame 386

1/4 the diameter is at the point: (511, 221)

Additional Notes

Labels

Push Input
Smooth Response-Push
Pinned Response-Push
Response Comparison-Push

1 2 3 4 5 6 7 8 9
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<thead>
<tr>
<th>Abs Frame</th>
<th>Filename</th>
<th>Time (s)</th>
<th>x-Scaled (mm)</th>
<th>y-Scaled (mm)</th>
<th>0'd Scaled (mm)</th>
<th>SF in/px</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.033</td>
<td>71.429</td>
<td>0.000</td>
<td>0.185</td>
<td></td>
</tr>
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<tr>
<td>Abs Frame</td>
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<td>Rel Frame x-px</td>
<td>y-px</td>
<td>Time (s) x-Scaled (mm) y-Scaled (mm) SF in/px</td>
<td></td>
<td></td>
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<tr>
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<td>----------</td>
<td>----------------</td>
<td>-----</td>
<td>---------------------------------------------</td>
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<tr>
<td>1</td>
<td>CL2_5900-5913_VDUB -&gt;</td>
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<td></td>
</tr>
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<td>2.569 47.578 5.389 0.186</td>
<td></td>
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<tr>
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Chapter 9

Appendix: Additional Vane Gap Images
Figure 9.1: Receding and advancing bulk menisci for $\phi_{vd} = 90^\circ$. 
Figure 9.2: Receding and advancing bulk menisci for $\phi_{vd} = 90^\circ$. 
Chapter 10

Appendix: Complete CFE Design Drawings
mass = 929 grams
Z = 0.96 mm
Y = 71.44 mm
X = 72.67 mm

CENTER OF GRAVITY IS AT
60083MA40200
Chapter 11

Appendix: CFE Flight Crew Procedures
OBJECTIVE:
Capillary Flow Experiment (CFE). In this procedure the crew will set up the CFE Unit and supporting equipment in order to test the flow of fluid in microgravity. During Progress /ATV/Shuttle flights different hardware will be sent up that will allow three types of Capillary Flow Experiments to be performed.

STATION PARTS:
CFE Contact Line 1 P/N 60083MA00100
CFE Contact Line 2 P/N 60083MA00200
CFE Interior Corner Flow 1 P/N 60083MA40100
CFE Interior Corner Flow 2 P/N 60083MA40200
CFE Vane Gap 1 P/N 60083MA20100
CFE Vane Gap 2 P/N 60083MA20200
Ziploc Bags (stowed in Foam)
Foam (stowed in CFE)

STATION TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Multi-use Bracket(s) P/N SEG33107631-301
PD100 Camcorder P/N SEZ16103293-301
Digital CC Video/Power IF Cable P/N SED33111490-303
Fine Point Sharpie P/N 528-40674-1
Scissors P/N 10104-20006-03
IP Clamp P/N SEG33111394-30X

STATION MATERIALS:
Dry Wipe P/N SEG33107170-306
Printer Paper (RIM) [2] P/N SEG33110070-301
General Purpose Tape 1” P/N 528-41798-5
Aluminum Tape P/N 3M425

1. Select a location for the Maintenance Work Area (MWA) based on the following criteria:

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<th>SHADOWS</th>
<th>CAMCORDER MOUNTING</th>
<th>CREW ACCESSIBILITY</th>
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Good lighting is critical to getting good images of the fluid in the vessels. Equal lighting front and back is required for best results. Select a mounting location that has working lights above the rack and directly across from the rack, both at full intensity. Adjacent lights should be set to equal intensity. Avoid any location that will cast shadows across the CFE vessel. Shadows adversely affect the video data. Shadows adjacent to the CFE vessel are acceptable including shadows across the white background pieces of paper. Mount PD100 Camcorder either from the deck or from the overhead using Multi-use Bracket(s) and crew ingenuity. Exact instructions cannot be given due to the dynamic nature of equipment mounting and location within the ISS. Shorter camera mounting is easier and may make it desirable to move the MWA closer to either the deck or overhead.

CAUTION
Do not mount the PD100 camcorder to the MWA because the camcorder needs to provide an independent record of motion to avoid loss of science data.

CFE is a crew intensive experiment with continued interaction from the crew. Position MWA to provide comfortable access for all activities.

Refer to 5.004 CFE VESSEL AND CAMERA CONFIGURATION.

2. MWA Work Surface Area is set up
   A.2.6 MAINTENANCE WORK AREA (MWA) INSTALLATION step 1, (US SODF: IFM: Reference (Volume 6): Appendix A: ISS IVA Tools)

3. Unstow and Tmpry stow near MWA Work Surface Area:
   MWA Utility Kit
   Multi-Use Bracket(s)
   IP Clamp
   PD100 Camcorder
   Digital CC Video/Power IF Cable
   Printer Paper (RIM) (two sheets)
   Scissors
   Dry Wipe
   General Purpose Tape 1"
   Fine Point Sharpie
   Aluminum Tape

CAUTION
Do not mount the PD100 camcorder to the MWA because the camcorder needs to provide an independent record of motion to avoid loss of science data.
4. Mount PD100 camcorder on Multi-Use Bracket(s) with the following constraints:

<table>
<thead>
<tr>
<th>MULTI-USE BRACKET(S)</th>
<th>CAMCORDER LENS</th>
<th>CAMCORDER SETUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount the Multi-use Bracket(s) to either an overhead or deck seat track or handrail. Mount the PD100 camcorder to the Multi-use Bracket(s). Mounting directly to the MWA is not acceptable. Refer to 5.004 CFE VESSEL AND CAMERA CONFIGURATION.</td>
<td>The camera lens used should be the wide conversion lens. That will allow a short working distance as pictured in 5.004 CFE VESSEL AND CAMERA CONFIGURATION.</td>
<td>The camera setup needs to provide the desired fields of view for the CFE vessel undergoing operations. Final adjustments to the camera setup are completed once the field of view is verified after the CFE vessel is mounted to the MWA.</td>
</tr>
</tbody>
</table>

5. Perform **6.201 PD100 NOMINAL SETUP**

**NOTE**
1. Contact Line vessels have dedicated foam boxes. Interior Corner Flow and Vane Gap vessels do not and were packed using loose pieces of foam. Steps below referring to the foam are referring to the Contact Line foam boxes.
2. Minimize fingerprints upon test chamber surfaces.

6. Unstow: **Contact Line 1 (Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2)** per Execution Note

7. Remove **Contact Line 1 (Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2)** from foam. Tmpry stow foam.

8. Verify no visible oil leakage in outer Ziploc Bag.

******************************************************************************
If leakage visible in outer bag,

Replace **Contact Line 1 (Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2)** in foam.
Stow: **Contact Line 1 (Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2)**
Notify POIC
   Tmpry stow Scissors.
   Refer to 5.007 CFE VESSEL HEAT SEAL.

10. Remove Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) from outer Ziploc Bag.
    Tmpry stow outer Ziploc Bag.

11. Verify no visible oil leakage in inner Ziploc Bag.

*******************************************************************************
If leakage visible in inner bag,
Replace Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) in outer Ziploc Bag.

Replace Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) in foam.
Stow: Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2)
* Notify POIC

*******************************************************************************

12. Using Scissors carefully cut heat seal from inner Ziploc Bag.
    Tmpry stow Scissors.

13. Remove Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) from inner Ziploc Bag.
    Tmpry stow inner Ziploc Bag.

14. Remove Kapton Tape from Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2).
    Dispose of Kapton Tape.

MWA Utility Kit 15. Unstow:
    #10 Fastener

MWA Work Surface Area 16. Set up Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) on Maintenance Work Area smooth surface between seat tracks avoiding contact with hinges and seat tracks.
There are two large center panels suitable for mounting CFE.
Mount the CFE vessel to the panel closest to the front edge of the MWA.
Align the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) to place #10 Fastener in the center of the mounting slot and install the #10 fastener.
√#10 fastener is securely tightened
Refer to 5.006 CFE SETUP DRAWING.

17. Using Dry wipe clean fingerprints from Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2).
Dispose of Dry Wipe.

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The Printer Paper (RIM) serves as a backlit screen for the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2)vessel and reflects light to illuminate the vessel from the back. This is the primary source of illumination. Proper lighting is necessary in order for data collection of the experiment.</td>
</tr>
<tr>
<td>2. Equal lighting in front and in back of test article should be ensured.</td>
</tr>
</tbody>
</table>

MWA 18. Using Aluminum Tape, place one sheet of Printer Paper (RIM) behind the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) in a location that allows the reflected light to illuminate the back side of the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2). Place the second sheet of Printer Paper (RIM) on the MWA Work Surface Area surface behind the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2). Refer to 5.014 CFE SETUP ILLUSTRATION.

PD 100 Camcorder 19. sel Menu

20. sel Etc, Others
21. sel REC Lamp
22. sel REC Lamp → OFF
23. REC Lamp – OFF

24. Using Fine Point Sharpie, color small piece of paper to cover reflective Sony emblem on the front of the PD100 camcorder. Attach paper with General Purpose Tape 1" so that emblem is completely covered and no tape is visible.

25. Position the PD100 Camcorder so that the field of view shows the close up of the test chamber of the Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2).

If CFE Contact Line, Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.
Zoom out the PD100 Camcorder so that the Field of View shows the entire CFE Contact Line 1(2).
Refer to 5.005 CFE CONTACT LINE CHAMBER FIELD OF VIEW.
If CFE Interior Corner Flow,
Set the Field of View per 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW.

If CFE Vane Gap,
Set the Field of View per 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.

26. Stow:
Scissors
Aluminum Tape
General Purpose Tape 1"

27. Insert inner Ziploc Bag in outer Ziploc Bag.
Insert outer Ziploc Bag in foam.
Stow:
Foam (containing Ziploc Bags)

RESTOW TOOLS, PARTS, AND MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS EXCEPT FOR:
MWA Utility Kit TO: proximity of MWA Work Surface Area
Multi-Use Bracket(s) TO: proximity of MWA Work Surface Area
PD100 Camcorder TO: proximity of MWA Work Surface Area
Digital CC Video/Power IF Cable TO: proximity of MWA Work Surface Area
Fine Point Sharpie TO: proximity of MWA Work Surface Area
IP Clamp TO: proximity of MWA Work Surface Area
MWA Work Surface Area TO: Per location chosen in step 1
Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) TO: proximity of MWA Work Surface Area
OREJCTIVE:
Capillary Flow Experiment (CFE). During this procedure the data for the CFE Contact Line tests is recorded via Camcorder video and sound. The CFE tests are titled Background, Tap, Axial, Push, Slide, Multi-Slide, Swirl, Displacement, Bubbles, and Drainage.

STATION PARTS:
CFE Contact Line 1 P/N 60083MA00100
CFE Contact Line 2 P/N 60083MA00200
Mini DVCAM Tape [9] P/N SED33111489-305

STATION TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Fine Point Sharpie P/N 528-40674-1
PD100 Camcorder P/N SEZ16103293-301

STATION MATERIALS:
Dry Wipe P/N SEG33107170-306

NOTE
1. This procedure contains Near Real - Time video downlink or LAB VTR recording requirements.
2. AOS may be required for POIC to configure on board system for downlink of science or LAB VTR recording.

1. CFE BACKGROUND TEST

1.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Refer to 5.013 CFE PINNING LIP COMPARISON. If the pinning lip needs to be cleared of fluid at any time during this step, Perform step 11 and then resume this step where exited.

1.2 √#10 fastener is securely tightened

1.3 Unstow: Mini DVCAM Tape (nine) Tmpry stow close to PD100 Camcorder. Insert Mini DVCAM Tape into PD100 Camcorder

1.4 √PD100 Camcorder for CFE Contact Line 1(2) entire Field of View √REC Lamp — OFF √Sony emblem is covered Refer to Figure 5.005 CFE CONTACT LINE CHAMBER FIELD OF VIEW

CAUTION
1. Once fluid dispensing into the test chambers has begun, the process
CAUTION

for turning the knob needs to be consistent or a loss of science will occur.

2. The smooth cylinder fluid will be dispensed before the pinning cylinder in order to reduce disturbances that could impact science associated with the pinning lip.

3. Loss of science will occur if the CFE Contact Line 1(2) is disturbed and agitated during the Background run. The Background run is not repeatable.

NOTE

1. Valve 2 and Knob 2 are associated with the smooth cylinder. Refer to 5.001 CFE CONTACT LINE. Valve 2 remains open during all subsequent operations.

2. Valve 1 and Knob 1 are associated with the pinning cylinder. Refer to 5.001 CFE CONTACT LINE. Valve 1 remains open during all subsequent operations.

3. Bubbles in the fluid reservoirs are expected and a normal occurrence. No action is necessary other than fluid deployment as described below. Once deployed, the bubbles will find their way to the surface and pop during the background test.

Start Video Activity

1.5 PD100 Camcorder → ON

1.6 Voice into the PD100 Camcorder GMT, "Background Test", "CFE Contact Line 1(2)”, and the module temperature from the PCS ECLSS page.

CFE Contact Line 1.7 With one hand supporting CFE Contact Line 1(2), gently pull Valve 2 to hard stop. High resistance may be encountered.

1.8 Slowly Turn Knob 2 CCW to stop at approximately 1/4 to 1/2 turn per second (approx. 40 revolutions, requires up to 2 to 3 minutes).

1.9 CFE Contact Line 1(2) fluid has been fully dispensed into the smooth cylinder.

CAUTION

CFE Contact Line 1(2) fluid leakage may occur around the valves, and/or the piston.

1.10 CFE Contact Line 1(2) for visible leakage

*************************************************************************
If leakage
Wipe with Dry Wipes.
If leakage continues,

√ POIC to report leakage

*************************************************************************

CAUTION

CFE Contact Line 1(2) fluid leakage may occur around the valves, and/or the piston.

1.14 √ CFE Contact Line 1(2) for visible leakage

*************************************************************************

If leakage

√ POIC to report leakage

*************************************************************************

1.15 Zoom in the PD100 Camcorder so that the small Field of View is recorded. Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.

1.16 Voice observations (into recording PD100 Camcorder) concerning symmetry of interface on pinning lip of pinning cylinder and presence and approximate size of any bubbles.

1.17 PD100 Camcorder recording CFE Contact Line 1(2) small Field of View

Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.

1.18 Allow video recording to continue for approximately 10 minutes or for the remainder of tape. This first 10 minutes comprises the CFE Background test, and the experiment setup should remain undisturbed during this period.
1.19 PD100 Camcorder → OFF
   Eject Mini DVCAM Tape (used)
   sw Mini DVCAM Tape → Save

1.20 Label Mini DVCAM Tape BACKGROUND and include approximate GMT.

1.21 Tmpry stow:
   Mini DVCAM Tape (used)

2. CFE TAP TEST

2.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Refer to 5.013 CFE PINNING LIP COMPARISON
   If the pinning lip needs to be cleared of fluid at any time during this step, Perform step 11 and then resume this step where exited.

2.2 \#10 fastener is securely tightened.

2.3 Retrieve:
   Mini DVCAM Tape (new)
   Install Mini DVCAM Tape (new) in PD100 Camcorder.

2.4 \REC Lamp – Off
   \Sony emblem is covered
   \PD100 Camcorder viewing CFE Contact Line 1(2) small Field of View
   Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW

---

**CAUTION**

1. The solitary Taps should begin very lightly and increase over time, but never to the point the pinning cylinder interface is destabilized or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Tap for the fluid motion to fully decay (damp out, settle, etc.) or science will be lost.

3. Each repeated Tap applied to the CFE Contact Line 1(2) must be in the same location, between the test cylinders, behind the CFE Contact Line 1(2), and within the Field of View without impairing the back lighting if this is possible. A tap location other than centered between the test chambers will not impart equal disturbances to each test chamber.

---

**NOTE**
2.002 CFE CONTACT LINE TEST OPERATIONS

NOTE

1. The solitary Taps increase in magnitude and may increase to the point of a medium knock. Never rap with knuckles. A Tap of a given magnitude is repeated once before increasing the magnitude of the Tap.

2. The small high frequency damped oscillations of the interface that result from solitary Tap will be recorded by video.

3. Valve 1 and Valve 2 remain open (extended) during the CFE test.

2.5 PD100 Camcorder → ON

2.6 Voice into the PD100 Camcorder GMT, "Tap Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

2.7 Using pad of index finger, very lightly apply one solitary Tap at the center of the backside of CFE Contact Line 1(2).

   Using the PD100 Camcorder, voice observations of the fluid response.

   Operator must wait at least 15 seconds after each tap.

   Repeat Tap one time.

2.8 Repeat step 2.7 with a medium tap.

2.9 Repeat step 2.7 with a hard tap.

2.10 PD100 Camcorder → OFF

   Eject Mini DVCAM Tape(used)

   sw Mini DVCAM Tape → Save

2.11 Label Mini DVCAM Tape TAP and include approximate GMT.

2.12 Tmpry stow:

   Mini DVCAM Tape (used)

3. CFE AXIAL TEST

3.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile.

   Refer to 5.013 CFE PINNING LIP COMPARISON.

   If the pinning lip needs to be cleared of fluid at any time during this step,

   Perform step 11 and then resume this step where exited.

3.2 √#10 fastener is securely tightened
3.3 Retrieve:
Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder.

3.4 PD100 Camcorder viewing CFE Contact Line 1(2) small Field of View
Sony emblem is covered
REC Lamp – Off
Camera view in front face of CFE Contact Line vessel is orthogonal.
Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.

---

**CAUTION**

1. The Axial disturbances should be very small to start and increase gradually with each disturbance. The disturbance should never be large enough to destabilize the pinning cylinder interface, form bubbles, or break-up the fluid interfaces. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Axial disturbance for the fluid motion to fully decay (damp out, settle, etc.) or science will be lost.

---

**NOTE**

1. An axial mode disturbance is created by deflecting and releasing the MWA much like a diver on a spring board. The disturbance will excite axial oscillation modes on the liquid surfaces in the cylinders.

2. Special care must be taken to impart the disturbance quickly. The action should be to depress the MWA with an immediate release to avoid seeing one disturbance from deflecting the MWA and another disturbance when releasing it.

3. Valve 1 and Valve 2 remain open (extended) during the CFE test.

---

3.5 PD100 Camcorder → ON

3.6 Voice into the PD100 Camcorder GMT, "Axial Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

3.7 Beginning with extremely weak deflections, using finger, depress and release the MWA (using MWA as cantilever) to impart an axial mode disturbance to the interfaces (much like a diver on a diving board)

   Operator must wait at least 15 seconds after each axial disturbance.

   Repeat disturbance with approximately same deflection.

3.8 Repeat step 3.7 with increased disturbance amplitude until it is perceived that further increases in disturbance amplitude will de-pin interface or eject liquid droplets from surface.
3.9 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used).
sw Mini DVCAM Tape → Save

3.10 Label Mini DVCAM Tape AXIAL TEST and include approximate GMT.

3.11 Tmpy stow:
Mini DVCAM Tape (used)

4. **CFE PUSH TEST**

4.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip.
Refer to **5.013 CFE PINNING LIP COMPARISON**.
If the pinning lip needs to be cleared of fluid at any time during this step,
Perform step 11 and then resume this step where exited.

4.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 1(2) to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 1(2) may slide smoothly left to right in field of view without excess slop.

4.3 Retrieve:
Mini DVCAM Tape (new)
Install a Mini DVCAM Tape (new) in PD100 Camcorder.

4.4 √PD100 Camcorder viewing CFE Contact Line 1(2) small Field of View is zoomed out to show entire range of motion.
√Sony emblem is covered
√REC LAMP – Off
√Camera view in front face of CFE Contact Line vessel is orthogonal
Refer to **5.002 CFE CONTACT LINE SMALL FIELD OF VIEW**.

### CAUTION

1. The Push should begin very light and increase gradually with each Push, but never to the point the pinning cylinder interface is de-pinned or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Push for the fluid motion to fully decay or science will be lost.
NOTE

1. The Push disturbance is a half period oscillation and is introduced when the Push stops abruptly and the fluid experiences a larger amplitude lateral impulse.

2. Valve 1 and Valve 2 remain open (extended) during the CFE test.

3. It is desirable to avoid abrupt impacts with the ends of the slot to reduce the risk of de-pinning the interface in the pinning cylinder.

4. Each push test and its repeat will be accomplished by pushing the CFE Contact Line 1(2) to the left, waiting the full 15 seconds, and then pushing it back to the right again waiting the full 15 seconds at the completion of motion.

5. Drift after a push can be minimized by readjusting the #10 fastener prior to each push as necessary.

4.5 PD100 Camcorder → ON

4.6 Voice into the PD100 Camcorder GMT, "Push Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

4.7 Very slowly slide the CFE Contact Line 1(2) right close to the end of the mounting slot. Avoid abrupt impact with slot end. Do not disturb the interface.

Operator must wait at least 15 seconds before proceeding.

4.8 With a finger on the right hand side of the CFE Contact Line 1(2), lightly push the CFE Contact Line 1(2) left at an approximately constant rate a distance of 10mm. Avoid abrupt impact with slot end.

Using the PD100 Camcorder, voice the event.
Using the PD100 Camcorder, voice observations of the fluid response.

Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.

Operator must wait at least 15 seconds after each push disturbance.

With a finger on the left hand side of the CFE Contact Line 1(2), lightly push the CFE Contact Line 1(2) right at an approximately constant rate a distance of 10mm. Avoid abrupt impact with slot end

Using the PD100 Camcorder, voice the event.
Using the PD100 Camcorder, voice observations of the fluid response.

Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.

Operator must wait at least 15 seconds after each push disturbance.

If interesting or noticeably different behavior between cylinders results,

Repeat Push up to two times.

4.9 Repeat step 4.8 moving 15 mm each time.

4.10 Repeat step 4.8 moving 20 mm each time.

4.11 Repeat step 4.8 moving 25 mm each time.

4.12 Repeat step 4.8 moving 30 mm each time.

4.13 PD100 Camcorder $\rightarrow$ OFF
Eject Mini DVCAM Tape (used).
sw Mini DVCAM Tape $\rightarrow$ Save

4.14 Label Mini DVCAM Tape PUSH and include approximate GMT.

4.15 Tmpry stow:
Mini DVCAM Tape (used)

5. CFE SLIDE TEST

5.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip.
Refer to 5.013 CFE PINNING LIP COMPARISON.
If the pinning lip needs to be cleared of fluid at any time during this step,
Perform step 11 and then resume this step where exited.

5.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 1(2) to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 1(2) may slide smoothly left to right in field of view without excess slop.

5.3 Retrieve:
Mini DVCAM Tape (new)
Install a Mini DVCAM Tape (new) in PD100 Camcorder.
5.4 PD100 Camcorder viewing CFE Contact Line 1(2) small Field of View is zoomed out to show entire range of motion. Sony emblem is covered
REC LAMP – Off
Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.

CAUTION

1. Begin with a weak Slide. The Slides should not increase to the point the pinning cylinder interface is de-pinned or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Slide test for the fluid motion to fully decay or science will be lost.

NOTE

1. A Slide is a one period lateral oscillation, (back and forth), completed within the Field of View at the approximate natural frequency of the interface (predicted to be approximately 1.5-2 Hz). Crew must identify the approximate natural frequency during operations.

2. Valve 1 and Valve 2 remain open (extended) during the CFE test.

3. It is desirable to avoid hitting the ends of the slot to reduce the risk of depinning the interface.

4. Drift after a slide can be minimized by readjusting the #10 fastener prior to each slide as necessary.

5. Each Slide applied to the CFE Contact Line 1(2) must be in same orientation (left to right) across the FIELD OF VIEW, with the same grip on the CFE Contact Line 1(2).

5.5 PD100 Camcorder → ON

5.6 Voice into the PD100 Camcorder GMT, "Slide Test", "CFE Contact Line 1(2)”, and the module temperature from the PCS ECLSS page.

5.7 Very slowly slide the CFE Contact Line 1(2) right, close to the end of the mounting slot. Avoid abrupt impact with slot end. Do not disturb the interface. Operator must wait at least 15 seconds before proceeding.

5.8 Lightly Slide CFE Contact Line 1(2) in Field of View laterally (left to right) one period a distance of about 10mm (peak to peak amplitude). Avoid abrupt impact with slot ends.
Using the PD100 Camcorder, voice the event.
Using the PD100 Camcorder, voice observations of the fluid response.
Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay. Operator must wait at least 15 seconds after each slide disturbance. 

Repeat one time. 
If interesting or noticeably different behavior between cylinders results, Repeat Slide up to two times.

5.9 Repeat step 5.8 moving 15 mm each time.

5.10 Repeat step 5.8 moving 20 mm each time.

5.11 Repeat step 5.8 moving 25 mm each time.

5.12 Repeat step 5.8 moving 30 mm each time.

6. CFE MULTI-SLIDE TEST

6.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip. Refer to 5.013 CFE PINNING LIP COMPARISON If the pinning lip needs to be cleared of fluid at any time during this step, Perform step 11 and then resume this step where exited.

6.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 1(2) to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 1(2) may slide smoothly left to right in field of view without excess slop.

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Begin with a weak multiple, lateral oscillation, (back and forth). The Slides should not increase to the point the pinning cylinder interface is de-pinned or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.</td>
</tr>
<tr>
<td>2. Time must be allowed after each Multi-Slide Test for the fluid motion to fully decay or science will be lost.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A Slide is now defined as multiple (2, 3, 4) period lateral oscillations completed within the Field of View, at the approximate natural frequency of the interface (predicted to be approximately 1.5-2 Hz). Crew must identify the approximate natural frequency during operations.</td>
</tr>
</tbody>
</table>
NOTE

2. Valve 1 and Valve 2 remain open (extended) during the CFE test.

3. It is desirable to avoid hitting the ends of the mounting slot to avoid the risk of de-pinning the interface.

4. Drift after a multi-slide can be minimized by readjusting the #10 fastener prior to each multi-slide as necessary.

5. Each multiple oscillation Slide applied to the CFE Contact Line 1(2) must be in same orientation (left to right) across the FIELD OF VIEW, with the same grip on the CFE Contact Line 1(2).

6.3 Voice into the PD100 Camcorder GMT, "Multi-Slide Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

6.4 Slide CFE Contact Line 1(2) two full cycles with a peak to peak distance of about 10mm in the Field of View. Avoid abrupt impact with slot ends.

Using the PD100 Camcorder, voice the event.
Using the PD100 Camcorder, voice observations of the fluid response.
Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.
Operator must wait at least 15 seconds after each slide disturbance.

Repeat Multi-Slide one time.
If interesting or noticeably different behavior between cylinders results,
Repeat multiple Slide up to two times.

6.5 Repeat step 6.4 moving 15 mm each time.

6.6 Repeat step 6.4 moving 20 mm each time.

6.7 Repeat step 6.4 moving 25 mm each time.

6.8 Repeat step 6.4 moving 30 mm each time.

6.9 As video tape allows, continue Slides of increasing number of oscillations (3, 4), being careful to avoid depinning the interface.

End Video Activity

6.10 PD100 Camcorder → OFF
   Eject Mini DVCAM Tape (used).
   sw Mini DVCAM Tape → Save

6.11 Label Mini DVCAM Tape SLIDE and include approximate GMT.
6.12 Tmpry stow:
Mini DVCAM Tape (used)

7. **CFE SWIRL TEST**

7.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip.
Refer to 5.013 CFE PINNING LIP COMPARISON.
Perform the first swirl test with a dry pinning lip. The remaining swirl tests may be performed with a wet pinning lip.
If the pinning lip needs to be cleared of fluid for the first test, Perform step 11 and then resume this step where exited.

7.2 Retrieve
Mini DVCAM Tape (new)
Install a Mini DVCAM Tape (new) in PD100 Camcorder.

7.3 √PD100 Camcorder viewing CFE Contact Line 1(2) small FIELD OF VIEW is zoomed out to show full range of motion
√Sony emblem is covered
√REC LAMP – Off
Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW.

<table>
<thead>
<tr>
<th><strong>CAUTION</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Begin with a single period Swirl at the approximate natural Swirl frequency, increasing the number of Swirl cycles for subsequent tests (1, 5, and 10 cycles). The decay of the Swirl perturbations to the fluid interfaces will be recorded on video. Try not to excite the surfaces to the point the pinning cylinder interface is depinned or fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.</td>
</tr>
<tr>
<td>2. Time must be allowed after each Swirl for the fluid motion to fully decay or science will be lost.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>NOTE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Swirl is a swirling slosh mode that may be induced into the fluid using an elliptical or circular sliding motion of the CFE Contact Line 1(2) in the plane of the Maintenance Work Area. A Swirl disturbance diameter is based on the natural frequency and will be determined by the crew during operations. It is expected to be no greater than 30 to 40 mm. When increasing the number of cycles in subsequent tests, try to keep at natural frequency of fluid. Note also that the Swirl frequency is likely to be lower than the previously tested Slide frequency.</td>
</tr>
<tr>
<td>2. Valve 1 and Valve 2 remain open (extended) during the CFE test.</td>
</tr>
</tbody>
</table>
NOTE
3. Each Swirl applied to the CFE Contact Line 1(2) must be in same orientation across the camera FIELD OF VIEW, with the same grip on the CFE Contact Line 1(2).

MWA

7.4 Remove and Tmpry stow #10 Fastener while holding with one hand the CFE Contact Line 1(2) to the MWA surface.

7.5 PD100 Camcorder → ON

7.6 Voice into the PD100 Camcorder GMT, "Swirl Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

7.7 Complete a one cycle Swirl using CFE Contact Line 1(2) in the Field of View with a Swirl diameter of about 30 to 40mm or less. Perform the swirl holding CFE Contact Line 1(2) against the MWA and release to free float when cycle(s) are complete.
   Using the PD100 Camcorder, voice the event.
   Using the PD100 Camcorder, voice observations of the fluid response.
   Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.
   Operator must wait at least 60 seconds after each swirl disturbance.

□ Repeat Swirl one time.
   If interesting or noticeably different behavior between cylinders results,
   Repeat Swirl up to two times.

7.8 Repeat step 7.7 with a five cycle Swirl.

7.9 Repeat step 7.7 with a ten cycle Swirl.

7.10 Attach CFE Contact Line 1(2) to Maintenance Work Area using #10 Fastener.

□ End Video Activity

7.11 PD100 Camcorder → OFF
   Eject Mini DVCAM Tape (used).
   sw Mini DVCAM Tape → Save

7.12 Label Mini DVCAM Tape SWIRL and include approximate GMT.

7.13 Tmpry Stow:
   Mini DVCAM Tape (used)

8. CFE DISPLACEMENT TEST
8.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip. Refer to 5.013 CFE PINNING LIP COMPARISON. Perform the first displacement test with a dry pinning lip. The remaining displacement tests may be performed with a wet pinning lip.

If the pinning lip needs to be cleared of fluid for the first test, perform step 11 and then resume this step where exited.

8.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 1(2) to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 1(2) may slide smoothly left to right in field of view without excess slop.

8.3 Retrieve Mini DVCAM Tape (new)

Install a Mini DVCAM Tape (new) in PD100 Camcorder.

8.4 √Sony emblem is covered
   √REC LAMP – Off

   Position the PD100 Camcorder for CFE Contact Line 1(2) tall Field of View.

Refer to 5.003 CFE CONTACT LINE TALL FIELD OF VIEW.

CAUTION

Time must be allowed after each Displacement for the fluid motion to fully decay or science will be lost.

NOTE

1. Displacement (abrupt start-stop) is accomplished by fairly rapid translation of the CFE Contact Line 1(2) to the degree that the pinning interface is destabilized. This is the first test where the interfaces are intentionally destabilized. A few drops and bubbles may be produced.

2. The test begins with light displacements which increase in vigor during the test sequence.

3. Interface disturbances caused by Displacement may take longer to damp out, three minutes predicted.

4. Valve 1 and Valve 2 remain open (extended) during the CFE test.

5. Drift after a restrained displacement can be minimized by readjusting the #10 fastener prior to each restrained displacement as necessary.

6. Try not to displace so significantly that the liquid moves a cylinder diameter distance above the pinning lip.
NOTE
7. Each displacement applied to the CFE Contact Line 1(2) must be in the same orientation across the camera FIELD OF VIEW, with the same grip on the CFE Contact Line 1(2).

8.5 PD100 Camcorder → ON

8.6 Voice into the PD100 Camcorder GMT, "Displacement Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

8.7 Displace in Field of View location (light abrupt start/stop) large enough to destabilize the pinned interface.
- Using the PD100 Camcorder, voice the event.
- Using the PD100 Camcorder, voice observations of the fluid response.
- Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.
- Operator must wait at least three minutes after each displacement disturbance.

Repeat one time.

8.8 Repeat step 8.7 with a medium abrupt start/stop.

MWA

8.9 Remove and Temp stow #10 Fastener while holding with one hand the CFE Contact Line 1(2) to the MWA surface.

8.10 Repeat step 8.7 three times, increasing vigor of disturbance with each Displacement. Maintain motion within field of view while sliding across MWA. Perform Displacement and release CFE Contact Line 1(2) to free float.

8.11 As video tape allows, continue with displacement, being careful to avoid large bubble formation.
- Alternate methods of displacement (suggest combination Slide and Swirl) at crew discretion.
- If interesting observation noted, Try to repeat it.

8.12 Attach CFE Contact Line 1(2) to Maintenance Work Area using #10 Fastener.

8.13 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used).
sw Mini DVCAM Tape → Save
8.14 Label Mini DVCAM Tape DISPLACEMENT and include approximate GMT.

8.15 Tmpry Stow:
Mini DVCAM Tape (used)

9. **CFE BUBBLES TEST**

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>The pinning lip does not need to be cleared for this test.</td>
</tr>
</tbody>
</table>

9.1 Retrieve:
Mini DVCAM Tape (new)
Insert Mini DVCAM Tape (new) into PD100 Camcorder.

9.2 √PD100 Camcorder viewing CFE Contact Line 1(2) tall Field of View
√Sony emblem is covered
√REC LAMP – Off
Refer to 5.003 CFE CONTACT LINE TALL FIELD OF VIEW.

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Each Bubble test applied to the CFE Contact Line 1(2) must be in same orientation across the camcorder Field of View, with the same grip on the CFE Contact Line 1(2). At first only a small number of large diameter Bubbles should be developed via light agitation.</td>
</tr>
<tr>
<td>2. Bubbles are created by shaking the CFE Contact Line 1(2). If you see something interesting, try to repeat it.</td>
</tr>
<tr>
<td>3. Valve 1 and Valve 2 remain open (extended) during the CFE test.</td>
</tr>
</tbody>
</table>

9.3 PD100 Camcorder → ON

9.4 Voice into the PD100 Camcorder GMT, "Bubbles Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

9.5 Remove #10 Fastener from Maintenance Work Area and Tmpry stow to allow the CFE Contact Line 1(2) to be held in hand(s).
Agitate (shake) the CFE Contact Line 1(2) within the field of view of PD100 Camcorder (number of bubbles is approximately 1 to 3). Reattach the CFE Contact Line 1(2) to Maintenance Work Area using #10 Fastener.
Using the PD100 Camcorder, voice observations of the fluid response.
Allow resulting Bubbles of both cylinders to coalesce up to 4 minutes continuing to voice observations. Not all bubbles will coalesce.
Using crew discretion, return rogue drops to fluid mass and force bubbles to coalesce using centrifugal force if necessary.

Repeat Bubble generation technique within the Field of View of Camcorder with similar number of Bubbles. Repeat anything unusual.

9.6 Repeat step 9.5 up to ten times, increasing number of bubbles each time until reaching as close to a foam like state as possible. Repeat anything unusual.

9.7 Attach CFE Contact Line 1(2) to Maintenance Work Area using #10 Fastener.

 repeat step 9.5 up to ten times, increasing number of bubbles each time until reaching as close to a foam like state as possible. Repeat anything unusual.

9.7 Attach CFE Contact Line 1(2) to Maintenance Work Area using #10 Fastener.

9.8 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used).
sw Mini DVCAM Tape → Save

9.9 Label Mini DVCAM Tape BUBBLES and include approximate GMT.

9.10 Tmpry stow:
Mini DVCAM Tape(used)

10. **CFE DRAINAGE**

10.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile.
Refer to 5.013 CFE PINNING LIP COMPARISON.
If the pinning lip needs to be cleared of fluid at any time during this step,
Perform step 11 and then resume this step where exited.

10.2 √ #10 fastener is securely tightened

10.3 Retrieve:
Mini DVCAM Tape (new).
Insert a Mini DVCAM Tape (new) in PD100 Camcorder.

10.4 √ Sony emblem is covered
√ REC LAMP – Off
√ PD100 Camcorder viewing CFE Contact Line 1(2) small FIELD OF VIEW is zoomed out to show full range of motion
Refer to 5.005 CFE CONTACT LINE CHAMBER FIELD OF VIEW.

10.5 PD100 Camcorder → ON
10.6 Voice into the PD100 Camcorder GMT, "Drainage Test", "CFE Contact Line 1(2)", and the module temperature from the PCS ECLSS page.

10.7 √ CFE Contact Line 1(2) Valve 2 is open, (valve pulled out to hard stop)

10.8 Remove the fluid as fast as possible by turning Knob 2 CW without ingesting air into the reservoir. Retraction of the fluid at the end of the process should be very slow, to avoid ingesting air into the fluid reservoir. Not all of the fluid will be removed.

10.9 With one hand supporting CFE Contact Line 1(2), gently push Valve 2 to overcome high resistance to hard stop (closed).

10.10 √ CFE Contact Line 1(2) Valve 1 is open, valve pulled out to (valve pulled out to hard stop)

10.11 Remove the fluid as fast as possible by turning Knob 1 CW without ingesting air into the reservoir. Retraction of the fluid at the end of the process should be very slow, to avoid ingesting air into the fluid reservoir. Not all of the fluid will be removed.

10.12 With one hand supporting CFE Contact Line 1(2), Gently push Valve 1 to overcome high resistance to hard stop (closed).

10.13 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used).

sw Mini DVCAM Tape → Save

10.14 Label Mini DVCAM Tape DRAINAGE and include approximate GMT.

10.15 Stow:
Mini DVCAM Tapes (nine)

11. CFE DRYING THE PINNING LIP

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. This process could take up to 15 minutes per attempt and may take several tries to get right, but is critical to achieving the science goals.</td>
</tr>
<tr>
<td>2. The most challenging aspect of the centrifuge method is slowing down smoothly without disturbing the pinning lip.</td>
</tr>
<tr>
<td>3. Liquid remaining in the groove serving as the pinning lip of the</td>
</tr>
</tbody>
</table>
NOTE

pinning cylinder should be cleared as needed. It is preferred that this liquid be moved to the base of the cylinder, clearing it by any force deemed acceptable.

4. Drops of fluid on the test chamber wall above the pinning lip are not a problem and may be ignored.

5. Small isolated drops residing in the pinning lip are also not a problem if they are clearly not touching the pinning cylinder walls below the pinning lip.

11.1 Remove test vessel from MWA and use centrifuge method (see movie clip for Mike Fincke’s method). A higher angular velocity will likely be required to clear the pinning lip.

11.2 If the previous effort does not clear the pinning lip perform the following:

11.3 Drain the pinning cylinder by turning Knob 1 CW, without ingesting air bubbles into the reservoir.

11.4 With one hand supporting CFE Contact Line 1(2), gently push Valve 1 to overcome high resistance to hard stop (closed).

11.5 Remove #10 Fastener from Maintenance Work Area and tmpry stow to allow the CFE Contact Line 1(2) to be held in hand(s).

11.6 Use impulse type disturbances to the vessel (jerks, ‘bonks’, whatever, etc.) to clear the fluid in the pinning lip and hopefully move it below the pinning lip.

11.7 A combination of centrifugal force with impulse disturbances may be required to clear the pinning lip.

11.8 Use something like the Fincke centrifuge method to return the fluid in the Smooth cylinder to the base of the cylinder.

11.9 Gently re-secure CFE vessel to the MWA using the #10 fastener.

11.10 Visually inspect the test chambers for any fingerprints. Use a dry wipe to remove any if found.

11.11 With one hand supporting CFE Contact Line 1(2), gently pull Valve 1 to hard stop. High resistance may be encountered.

11.12 Slowly Turn Knob 1 CCW to stop at approximately 1/4 to 1/2 turn per second (approx. 40 revolutions, requires up to 2 to 3 minutes).
11.13 CFE Contact Line 1(2) fluid has been fully dispensed into the pinning cylinder.

11.14 Continue operations.

RESTOW TOOLS, PARTS, MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS, EXCEPT FOR:
Mini DVCAM Tape [9] P/N SED33111489-305 TO: CTB, for return to Houston
OBJECTIVE:
Capillary Flow Experiment (CFE). This procedure stows the CFE experiment and its supporting equipment.

STATION PARTS:
- CFE Contact Line 1 P/N 60083MA00100
- CFE Contact Line 2 P/N 60083MA00200
- CFE Interior Corner Flow 1 P/N 60083MA40100
- CFE Interior Corner Flow 2 P/N 60083MA40200
- CFE Vane Gap 1 P/N 60083MA20100
- CFE Vane Gap 2 P/N 60083MA20200
- Ziploc Bags (stowed in foam)
- Foam (stowed in CFE)

STATION TOOLS:
- MWA Work Surface Area P/N SEG33110270-301
- MWA Utility Kit P/N SJG33110310-301
- Multi-Use Bracket(s) P/N SEG33107631-301
- IP Clamp P/N SEG33111394-30X
- PD100 Camcorder P/N SEZ16103293-301
- Digital CC Video/Power IF Cable P/N SED33111490-303
- Fine Point Sharpie P/N 528-40674-1
- IP Clamp P/N SEG33111394-30x

NOTE
Contact Line vessels have dedicated foam boxes. Interior Corner Flow and Vane Gap vessels do not and were packed using loose pieces of foam. Steps below referring to the foam are referring to the Contact Line foam boxes.

1. Unstow:
   - Ziploc Bags
   - Foam

2. Remove inner Ziploc Bag from Outer Ziploc bag. Tmpry stow both bags.

MWA Work Surface Area 3. Remove #10 Fastener from Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) and Tmpry stow # 10 Fastener.

4. Remove Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) from Maintenance Work Surface Area.

5. Insert Contact Line 1(Contact Line 2,Interior Corner Flow 1,Interior Corner Flow 2,Vane Gap 1,Vane Gap 2) into inner Ziploc Bag. Seal inner Ziploc Bag.
6. Insert Contact Line 1, Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2 into outer Ziploc Bag such that Ziploc seal is at opposing ends of vessel. Seal outer Ziploc Bag.

7. Insert Contact Line 1, Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2 into foam.

8. Stow:
   Contact Line 1, Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2

MWA Utility Kit
9. Stow:
   #10 Fastener

10. √CFE tape has been removed from PD100 Camcorder and stowed.

11. Remove Sony emblem cover from PD100 Camcorder. Dispose of Sony emblem cover.

PD100 Camcorder
12. sel Menu
    sel Etc, Others
    sel REC Lamp
    REC Lamp → ON
    √REC Lamp – On

13. Remove Printer Paper (RIM) and Aluminum Tape. Dispose of Printer Paper (RIM) and Aluminum Tape in ISS trash.

14. Stow:
    MWA Utility Kit
    Multi-Use Bracket(s)
    IP Clamp
    PD100 Camcorder
    Digital CC Video/Power IF Cable
    Fine Point Sharpie

RESTOW TOOLS, PARTS, AND MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS EXCEPT FOR:
MWA Utility Kit TO: Stowage List
Multi-Use Bracket(s) TO: Stowage List
PD100 Camcorder TO: Stowage List
Digital CC Video/Power IF Cable TO: Stowage List
Fine Point Sharpie TO: Stowage List
IP Clamp TO: Stowage List
Contact Line 1, Contact Line 2, Interior Corner Flow 1, Interior Corner Flow 2, Vane Gap 1, Vane Gap 2) TO: Stowage List
OBJECTIVE:
Capillary Flow Experiments (CFE). The objectives of CFE Interior Corner Flow are to record the passive capillary driven redistribution of liquid in a container in low-g due to the specific fluid properties and 3-D geometry of the container. The digitized video will be compared with current theory. Tests will also be performed to note the spontaneous phase separation characteristics of such flows when bubbles are introduced into the liquid.

PARTS:
CFE Interior Corner Flow 1 P/N 60083MA40100
CFE Interior Corner Flow 2 P/N 60083MA40200
Mini DVCAM Tape (per execution note) P/N SED33111489-305

TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Fine Point Sharpie P/N 528-40674-1
PD100 Camcorder P/N SEZ16103293-301

MATERIALS:
Dry Wipe
Gray Tape - crew choice

1. INTERIOR CORNER FLOW CAMERA SETUP

1.1 Unstow: Mini DVCAM Tape (per execution note)
Tmpry stow close to PD100 Camcorder.
Insert Mini DVCAM Tape into PD100 Camcorder.

1.2 #10 fastener is securely tightened.

NOTE
The camera view and the front face of the Interior Corner Flow vessel should be orthogonal.

PD100 Camcorder
1.3 PD100 Camcorder for CFE Interior Corner Flow 1(2)
Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW
REC Lamp – Off
Sony emblem is covered
PD100 Camcorder view is orthogonal to the front face of the Interior Corner Flow vessel.
Gauge by eye.

Start Video Activity

1.4 PD100 Camcorder → On

CFE Interior Corner Flow
1.5 Open VALVE 2 (1/4 turn CCW to hard stop)

1.6 Turn KNOB 1 CCW to prime the tube between VALVE 2 and vertex of the test chamber. Add fluid to the point the liquid interface
reaches the end of the tube without injecting fluid into the test chamber.

Refer to 5.009 CFE INTERIOR CORNER FLOW CHAMBER PRIMING LOCATION

1.7 Close VALVE 2 (1/4 turn CW to hard stop).

2. **DRY SURFACE TEST**

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Surface Test is not repeatable.</td>
</tr>
</tbody>
</table>

2.1 Voice into the PD100 Camcorder GPS time, "Dry Surface Test", "CFE Interior Corner Flow 1(2)", and the module temperature from the PCS ECLSS page.

2.2 Open VALVE 1 (1/4 turn CCW to hard stop).

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>As the fluid is dispensed into the test chamber, the process for turning the knob needs to remain rapid and as nearly steady and continuous as possible or a loss of science may occur.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several small bubbles may form in the transport line and reservoir during the initial fill. These initial bubbles are unavoidable and are acceptable.</td>
</tr>
</tbody>
</table>

2.3 In a fairly rapid but continuous manner, turn KNOB 1 CCW to hard stop at approximately 1-2 revolutions per second (approximately 10 revolutions, requires up to 5 to 10 seconds).

2.4 √CFE Interior Corner Flow 1(2) fluid has been fully dispensed into the test chamber.

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFE Interior Corner Flow 1(2) fluid leakage may occur around the valves, and/or the piston.</td>
</tr>
</tbody>
</table>

2.5 √CFE Interior Corner Flow 1(2) for visible leakage (without moving the unit or obscuring the camera field of view)

****************************************************************************************************
If leakage, wipe with Dry Wipes.

* If leakage continues,

√POIC to report leakage

****************************************************************************************************
2.004 CFE INTERIOR CORNER FLOW TEST OPERATIONS

2.6 With hands off the vessel, observe the flow of the fluid from the base of the test chamber to the vertex (top), and voice observations of general fluid behavior, (bubbles if any, etc.) into the PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

2.7 Wait 3 minutes to allow the fluid to reach its equilibrium condition.

3. WET SURFACE TESTS

3.1 PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View

Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW

3.2 Use tape or paper to mark the footprint of the Interior Corner Flow vessel on the MWA surface so that it can easily be returned to approximately the same position.

Provide two pieces of tape at diagonally opposite corners of the base plate to provide temporary restraint during repeated removal/install cycles in this step and the next.

3.3 Remove #10 Fastener and temp stow. Use tape to secure the vessel to the MWA

3.4 PD100 Camcorder → On

3.5 Voice into the PD100 Camcorder: GPS time, “Wet Surface Tests 1(2)”, "CFE Interior Corner Flow 1(2)” and the module temperature from the PCS ECLSS page.
3.6 Remove the vessel from the MWA and use Jeff Williams' CFE centrifuge method to relocate the fluid to the base of the vessel. As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

3.7 Without obstructing the camera view, observe the flow of the fluid from the base of the test chamber to the vertex (top), and voice observations of general fluid behavior, (bubbles if any, etc.) into the PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

3.8 Wait 3 minutes for fluid to reach its equilibrium condition.

3.9 Repeat step 3.6 to step 3.8.

4. LOOP TESTS

4.1 Open VALVE 2 (1/4 turn CCW to hard stop)

:\n
\sqrt{\text{VALVE 1 -- Open}}

4.2 PD100 Camcorder → On

End Video Activity

Start Video Activity

4.3 Voice into the PD100 Camcorder, GPS time, "Interior Corner Flow Loop Tests", "CFE Interior Corner Flow 1(2)" and the module temperature from the PCS ECLSS page.

4.4 Remove the vessel from the MWA and use Jeff Williams' CFE centrifuge method to relocate the fluid to the base of the vessel. As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

4.5 Without obstructing the camera view, observe the flow of the fluid from the base of the test chamber to the vertex (top), and voice observations of general fluid behavior, (bubbles if any, etc.) into the PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.
4.6 Wait 3 minutes for fluid to reach its equilibrium condition.

4.7 Repeat step 4.4 to step 4.6.

4.8 PD100 Camcorder → Off

4.9 Retrieve the #10 fastener and re-secure the CFE Interior Corner Flow vessel to the MWA.

5. SLOSH TESTS

5.1 √PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View
   Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW
   √REC Lamp – Off
   √Sony emblem is covered

5.2 Close VALVE 2 (1/4 turn CW to hard stop).

5.3 √All fluid from reservoir dispensed into test chamber
   Close VALVE 1 (1/4 turn CW to hard stop).

5.4 PD100 Camcorder → On

5.5 Voice into PD100 Camcorder: GPS time, "Interior Corner Flow Slosh Tests", "CFE Interior Corner Flow 1(2)", and module temperature from the PCS ECLSS page.

5.6 Loosen #10 fastener securing Interior Corner Flow to MWA Work Surface Area allowing vessel to slide laterally in the field of view while remaining flush with the MWA Work Surface Area.

5.7 Using a variety of lateral slides (left to right in field of view) on the MWA Work Surface Area, laterally oscillate the Interior Corner Flow vessel (i.e. approximately 10 complete cycles), at the approximate natural frequency of the fluid surface (crew determined on orbit), to reorient the fluid in the test chamber to the point of forming large bubbles.
   An observable redistribution of the fluid from the vertex to the base of the container is expected.

5.8 Before removing hands from vessel,
   √Vessel is orthogonal to the camera
   Lightly tighten the #10 fastener to keep the vessel snug to the MWA.
5.9 Remove hands from the vessel and observe the return of the fluid to equilibrium. 
Voice observations into PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

5.10 Wait 3 minutes for the fluid to reach its equilibrium condition.

5.11 Repeat step 5.6 to step 5.10, increasing the lateral slide frequency to approximately double the natural frequency which was determined during the first set of lateral slides.

Repeat once increasing the lateral slide frequency to approximately triple the natural frequency or as high as possible by hand.

End Video Activity

5.12 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

5.13 Label Mini DVCAM Tape: CFE ICF Test and include GPS time.

5.14 Tmpry stow : Mini DVCAM Tape (used)

6. BUBBLE SHAKE TEST

6.1 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

6.2 √PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View
Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW
√REC Lamp – Off
√Sony emblem is covered
√PD100 Camcorder view is orthogonal to the front face of the Interior Corner Flow vessel.
Gauge by eye.

6.3 √All fluid is in the test chamber
√VALVE 1, VALVE 2 – closed

6.4 Use tape or paper to mark the footprint of the Interior Corner Flow vessel on the MWA surface so that it can easily be returned to approximately the same position.

Provide two pieces of tape at diagonally opposite corners of the base plate to provide temporary restraint during repeated removal/install cycles in this step and the next.
6.5 Remove #10 fastener and temp stow. Use tape to secure the vessel to the MWA.

6.6 PD100 Camcorder → On

6.7 Voice into the PD100 Camcorder: GPS time, Interior Corner Flow Bubble Shake Tests", "CFE Interior Corner Flow 1(2) and the module temperature from the PCS ECLSS page.

6.8 Remove the vessel from the MWA and shake vessel vigorously in a manner that produces bubbles (in field of view if possible).

As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

6.9 Without obstructing the camera view, observe the return of the fluid to equilibrium, including phase separation and coalescence (If any) Voice observations into PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

6.10 Wait 5 to 15 minutes for the fluid to reach its equilibrium condition.

6.11 Repeat step 6.8 to step 6.10, as many times as Mini DVCAM Tape allows.

6.12 PD100 Camcorder → Off

Eject Mini DVCAM Tape (used)

sw Mini DVCAM Tape → Save

6.13 Label Mini DVCAM Tape: CFE- Bubble Shake Test and include GPS time.

6.14 Tmpry stow: Mini DVCAM Tape (used)

7. BUBBLE RESERVOIR TEST

7.1 Retrieve: Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder

7.2 √PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View

Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW

√REC Lamp – Off
7.3 Use tape or paper to mark the footprint of the Interior Corner Flow vessel on the MWA surface so that it can easily be returned to approximately the same position.

Provide two pieces of tape at diagonally opposite corners of the base plate to provide temporary restraint during repeated removal/install cycles in this step.

> Sony emblem is covered

7.4 PD100 Camcorder → On

7.5 Open VALVE 2 (1/4 turn CCW to hard stop)

> VALVE 1 – closed

7.6 Turn KNOB 1 CW at a rate of approximately 1-2 revolutions per second. This withdrawal rate should ingest air into the transport tubes and reservoir. Turn KNOB 1 CW until the bottom of the piston reaches the Fill Line noted on the reservoir. The intent is to get both air and liquid into the reservoir.

7.7 Close VALVE 2 (1/4 turn CW to hard stop)

Open VALVE 1 (1/4 turn CCW to hard stop)

7.8 Remove #10 fastener and temp stow. Use tape to secure the vessel to the MWA.

7.9 Voice into the PD100 Camcorder: "GPS time, Interior Corner Flow Bubble Reservoir Tests", "CFE Interior Corner Flow 1(2) and the module temperature from the PCS ECLSS page.

7.10 Remove the Interior Corner Flow vessel from the MWA and shake vessel vigorously in a manner that produces bubbles (in field of view if possible).

7.11 As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

In a fairly rapid but continuous manner, turn KNOB 1 CCW to hard stop at approximately 1-2 revolutions per second (approximately 10 revolutions, requires up to 5 to 10 seconds).
7.12 Remove hands from vessel and observe the return of the fluid to equilibrium, including phase separation and coalescence (If any) Voice observations into PD100 Camcorder.

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

7.13 Wait 10 to 15 minutes for the fluid to reach its equilibrium condition.

7.14 Close VALVE 1 (1/4 turn CW to hard stop).

7.15 Repeat step 7.5 to step 7.14, as many times as Mini DVCAM Tape allows.

End Video Activity

7.16 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

7.17 Label Mini DVCAM Tape: CFE- Bubble Res Test and include GPS time.

7.18 Tmpry stow : Mini DVCAM Tape (used)

8. FOAM SHAKE TEST

8.1 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

8.2 \PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View
Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW
\REC Lamp → Off
\Sony emblem is covered
\PD100 Camcorder view is orthogonal to the front face of the Interior Corner Flow vessel.
Gauge by eye.

8.3 \All fluid is in the test chamber
Close VALVE 1 (1/4 turn CW to hard stop)
Close VALVE 2 (1/4 turn CW to hard stop)

8.4 Use tape or paper to mark the footprint of the Interior Corner Flow vessel on the MWA surface so that it can easily be returned to approximately the same position.
Provide two pieces of tape at diagonally opposite corners of the base plate to provide temporary restraint during repeated removal/install cycles in this step.
8.5 Remove #10 fastener and temp stow. Use tape to secure the vessel to the MWA.

8.6 PD100 Camcorder → On

8.7 Voice into the PD100 Camcorder: "GPS time, Interior Corner Flow Foam Shake Tests, "CFE Interior Corner Flow 1(2) and the module temperature from the PCS ECLSS page.

8.8 Remove the vessel from the MWA and shake vessel vigorously in a manner that produces foam (many small bubbles) in field of view if possible. Select the shake direction which produces the best foam.

As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

8.9 Without obstructing the camera view, observe the return of the fluid to equilibrium, including phase separation and coalescence (If any)

Voice observations into PD100 Camcorder

Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

8.10 Wait 5 to 15 minutes for the fluid to reach its equilibrium condition.

8.11 Repeat step 8.8 to step 8.10 as many times as Mini DVCAM Tape allows. The operator should try different shake directions to find the best foam and should also investigate the use of centrifugal force to locate the foam in the base of the test chamber.

8.12 PD100 Camcorder → Off

Eject Mini DVCAM Tape (used)

sw Mini DVCAM Tape → Save

8.13 Label Mini DVCAM Tape: CFE Foam Shake Test and include GPS time.

8.14 Tmpry stow : Mini DVCAM Tape (used)

8.15 Retrieve the #10 fastener and re-secure the CFE Interior Corner Flow vessel to the MWA.

9. FOAM RESERVOIR TEST
9.1 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

9.2 PD100 Camcorder for CFE Interior Corner Flow 1(2) entire Field of View
Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW
√ REC Lamp – Off
√ Sony emblem is covered
√ PD100 Camcorder view is orthogonal to the front face of the Interior Corner Flow vessel.
Gauge by eye.

9.3 Use tape or paper to mark the footprint of the Interior Corner Flow vessel on the MWA surface so that it can easily be returned to approximately the same position.
Provide two pieces of tape at diagonally opposite corners of the base plate to provide temporary restraint during repeated removal/install cycles in this step.

9.4 PD100 Camcorder → On

9.5 Open VALVE 2 (1/4 turn CCW to hard stop).
√ VALVE 1 – Closed

9.6 Turn KNOB 1 CW at a rate of approximately 1-2 revolutions per second. This withdrawal rate should ingest air and most of the fluid into the transport tubes and reservoir. Turn KNOB 1 CW until the bottom of the piston reaches the Fill Line noted on the reservoir. Continue turning KNOB 1 CW until the bottom of the piston is about twice as high as the Fill Line. The intent is to get equal parts air and liquid into the reservoir.

9.7 Close VALVE 2 (1/4 turn CW to hard stop)
Open VALVE 1 (1/4 turn CCW to hard stop)

9.8 Remove #10 Fastener and temp stow. Use tape to secure the vessel to the MWA.

9.9 Voice into the PD100 Camcorder: GPS time, Interior Corner Flow Foam Reservoir Tests", "CFE Interior Corner Flow 1(2) and the module temperature from the PCS ECLSS page.

9.10 Remove the Interior Corner Flow vessel from the MWA and shake vessel vigorously in a manner that produces foam (in field of view if possible).

9.11 As gently as possible, return the vessel to the MWA within five seconds and reattach using the tape. Minor bumps on contact are
acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

In a fairly rapid but continuous manner, turn KNOB 1 CCW to hard stop at approximately 1-2 revolutions per second (approximately 20 revolutions, requires up to 10 to 15 seconds).

9.12 Remove hands from vessel and observe the return of the fluid to equilibrium, including phase separation and coalescence (If any) Voice observations into PD100 Camcorder Refer to 5.011 CFE INTERIOR CORNER FLOW EQUILIBRIUM PATTERNS for expected final fluid configuration.

9.13 Wait 10 to 15 minutes for the fluid to reach its equilibrium condition.

9.14 Close VALVE 1(1/4 turn CW to hard stop)

9.15 Repeat step 9.5 to step 9.14 as many times as Mini DVCAM Tape allows. The operator should try different shake directions to find the best foam and may also investigate varying the amount of air in the test chamber.

End Video Activity

9.16 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

9.17 Label Mini DVCAM Tape: CFE- Foam Res Test and include GPS time.

9.18 Tmpry stow : Mini DVCAM Tape (used)

9.19 Retrieve the #10 fastener and re-secure the CFE Interior Corner Flow vessel to the MWA.

10. DRAINAGE

10.1 Open VALVE 2 (1/4 turn CCW to hard stop)

\(\sqrt{\text{VALVE 1 – closed}}\)

**NOTE**
Additional ingestion of bubbles into the transport line is not desirable at this point and may be minimized by reducing the rate of liquid withdrawal. Small flow reversals might help recover from bubble ingestion events. Bubbles already in the transport lines should be ignored.
10.2 Slowly turn KNOB 1 CW, withdrawing the fluid contents back into the reservoir to the approximate condition of the initial pre-primed state. Refer to 5.008 CFE INTERIOR CORNER FLOW FIELD OF VIEW

10.3 Close VALVE 2 (1/4 turn CW to hard stop).

10.4 √VALVE 1, VALVE 2 – closed

10.5 Notify POIC of tape serial number and/or sequence number for each used tape.

10.6 Stow:
Mini DVCAM Tape (per execution note, used)
CFE Interior Corner Flow

RESTOW TOOLS, PARTS, MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS EXCEPT FOR:
Mini DVCAM Tape (per execution note) P/N SED33111489-305 TO: For return to Houston
OBJECTIVE:
Capillary Flow Experiments (CFE). The objective of this experiment is to observe fluid interface and critical wetting behavior in a cylindrical chamber with elliptic cross-section and an adjustable central vane. The critical vane-gap wetting phenomenon occurs at a critical vane angle where the fluid rises all the way up the vane gap. Vane Gap 1 provides a collection of data points for a perfectly wetting surface. Vane Gap 2 provides a collection of data points for a partially wetting surface. These two cases provide a reasonable approximation of the most common fluids stored in tanks for spaceflight applications.

STATION PARTS:
CFE Vane Gap 1 P/N 60083MA20100
Mini DVCAM Tape (per execution note) P/N SED33111489-305

STATION TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Fine Point Sharpie P/N 528-40674-1
PD100 Camcorder P/N SEZ16103293-301
1/8" L-Wrench (2 1/4" length) P/N AW4

STATION MATERIALS:
Dry Wipe
Gray Tape (crew preference)

NOTE
1. This procedure contains Near Real-Time video downlink or LAB VTR recording requirements.
2. AOS may be required for POIC to configure on board system for downlink of science or LAB VTR recording.
3. Minimize fingerprints within chamber field of view.
4. Bubbles in the fluid reservoirs are expected and a normal occurrence. No action is necessary other than fluid deployment as described below. Once deployed, the bubbles will find their way to the surface and pop during subsequent testing.

1. VANE GAP 1 BACKGROUND TEST

1.1 Unstow: Mini DVCAM Tape (per execution note)
Tmpry stow close to PD100 Camcorder.
Insert Mini DVCAM Tape into PD100 Camcorder.

1.2 ✓#10 Fastener is securely tightened

CAUTION
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

1.3 ✓PD100 Camcorder for CFE Vane Gap 1 entire Field of View
CAUTION
After the fluid is dispensed into the elliptic test chamber, care should be taken not to disturb (i.e. adjust) the CFE Vane Gap 1 Vessel. Loss of science will occur if the vessel is disturbed and agitated during the background run. The Background run is not repeatable.

1.4 PD100 Camcorder ➔ ON

1.5 Voice into the PD100 Camcorder GPS time, "Background Test", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

CAFE Vane Gap 1

1.6 With one hand supporting CFE Vane Gap 1, gently pull VALVE 1 to hard stop.

1.7 Slowly turn KNOB 1 CCW at approximately ¼ to ½ turn per second to stop. (Approximately 46 revolutions, requires up to 3 minutes).

1.8 √ CFE Vane Gap 1 fluid has been fully dispensed into the test chamber.

CAUTION
CFE Vane Gap 1 fluid leakage may occur around the valve and/or the piston.

1.9 √ CFE Vane Gap 1 for visible leakage

**************************************************************************
If leakage,  
| Wipe with Dry Wipes.
If leakage continues,  
√ POIC to report leakage
**************************************************************************
1.10 Voice observations about the fluid into recording PD100 Camcorder. (Include comments about the symmetry of the fluid in front of the vane relative to the fluid behind the vane).

If the fluid is not symmetric,

Use the pad of index finger and lightly tap the backside of the vessel within the PD100 Camcorder field of view (if possible).

Voice approximate number, size and location of any bubbles present.

1.11 PD100 Camcorder recording CFE Vane Gap 1 Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

PD100 Camcorder → Off

2. VANE GAP 1 CW DRY TEST

CAUTION

Special care should be taken to avoid any disturbances larger than a tap since the CW Dry Test is not repeatable.

NOTE

1. All references to critical vane gap wetting are specific to the vane gap on the front face of the vessel nearest the camera. Critical wetting does occur for the vane gap on the back face of the vessel, but is not pertinent to the crew procedures. The vane angles are selected to investigate the approach to the critical wetting angle and not the departure.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. After each vane angle adjustment a series of taps are applied to the Vane Gap 1 vessel. The small high frequency damped oscillations of the interface that result from taps will be recorded by video. The taps should allow the interface to relax and achieve a more ideal equilibrium. Taps are defined as: a set of 4 finger taps on the back side of the Vane Gap vessel imparted at an approximate rate metered by each syllable of a one second count “one-one-thousand” (similar to finger taps on the side of a fish tank).

5. Approximately 10 seconds should be allowed after each set of taps for all interface disturbances to decay (damp out, settle, etc.). As the crew becomes accustomed to the sensitivity of the liquid surface to
## NOTE
The finger taps, the taps may be applied as necessary to speed (or coax) the establishment of an equilibrium surface.

6. Each set of taps is applied to the back side of CFE Vane Gap 1 and must be in the same location within the Field of View if possible.

7. Nominal prescribed vane angles are provided with preset angle increment. Smaller angle increments (5 deg) are used near the expected critical vane wetting angles (predicted to be approximately 60 and 225 degrees). However, true critical angles will be determined in flight and crew discretion is requested to determine vane angle increments as critical conditions are approached. Critical vane angle precision is not expected to be better than ±5 deg, but may be improved as determined in flight by crew.

8. The critical vane gap wetting phenomena occurs at a critical vane angle where the fluid rises all the way up the vane gap. It is recommended that the crew note (i.e. by jotting down) the two experimentally determined critical vane angles (predicted to be approximately 60 and 225 degrees) during the first performance of the experiment to better anticipate vane angle increments during subsequent and repeat runs of the experiment.

9. The tap and wait process is repeated for each vane angle setpoint.

10. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

11. If uncertain of PD100 Camcorder tape remaining time, replace tape as necessary.

### 2.1 Voice into the PD100 Camcorder GPS time, "CW Dry Test", "CFE Vane Gap 1" and the module temperature from the PCS ECLSS page.

### 2.2 Slowly rotate Vane Position Indicator CW to a Vane Position of 15 degrees.
- Allow 30 sec for the fluid surface to stabilize.
- Using pad of index finger, lightly apply taps at prescribed location on CFE Vane Gap 1.
- Wait ten seconds while observing fluid surface response.

If the fluid surface changes shape or position after the set of taps,
- Apply another set of taps and observe the fluid surface for any change in shape or position again waiting ten seconds.

If any change in shape occurs,
- Repeat as necessary until fluid shape and position are stable.
Using the PD100 Camcorder, voice observations of the fluid response.

Allow resulting interface oscillations (if any) to fully decay (settle, dampen, approximately 10 seconds) continuing to voice observations.

Repeat for the following vane positions: 30, 40, 45, 50, 55, 60, 65, 75, 90, 105, 120, 135, 150, 165, 180, 195, 210, 220, 225, 230, 235, 240, 245, 250, 265, 280, 295, 310, 325, 340, 0.

End Video Activity

PD100 Camcorder  2.3  PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

2.4 Label Mini DVCAM Tape: CFE-Vane Gap 1 Background-CW Dry Test and include GPS time.

2.5 Tmpry stow : Mini DVCAM Tape (used)

3. VANE GAP 1 CW WET TESTS

3.1 Visually inspect the fluid in the vessel without moving it. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,
Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

3.2 #10 fastener is securely tightened

3.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

3.4 PD100 Camcorder for CFE Vane Gap 1 entire Field of view
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
REC Lamp – Off
Sony emblem is covered
Vane position - 0 degrees
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel
Gauge by eye checking both the top view and the side view

NOTE
NOTE
All of the notes in step 2 apply to this step and should be reviewed if necessary.

3.5 PD100 Camcorder → ON

3.6 Voice into the PD100 Camcorder GPS time, "CW Wet Test 1", "CFE Vane Gap 1" and the module temperature from the PCS ECLSS page.

3.7 Repeat step 2.2.

3.8 Voice into the PD100 Camcorder GPS time, “CW Wet Test 2”, CFE Vane Gap 1" and the module temperature from the PCS ECLSS page.

3.9 Repeat step 2.2.

3.10 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

3.11 Label Mini DVCAM Tape: CFE-Vane Gap 1 CW Wet Tests 1 and 2 and include GPS time.

3.12 Tmpry stow : Mini DVCAM Tape (used)

4. VANE GAP 1 CCW WET TESTS

4.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

4.2 #10 fastener is securely tightened

4.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.
4.4 √ PD100 Camcorder for CFE Vane Gap 1 entire Field of View
   Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
√ REC Lamp – Off
√ Sony emblem is covered
√ Vane position – 0 degrees
√ PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel
Gauge by eye checking both the top view and the side view

   NOTE
All of the notes in step 2 apply to this step and should be reviewed if necessary.

4.5 PD100 Camcorder → On

4.6 Voice into the PD100 Camcorder GPS time, "CCW Wet Test 1(2)", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

4.7 Slowly rotate Vane Position Indicator CCW to a Vane Position of 340 degrees.
   Allow 30 sec for the fluid and surface to stabilize.
   Using pad of index finger, lightly apply taps at prescribed location on CFE Vane Gap 1.
   Wait ten seconds while observing fluid surface response.
   If the fluid surface changes shape or position after the set of finger taps,
   Apply another set of taps and observe the fluid surface for any change in shape or position again waiting ten seconds.
   If any change in shape occurs,
   Repeat as necessary until fluid shape and position is stable

   Using the PD100 Camcorder, voice observations of the fluid response.
   Allow resulting interface oscillations (if any) to fully decay (settle, dampen, approximately 10 seconds) continuing to voice observations.
   Repeat for the following vane positions: 325, 310, 295, 280, 265, 250, 245, 240, 235, 230, 225, 220, 210, 195, 180, 165, 150, 135, 120, 105, 90, 75, 65, 60, 55, 50, 45, 40, 30, 15, 0. )

4.8 Repeat step 4.7
4.10 Label Mini DVCAM Tape: Vane Gap 1 CCW Wet Test and include GPS time.

4.11 Temp stow : Mini DVCAM Tape (used)

5. VANE GAP 1 CONTINUOUS ROTATION TESTS

5.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

5.2 #10 fastener is securely tightened

5.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder.

**CAUTION**
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

5.4 PD100 Camcorder for CFE Vane Gap 1 entire Field of view
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.
REC Lamp — Off
Sony emblem is covered
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel
Gauge by eye checking both the top view and the side view.

**NOTE**
1. For these tests a 1/8" L-wrench is taped to the Vane Position Indicator like a crank so that the vane can be rotated smoothly and nearly continuously by hand.
2. After taping 1/8" L-Wrench to Vane Position Indicator, the wrench should be able to clear KNOB 1 when revolved.
3. Care should be taken not to obstruct the camera field of view of the Vane Angle Indicator.
4. Crew should concentrate more on maintaining constant rate of
NOTE

revolution than on data observation for this test.

5. This test provides dynamic data for comparison to the static data collected in the previous tests.

5.5 Retrieve:

1/8" L-Wrench
Gray Tape

5.6 Tear off two pieces of Gray Tape approximately 2" by 1".

Lay the 1/8" L-Wrench flat across the top of Vane Position Indicator shaft, centering wrench on shaft with the short end of the wrench pointing out from the test chamber like a crank handle.

Refer to 5.012 CFE VANE GAP L-WRENCH SET-UP

One at a time, place strips of gray tape over wrench and shaft, securing the wrench to the Vane Position Indicator. Add additional strips of tape as necessary to secure wrench.

5.7 Temp stow:

Gray Tape

5.8 √ Vane Position - 0 degrees

Wait ten seconds for any fluid oscillations to dampen out.

5.9 PD100 Camcorder → On

5.10 Voice into the PD100 Camcorder GPS time, "CW Continuous Rotation Test", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

5.11 Using the 1/8" L-Wrench attached to the Vane Position Indicator, rotate the vane CW through 720 degrees, at a rate of 10 deg/sec (2 complete revolutions, approximately 36 seconds per revolution).

5.12 √ Vane Position - 0 degrees

Wait ten seconds for any fluid oscillations to dampen out.

5.13 Voice into the PD100 Camcorder GPS time, "CCW Continuous Rotation Test", "CFE Vane Gap 1" and the module temperature from the PCS ECLSS page.

5.14 Using the 1/8" L-Wrench attached to the Vane Position Indicator, rotate the vane CCW through 720 degrees, at a rate of 10 deg/sec (2 complete revolutions, approximately 36 seconds per revolution).
5. Label Mini DVCAM Tape: Vane Gap 1 Continuous Rotation Tests and include GPS time.

5.17 Tmpy stow : Mini DVCAM Tape (used)

Carefully remove the 1/8” L-Wrench and gray tape from the Vane Position Indicator. Be gentle as the vane shaft is plastic. Remove the gray tape from the 1/8” L-Wrench and dispose of in ISS trash.

6. VANE GAP 1 STEADY STATE FIRST QUADRANT TEST

6.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus. If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

6.2 #10 fastener is securely tightened.

6.3 Retrieve: Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder.

CAUTION

The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

6.4 PD100 Camcorder for CFE Vane Gap 1 entire Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.

REC Lamp – Off

Sony emblem is covered

Vane position – 0 degrees

PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.
NOTE

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

5. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before changing to the next setpoint.

6.5 PD100 Camcorder → On

6.6 Voice into the PD100 Camcorder GPS time, "Steady State Test", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

6.7 Allow 1 minute for camcorder to record baseline condition.

6.8 Per the table below, slowly rotate Vane Position Indicator CW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>1 minute</td>
<td>Last symmetric surface</td>
</tr>
<tr>
<td>43</td>
<td>15 minutes</td>
<td>Small gap critical wetting</td>
</tr>
<tr>
<td>52</td>
<td>15 minutes</td>
<td>Last angle before large gap wetting</td>
</tr>
<tr>
<td>58</td>
<td>15 minutes</td>
<td>Large gap critical wetting</td>
</tr>
<tr>
<td>75</td>
<td>5 minutes</td>
<td>Enroute to 90</td>
</tr>
</tbody>
</table>

NASA/CR—2009-215586 265
Vane Position | Wait Time | Setpoint description
---|---|---
90 | 5 minutes | Full asymmetric equilibrium

Repeat for the remaining vane positions and wait times:

6.9 Per the table below, rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time. Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>15 minutes</td>
<td>Large gap dewetting</td>
</tr>
<tr>
<td>37</td>
<td>15 minutes</td>
<td>Small gap dewetting</td>
</tr>
<tr>
<td>0</td>
<td>1 minute</td>
<td>Baseline</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:

6.10 Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

6.11 Label Mini DVCAM Tape: CFE Vane Gap 1 Steady State Test and include GPS time.

6.12 Tmpry stow : Mini DVCAM Tape (used)

7. **VANE GAP 1 SYMMETRY TEST**

7.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform [4.001 CFE VANE GAP FLUID RELOCATION](#) all, then:

7.2 √ #10 fastener is securely tightened.

7.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder.
CAUTION

The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

7.4 PD100 Camcorder for CFE Vane Gap 1 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.

√ REC Lamp – Off
√ Sony emblem is covered
√ Vane position – 0 degrees
√ PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each setpoint without disturbing the vessel.

2. Vane angle adjustments for this test are different than the other tests in this procedure. For this test only, a large change in position needs to occur in a short time. This will require gripping the Vane Position Indicator in a different manner to allow for a quick 90 degree rotation in one motion if possible. Multiple steps are acceptable, but the motion needs to be completed in two seconds.

3. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

4. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View when the motion is completed. Temporarily obstructing the view of the Vane Position Indicator while making this quick 90 degree rotation is acceptable.

5. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

6. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before performing the next setpoint.

7.5 PD100 Camcorder → On

7.6 Voice into the PD100 Camcorder GPS time, "Symmetry Test", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.
7.7 Allow 1 minute for camcorder to record baseline condition.

7.8 Quickly rotate Vane Position Indicator CW to a Vane Position of 90 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 15 minutes. This will assure that the fluid achieves a steady state condition.

7.9 Quickly rotate Vane Position Indicator CCW to a Vane Position of 0 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 3 minutes. This will assure that the fluid achieves a steady state condition.

End Video Activity

PD100 Camcorder

7.10 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

7.11 Label Mini DVCAM Tape: CFE Vane Gap 1 Symmetry Test and include GPS time.

7.12 Tmpry stow : Mini DVCAM Tape (used)

8. VANE GAP 1 STEADY STATE FOURTH QUADRANT TEST

8.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

8.2 #10 fastener is securely tightened

8.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder
CAUTION

The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

8.4 √PD100 Camcorder for CFE Vane Gap 1 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
√REC Lamp — Off
√Sony emblem is covered
√Vane position — 0 degrees
√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

5. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before changing to the next setpoint.

8.5 PD100 Camcorder → On

8.6 Voice into the PD100 Camcorder GPS time, "Steady State Test 2", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

8.7 Allow 1 minute for camcorder to record baseline condition.

8.8 Per the table below, slowly rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.
<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>335</td>
<td>1 minute</td>
<td>Intermediate symmetric</td>
</tr>
<tr>
<td>320</td>
<td>1 minute</td>
<td>Last symmetric surface</td>
</tr>
<tr>
<td>315</td>
<td>15 minutes</td>
<td>Global asymmetric shift</td>
</tr>
<tr>
<td>311</td>
<td>5 minutes</td>
<td>Small gap critical wetting</td>
</tr>
<tr>
<td>308</td>
<td>5 minutes</td>
<td>Large gap critical wetting</td>
</tr>
<tr>
<td>290</td>
<td>1 minute</td>
<td>Intermediate asymmetric</td>
</tr>
<tr>
<td>270</td>
<td>1 minute</td>
<td>Full asymmetric equilibrium</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:

8.9. Per the table below, slowly rotate Vane Position Indicator CW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>311</td>
<td>5 minutes</td>
<td>Large gap de-wetting</td>
</tr>
<tr>
<td>315</td>
<td>5 minutes</td>
<td>Small gap de-wetting</td>
</tr>
<tr>
<td>320</td>
<td>15 minutes</td>
<td>Global asymmetric shift</td>
</tr>
<tr>
<td>335</td>
<td>1 minute</td>
<td>Intermediate symmetric</td>
</tr>
<tr>
<td>0</td>
<td>3 minutes</td>
<td>Baseline</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:
8.11 Label Mini DVCAM tape CFE Vane Gap 1 SS Q4 and include GPS time.

8.12 Tmpry stow : Mini DVCAM Tape (used)

9. VANE GAP 1 SYMMETRY TEST 2

9.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,
Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

9.2 #10 fastener is securely tightened.

9.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder.

CAUTION
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

9.4 PD100 Camcorder for CFE Vane Gap 1 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.

REC Lamp – Off
Sony emblem is covered
Vane position – 0 degrees
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each setpoint without disturbing the vessel.

2. Vane angle adjustments for this test are different than the other tests in this procedure. For this test only, a large change in position needs to occur in a short time. This will require gripping the Vane Position Indicator in a different manner to allow for a quick 90 degree rotation in one motion if possible. Multiple steps are acceptable, but the motion needs to be completed in
### 3. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

### 4. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View when the motion is completed. Temporarily obstructing the view of the Vane Position Indicator while making this quick 90 degree rotation is acceptable.

### 5. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

### 6. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before performing the next setpoint.

---

**Start Video Activity**

### 9.5 PD100 Camcorder → On

### 9.6 Voice into the PD100 Camcorder GPS time, "Symmetry Test ", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

### 9.7 Allow 1 minute for camcorder to record baseline condition.

### 9.8 Quickly rotate Vane Position Indicator CCW to a Vane Position of 270 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 15 minutes. This will assure that the fluid achieves a steady state condition.

### 9.9 Quickly rotate Vane Position Indicator CW to a Vane Position of 0 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 3 minutes. This will assure that the fluid achieves a steady state condition.

---

**End Video Activity**
2.005 CFE VANE GAP 1 TEST OPERATIONS

9.11 Label Mini DVCAM Tape: CFE Vane Gap 1 Symmetry Test and include GPS time.

9.12 Tmpy stow : Mini DVCAM Tape (used)

10. VANE GAP 1 STEADY STATE SECOND QUADRANT TEST

10.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

10.2 √ #10 fastener is securely tightened

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.</td>
</tr>
</tbody>
</table>

10.3 √ PD100 Camcorder for CFE Vane Gap 1 entire Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

√ REC Lamp – Off
√ Sony emblem is covered
√ Vane position – 180 degrees
√ PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.</td>
</tr>
</tbody>
</table>

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.
NOTE

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

5. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before changing to the next setpoint.

10.4 PD100 Camcorder → On

10.5 Voice into the PD100 Camcorder GPS time, "Steady State Test 3", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

10.6 Allow 1 minute for camcorder to record baseline condition.

10.7 Per the table below, slowly rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>1 minute</td>
<td>Intermediate symmetric</td>
</tr>
<tr>
<td>139</td>
<td>1 minute</td>
<td>Last symmetric surface</td>
</tr>
<tr>
<td>137</td>
<td>15 minutes</td>
<td>Possible global asymmetric shift</td>
</tr>
<tr>
<td>135</td>
<td>15 minutes</td>
<td>Small gap critical wetting (certain global shift)</td>
</tr>
<tr>
<td>128</td>
<td>1 minute</td>
<td>Intermediate between wettings</td>
</tr>
<tr>
<td>125</td>
<td>5 minutes</td>
<td>Large gap critical wetting</td>
</tr>
<tr>
<td>120</td>
<td>1 minute</td>
<td>Enroute to 90</td>
</tr>
<tr>
<td>90</td>
<td>3 minutes</td>
<td>Full asymmetric equilibrium</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:
10.8- Per the table below, slowly rotate Vane Position Indicator CW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>1 minute</td>
<td>Intermediate asymmetric equilibrium</td>
</tr>
<tr>
<td>127</td>
<td>5 minutes</td>
<td>Large gap dewetting</td>
</tr>
<tr>
<td>133</td>
<td>1 minute</td>
<td>Intermediate between dewettings</td>
</tr>
<tr>
<td>136</td>
<td>15 minutes</td>
<td>Possible global shift</td>
</tr>
<tr>
<td>139</td>
<td>5 minutes</td>
<td>Small gap dewetting</td>
</tr>
<tr>
<td>160</td>
<td>1 minute</td>
<td>Intermediate symmetric</td>
</tr>
<tr>
<td>180</td>
<td>3 minutes</td>
<td>Baseline</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:

--- End Video Activity ---

10.9 PD100 Camcorder

Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

10.10 Label Mini DVCAM Tape: CFE Vane Gap 1 SS Q2 and include GPS time.

10.11 Tmpry stow : Mini DVCAM Tape (used)

11. VANE GAP 1 SYMMETRY TEST 3

11.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.
If at any time during this step the fluid configuration departs from this state, Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

11.2 √#10 fastener is securely tightened.

11.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder.

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.</td>
</tr>
</tbody>
</table>

11.4 √PD100 Camcorder for CFE Vane Gap 1 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.
√REC Lamp – Off
√Sony emblem is covered
√Vane position – 180 degrees
√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each setpoint without disturbing the vessel.</td>
</tr>
</tbody>
</table>

2. Vane angle adjustments for this test are different than the other tests in this procedure. For this test only, a large change in position needs to occur in a short time. This will require gripping the Vane Position Indicator in a different manner to allow for a quick 90 degree rotation in one motion if possible. Multiple steps are acceptable, but the motion needs to be completed in two seconds.

3. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

4. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View when the motion is completed. Temporarily obstructing the view of the Vane Position Indicator while making this quick 90 degree rotation is acceptable.

5. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.
NOTE
6. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before performing the next setpoint.

11.5 PD100 Camcorder → On

11.6 Voice into the PD100 Camcorder GPS time, "Symmetry Test 3", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

11.7 Allow 1 minute for camcorder to record baseline condition.

11.8 Quickly rotate Vane Position Indicator CCW to a Vane Position of 90 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 15 minutes. This will assure that the fluid achieves a steady state condition.

11.9 Quickly rotate Vane Position Indicator CW to a Vane Position of 139 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 5 minutes. This will assure that the fluid achieves a steady state condition.

11.10 Quickly rotate Vane Position Indicator CW to a Vane Position of 180 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 3 minutes. This will assure that the fluid achieves a steady state condition.

End Video Activity

PD100 Camcorder → Off

Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

11.12 Label Mini DVCAM Tape: CFE Vane Gap 1 Symmetry Test 3 and include GPS time.

11.13 Tmpry stow : Mini DVCAM Tape (used)

12. VANE GAP 1 STEADY STATE THIRD QUADRANT TEST

12.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state, Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

12.2 √#10 fastener is securely tightened

12.3 Retrieve: Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION

The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

12.4 √PD100 Camcorder for CFE Vane Gap 1 entire Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

√REC Lamp – Off

√Sony emblem is covered

√Vane position – 180 degrees

√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.
NOTE
3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

5. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before changing to the next setpoint.

12.5 PD100 Camcorder → On

12.6 Voice into the PD100 Camcorder GPS time, "Steady State Test 4", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

12.7 Allow 1 minute for camcorder to record baseline condition.

12.8 Per the table below, slowly rotate Vane Position Indicator CW to the Vane Position listed and wait the prescribed time.

   Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>1 minute</td>
<td>Last symmetric surface</td>
</tr>
<tr>
<td>224</td>
<td>15 minutes</td>
<td>Small gap critical wetting (possibly no global shift)</td>
</tr>
<tr>
<td>230</td>
<td>15 minutes</td>
<td>Global asymmetric shift</td>
</tr>
<tr>
<td>232</td>
<td>5 minutes</td>
<td>Large gap critical wetting</td>
</tr>
<tr>
<td>250</td>
<td>1 minute</td>
<td>Intermediate asymmetric</td>
</tr>
<tr>
<td>270</td>
<td>3 minutes</td>
<td>Full asymmetric equilibrium</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:
12.9 Per the table below, slowly rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint description</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>1 minute</td>
<td>Intermediate asymmetric</td>
</tr>
<tr>
<td>230</td>
<td>5 minutes</td>
<td>Large gap dewetting</td>
</tr>
<tr>
<td>225</td>
<td>15 minutes</td>
<td>Global symmetric shift</td>
</tr>
<tr>
<td>220</td>
<td>5 minutes</td>
<td>Small gap dewetting</td>
</tr>
<tr>
<td>200</td>
<td>1 minute</td>
<td>Intermediate symmetric</td>
</tr>
<tr>
<td>180</td>
<td>3 minutes</td>
<td>Baseline</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times:

End Video Activity

PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)

sw Mini DVCAM Tape → Save

12.11 Label Mini DVCAM Tape: CFE Vane Gap 1 SS Q3 and include GPS time.

12.12 Tmpry stow : Mini DVCAM Tape (used)

13. VANE GAP 1 SYMMETRY TEST 4

13.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:
13.2 √#10 fastener is securely tightened.

13.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder.

CAUTION
The camera view and the front face of the Vane Gap 1 vessel should be orthogonal or loss of science may occur.

13.4 √PD100 Camcorder for CFE Vane Gap 1 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW.
√REC Lamp – Off
√Sony emblem is covered
√Vane position – 180 degrees
√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 1 vessel. Gauge by eye checking both the top view and the side view.

NOTE
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each setpoint without disturbing the vessel.

2. Vane angle adjustments for this test are different than the other tests in this procedure. For this test only, a large change in position needs to occur in a short time. This will require gripping the Vane Position Indicator in a different manner to allow for a quick 90 degree rotation in one motion if possible. Multiple steps are acceptable, but the motion needs to be completed in two seconds.

3. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

4. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View when the motion is completed. Temporarily obstructing the view of the Vane Position Indicator while making this quick 90 degree rotation is acceptable.

5. VALVE 1 remains open (extended) during all the CFE Vane Gap 1 tests.

6. If the PD100 Camcorder tape remaining time is less than the prescribed wait time for the next setpoint, replace the tape before performing the next setpoint.
13.5 PD100 Camcorder → On

13.6 Voice into the PD100 Camcorder GPS time, "Symmetry Test 4", "CFE Vane Gap 1", and the module temperature from the PCS ECLSS page.

13.7 Allow 1 minute for camcorder to record baseline condition.

13.8 Quickly rotate Vane Position Indicator CW to a Vane Position of 270 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 15 minutes. This will assure that the fluid achieves a steady state condition.

13.9 Quickly rotate Vane Position Indicator CW to a Vane Position of 320 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 5 minutes. This will assure that the fluid achieves a steady state condition.

13.10 Quickly rotate Vane Position Indicator CW to a Vane Position of 0 degrees. The motion must be completed in approximately two seconds or less including any fine adjustments. It is desirable to perform the position change in one continuous motion if possible.

Using the PD100 Camcorder, voice observations of the fluid response.

Wait 3 minutes. This will assure that the fluid achieves a steady state condition.

PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save
13.12 Label Mini DVCAM Tape: CFE Vane Gap 1 Symmetry Test 4 and include GPS time.

13.13 Tmpy stow : Mini DVCAM Tape (used)

14. VANE GAP 1 POST TEST FLUID WITHDRAWAL

14.1 Visually inspect the fluid in the vessel. There should not be any obvious amount of liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state, Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

14.2 √#10 fastener is securely tightened

CFE Vane Gap 14.3 Position vane angle to 0 degrees.

14.4 Slowly turn KNOB 1 CW initially at approximately ½ turn per second to stop (approx. 46 revolutions), retracting as much fluid into reservoir without ingesting bubbles. Withdrawal rate must be reduced significantly to avoid ingestion of air bubbles during the final stages of the drain procedure (complete drain could take up to 5 minutes). Not all fluid will be removed from container. Remove only as much as is possible without ingesting bubbles beyond VALVE 1.

14.5 With one hand supporting CFE Vane Gap 1, gently push VALVE 1 to hard stop.

14.6 Stow:
Mini DVCAM Tapes (per execution note, used)
Gray Tape
CFE Vane Gap
1/8” L-Wrench (2 1/4” length)

RESTOW TOOLS, PARTS, MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS EXCEPT FOR:
Mini DVCAM Tape (per execution note) P/N SED33111489-305 TO: For return to Houston
OBJECTIVE:
Capillary Flow Experiments (CFE). The objective of this experiment is to observe fluid interface and critical wetting behavior in a cylindrical chamber with elliptic cross-section and an adjustable central vane. The critical vane-gap wetting phenomenon occurs at a critical vane angle where the fluid rises all the way up the vane gap. Vane Gap 2 provides a collection of data points for a partially wetting surface. Vane Gap 1 provides a collection of data points for a perfectly wetting surface. These two cases provide a reasonable approximation of the most common fluids stored in tanks for spaceflight applications.

STATION PARTS:
CFE Vane Gap 2 P/N 60083MA20200
Mini DVCAM Tape [per execution note] P/N SED33111489-305

STATION TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Fine Point Sharpie P/N 528-40674-1
PD100 Camcorder P/N SEZ16103293-301
1/8" L-Wrench (2 1/4" length) P/N AW4

STATION MATERIALS:
Dry Wipe
Gray Tape (crew preference)

NOTE
1. This procedure contains Near Real - Time video downlink or LAB VTR recording requirements.
2. AOS may be required for POIC to configure on board system for downlink of science or LAB VTR recording.
3. Minimize fingerprints within chamber field of view.
4. Bubbles in the fluid reservoirs are expected and a normal occurrence. No action is necessary other than fluid deployment as described below. Once deployed, the bubbles will find their way to the surface and pop during subsequent testing.

1. VANE GAP 2 BACKGROUND TEST

1.1 Unstow: Mini DVCAM Tape (per execution note)
Tmpry stow close to PD100 Camcorder.
Insert Mini DVCAM Tape into PD100 Camcorder.

1.2 #10 Fastener is securely tightened.

CAUTION
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

1.3 PD100 Camcorder for CFE Vane Gap 2 entire Field
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
√REC Lamp – Off
√Sony emblem is covered
√Vane Position - 0 degrees
√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel

Gauge by eye checking both the top view and the side view

CAUTION
After the fluid is dispensed into the elliptic test chamber, care should be taken not to disturb (i.e. adjust) the CFE Vane Gap 2 Vessel. Loss of science will occur if the vessel is disturbed and agitated during the background run. The Background run is not repeatable.

1.4 PD100 Camcorder → ON

1.5 Voice into the PD100 Camcorder GPS time, "Background Test", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

CFE Vane Gap 2

1.6 With one hand supporting CFE Vane Gap 2, gently pull VALVE 1 to hard stop.

1.7 Slowly turn KNOB 1 CCW at approximately 1/4 to 1/2 turn per second to stop. (Approximately 46 revolutions, requires up to 3 minutes).

1.8 √CFE Vane Gap 2 fluid has been fully dispensed into the test chamber.

CAUTION
CFE Vane Gap 2 fluid leakage may occur around the valve, and/or the piston.

1.9 √CFE Vane Gap 2 for visible leakage

**************************************************************************
If leakage,
   Wipe with Dry Wipes.
If leakage continues,
   √ POIC to report leakage
1.10 Voice observations about the fluid into recording PD100 Camcorder. (Include comments about the symmetry of the fluid in front of the vane relative to the fluid behind the vane.).

If the fluid is not symmetric,

- Use the pad of index finger and lightly tap the backside of the vessel within the PD100 Camcorder field of view (if possible).
- Voice approximate number, size and location of any bubbles present.

1.11 PD100 Camcorder recording CFE Vane Gap 2 Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

2. VANE GAP 2 CW DRY TEST

**CAUTION**

Special care should be taken to avoid any disturbances larger than a tap since the CW Dry Test is not repeatable.

**NOTE**

1. All references to critical vane gap wetting are specific to the vane gap on the front face of the vessel nearest the camera. Critical wetting does occur for the vane gap on the back face of the vessel, but is not pertinent to the crew procedures. The vane angles are selected to investigate the approach to the critical wetting angle and not the departure.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. After each vane angle adjustment a series of taps are applied to the Vane Gap 2 vessel. The small high frequency damped oscillations of the interface that result from taps will be recorded by video. The taps should allow the interface to relax and achieve a more ideal equilibrium. Taps are defined as: a set of 4 finger taps on the back side of the Vane Gap vessel imparted at an approximate rate metered by each syllable of a one second count “one-one-thousand” (similar to finger taps on the side of a fish tank).

5. Approximately 10 seconds should be allowed after each set of taps for all interface disturbances to decay (damp out, settle, etc.). As the crew becomes accustomed to the sensitivity of the liquid surface to the finger taps, the taps may be applied as necessary to speed (or...
6. Each set of taps is applied to the back side of CFE Vane Gap 2 and must be in the same location within the Field of View if possible.

7. Nominal prescribed vane angles are provided with preset angle increment. Smaller angle increments (5deg) are used near the expected critical vane wetting angles (predicted to be approximately 60 and 225 degrees). However, true critical angles will be determined in flight and crew discretion is requested to determine vane angle increments as critical conditions are approached. Critical vane angle precision is not expected to be better than ±5 degrees, but may be improved as determined in flight by crew.

8. The critical vane gap wetting phenomena occurs at a critical vane angle where the fluid rises all the way up the vane gap. It is recommended that the crew note (i.e. by jotting down) the two experimentally determined critical vane angles (predicted to be approximately 60 and 225 degrees) during the first performance of the experiment to better anticipate vane angle increments during subsequent and repeat runs of the experiment.

9. The tap and wait process is repeated for each vane angle setpoint.

10. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

11. If uncertain of PD100 Camcorder tape remaining time, replace tape as necessary.

2.1 Voice into the PD100 Camcorder GPS time, "CW Dry Test", "CFE Vane Gap 2" and the module temperature from the PCS ECLSS page.

2.2 Slowly rotate Vane Position Indicator CW to a Vane Position of 15 degrees.

   Allow 30 sec for the fluid and surface to stabilize.
   Using pad of index finger, apply taps at prescribed location on CFE Vane Gap 2.
   Wait ten seconds while observing fluid surface response.

   If the fluid surface changes shape or position after the set of taps,
   Apply another set of taps and observe the fluid surface for any change in shape or position again waiting ten seconds.
   If any change in shape occurs,
   Repeat as necessary until fluid shape and position are stable.

   Using the PD100 Camcorder, voice observations of the fluid response.
Allow resulting interface oscillations (if any) to fully decay (settle, dampen, approximately 10 seconds) continuing to voice observations.

Repeat for the following vane positions: 30, 45, 60, 65, 70, 75, 80, 90, 105, 120, 135, 150, 165, 180, 195, 210, 230, 235, 240, 245, 250, 255, 265, 280, 295, 310, 325, 340, 0.

PD100 Camcorder 2.3  PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

2.4 Label Mini DVCAM Tape: CFE-Vane Gap 2 Background - CW Dry Test and include GPS time time.

2.5 Tmpry stow : Mini DVCAM Tape (used)

3. VANE GAP 2 CW WET TESTS

3.1 Visually inspect the fluid in the vessel without moving it. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

3.2 √#10 fastener is securely tightened

3.3 Retrieve: Mini DVCAM Tape (new) Install Mini DVCAM Tape (new) in PD100 Camcorder.

**CAUTION**
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

3.4 PD100 Camcorder for CFE Vane Gap 2 entire Field of view
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
REC Lamp – Off
Sony emblem is covered
Vane position - 0 degrees
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel

Gauge by eye checking both the top view and the side view

**NOTE**
All of the notes in step 2 apply to this step and should be reviewed
3.5 PD100 Camcorder → ON

3.6 Voice into the PD100 Camcorder GPS time, "CW Wet Test 1(2)", "CFE Vane Gap 2" and the module temperature from the PCS ECLSS page.

3.7 Repeat step 2.2, twice.

3.8 PD100 Camcorder → Off

Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

3.9 Label Mini DVCAM Tape: CFE-Vane Gap 2 CW Wet Tests 1 and 2 and include GPS time.

3.10 Tempy stow : Mini DVCAM Tape (used)

4. VANE GAP 2 CCW WET TESTS

4.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,
Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

4.2 √#10 fastener is securely tightened.

4.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

4.4 √PD100 Camcorder for CFE Vane Gap 2 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
√REC Lamp – Off
√Sony emblem is covered
√Vane position - 0 degrees
2.006  CFE VANE GAP 2 TEST OPERATIONS  
(cfe1all000038) Page 7 of 24 pages

PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. 
Gauge by eye checking both the top view and the side view. 

NOTE 
All of the notes in step 2 apply to this step and should be reviewed if necessary.

| Start Video Activity |

4.5 PD100 Camcorder → On

4.6 Voice into the PD100 Camcorder GPS time, "CCW Wet Test 1(2)", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

4.7 Slowly rotate Vane Position Indicator CCW to a Vane Position of 340 degrees. 
   Allow 30 sec for the fluid and surface to stabilize. 
   Using pad of index finger, lightly apply taps at prescribed location on CFE Vane Gap 2. 
   Wait ten seconds while observing fluid surface response. 
   If the fluid surface changes shape or position after the set of taps, 
   Apply another set of taps and observe the fluid surface for any change in shape or position again waiting ten seconds. 
   If any change in shape occurs, Repeat as necessary until fluid shape and position is stable

Using the PD100 Camcorder, voice observations of the fluid response. 
Allow resulting interface oscillations (if any) to fully decay (settle, dampen, approximately 10 seconds) continuing to voice observations. 
Repeat for the following vane positions: 325, 310, 295, 280, 265, 255, 250, 245, 240, 235, 230, 210, 195, 180, 165, 150, 135, 120, 105, 90, 80, 75, 70, 65, 60, 45, 30, 15, 0.

4.8 Repeat step 4.7

| End Video Activity |

PD100 Camcorder 4.9 PD100 Camcorder → Off 
Eject Mini DVCAM Tape (used) 
sw Mini DVCAM Tape → Save
4.10  Label Mini DVCAM Tape: Vane Gap 2 CCW Wet Test and include GPS time time.

4.11  Tmpry stow : Mini DVCAM Tape (used)

5.  **VANE GAP 2 CONTINUOUS ROTATION TESTS**

5.1  Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

5.2  √#10 fastener is securely tightened

5.3  Retrieve: Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.</td>
</tr>
</tbody>
</table>

5.4  √PD100 Camcorder for CFE Vane Gap 2 entire Field of view

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

√REC Lamp – Off

√Sony emblem is covered

√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel

Gauge by eye checking both the top view and the side view

<table>
<thead>
<tr>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. For these tests a 1/8” L-wrench is taped to the Vane Position Indicator like a crank so that the vane can be rotated smoothly and nearly continuously by hand</td>
</tr>
</tbody>
</table>

2. After taping 1/8” L-Wrench to Vane Position Indicator, the wrench should be able to clear KNOB 1 when revolved.

3. Care should be taken not to obstruct the camera field of view of the Vane Angle Indicator.

4. Crew should concentrate more on maintaining constant rate of revolution than on data observation for this test.

5. This test provides dynamic data for comparison to the static data collected in the previous tests.

5.5  Retrieve:

1/8” L-Wrench
Gray Tape

5.6 Tear off two pieces of Gray Tape approximately 2” by 1”.

Lay the 1/8” L-Wrench flat across the top of Vane Position Indicator shaft, centering wrench on shaft with the short end of the wrench pointing out from the test chamber like a crank handle. Refer to 5.012 CFE VANE GAP L-WRENCH SET-UP

One at a time, place strips of gray tape over wrench and shaft, securing the wrench to the Vane Position Indicator. Add additional strips of tape as necessary to secure wrench.

5.7 Tempy stow:
Gray Tape

5.8 √Vane Position - 0 degrees
Wait ten seconds for any fluid oscillations to dampen out.

5.9 PD100 Camcorder → On

5.10 Voice into the PD100 Camcorder GPS time, "CW Continuous Rotation Test", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

5.11 Using the 1/8” L-Wrench attached to the Vane Position Indicator, rotate the vane CW through 720 degrees, at a rate of 10 deg/sec (2 complete revolutions, approximately 36 seconds per revolution).

5.12 √Vane Position - 0 degrees
Wait ten seconds for any fluid oscillations to dampen out.

5.13 Voice into the PD100 Camcorder GPS time, "CCW Continuous Rotation Test", "CFE Vane Gap 2" and the module temperature from the PCS ECLSS page.

5.14 Using the 1/8” L-Wrench attached to the Vane Position Indicator, rotate the vane CCW through 720 degrees, at a rate of 10 deg/sec (2 complete revolutions, approximately 36 seconds per revolution).

PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

5.15 PD100 Camcorder

5.16 Label Mini DVCAM Tape: Vane Gap 2 Continuous Rotation Tests and include GPS time time.

5.17 Tempy stow : Mini DVCAM Tape (used)
5.18 Carefully remove the 1/8” L-Wrench and gray tape from the Vane Position Indicator. Be gentle as the vane shaft is plastic. Remove the gray tape from the 1/8” L-Wrench and dispose of in ISS trash.

6. **VANE GAP 2 CW WET TEST PART TWO**

6.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform **4.001 CFE VANE GAP FLUID RELOCATION** all, then:

6.2 √#10 fastener is securely tightened

6.3 Retrieve: Mini DVCAM Tape (new)

Install Mini DVCAM Tape (new) in PD100 Camcorder

<table>
<thead>
<tr>
<th><strong>CAUTION</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.</td>
</tr>
</tbody>
</table>

6.4 √PD100 Camcorder for CFE Vane Gap 2 entire Field of View

Refer to **5.010 CFE VANE GAP CHAMBER FIELD OF VIEW**

√REC Lamp – Off

√Sony emblem is covered

√Vane position – 0 degrees

√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

<table>
<thead>
<tr>
<th><strong>NOTE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.</td>
</tr>
</tbody>
</table>

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.
## 6. VANE GAP 2 CW WET TEST PART TWO

6.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

- Perform **4.001 CFE VANE GAP FLUID RELOCATION** all, then:

6.2 √ #10 fastener is securely tightened.

6.3 Retrieve: Mini DVCAM Tape (new)

### 6. PD100 Camcorder

<table>
<thead>
<tr>
<th>Start Video Activity</th>
<th>End Video Activity</th>
</tr>
</thead>
</table>

6.5 PD100 Camcorder → On

6.6 Voice into the PD100 Camcorder GPS time, "CW Wet Test Part Two", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

6.7 Allow 1 minute for camcorder to record baseline condition.

6.8 Slowly rotate Vane Position Indicator CW to a Vane Position of 53 degrees.

- Allow 30 seconds for the fluid surface to stabilize. If slight fluid motion persists, wait an additional 2 minutes.
- Using the PD100 Camcorder, voice observations of the fluid response.

- Repeat for the following vane positions: 57, 62, 68, 73, 77, 82, 118, 125, 130, 135, 142, 233, 237, 242, 243, 247, 253, 257, 270, 293, 297, 302, 308, 313, 318, 323, 0.

6.9 PD100 Camcorder → Off

- Eject Mini DVCAM Tape (used)
- sw Mini DVCAM Tape → Save

6.10 Label Mini DVCAM Tape: CFE-Vane Gap 2 CW Wet Test Two and include GPS time.

6.11 Tmpry stow: Mini DVCAM Tape (used)

## 7. VANE GAP 2 CCW WET TEST PART TWO

7.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

- Perform **4.001 CFE VANE GAP FLUID RELOCATION** all, then:

7.2 √ #10 fastener is securely tightened.

7.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

### CAUTION

The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

#### 7.4 PD100 Camcorder for CFE Vane Gap 2 entire Field of View

Refer to [5.010 CFE VANE GAP CHAMBER FIELD OF VIEW](#)

- REC Lamp – Off
- Sony emblem is covered
- Vane position – 0 degrees
- PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

### NOTE

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

#### 7.5 PD100 Camcorder ➔ On

#### 7.6 Voice into the PD100 Camcorder GPS time, "CCW Wet Test Part Two", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

#### 7.7 Allow 1 minute for camcorder to record baseline condition.

#### 7.8 Slowly rotate Vane Position Indicator CCW to a Vane Position of 323 degrees.

Allow 30 seconds for the fluid surface to stabilize. If slight fluid motion persists, wait an additional 2 minutes.
Using the PD100 Camcorder, voice observations of the fluid response. Repeat for the following vane positions: 318, 313, 308, 302, 297, 293, 270, 257, 253, 247, 243, 237, 233, 142, 135, 130, 125, 118, 82, 77, 73, 68, 62, 57, 53, 0.

PD100 Camcorder 7.9
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

7.10 Label Mini DVCAM Tape: CFE-Vane Gap 2 CCW Wet Test Two and include GPS time.

7.11 Tmpry stow : Mini DVCAM Tape (used)

8. VANE GAP 2 CW WET TEST PART THREE

8.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

8.2 #10 fastener is securely tightened.

8.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

8.4 PD100 Camcorder for CFE Vane Gap 2 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
REC Lamp – Off
Sony emblem is covered
Vane position – 0 degrees
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

NOTE
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without
2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

8.5 PD100 Camcorder → On

8.6 Voice into the PD100 Camcorder GPS time, "CW Wet Test Part Three", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

8.7 Allow 1 minute for camcorder to record baseline condition.

8.8 Slowly rotate Vane Position Indicator CW to a Vane Position of 50 degrees. Allow 30 seconds for the fluid surface to stabilize. If slight fluid motion persists, wait an additional 2 minutes. Using the PD100 Camcorder, voice observations of the fluid response. Repeat for the following vane positions: 52, 54, 56, 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 90, 118, 120, 122, 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, 144, 146, 148, 180

8.9 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

8.10 Label Mini DVCAM Tape: CFE-Vane Gap 2 CW Wet Test Three and include GPS time.

8.11 Tmpry stow : Mini DVCAM Tape (used)

9. **VANE GAP 2 CCW WET TEST PART THREE**
9.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,
Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

9.2 \#10 fastener is securely tightened.

9.3 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

**CAUTION**
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

9.4 PD100 Camcorder for CFE Vane Gap 2 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
REC Lamp – Off
Sony emblem is covered
Vane position – 180 degrees
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

**NOTE**
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

9.5 PD100 Camcorder→On
9.6 Voice into the PD100 Camcorder GPS time, "CCW Wet Test Part Three", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

9.7 Allow 1 minute for camcorder to record baseline condition.

9.8 Slowly rotate Vane Position Indicator CCW to a Vane Position of 148 degrees.

Allow 30 seconds for the fluid surface to stabilize. If slight fluid motion persists, wait an additional 2 minutes

Using the PD100 Camcorder, voice observations of the fluid response.

Repeat for the following vane positions: 146, 144, 142, 140, 138, 136, 134, 132, 130, 128, 126, 124, 122, 120, 118, 90, 80, 78, 76, 74, 72, 70, 68, 66, 64, 62, 60, 58, 56, 54, 52, 50, 0

PD100 Camcorder

9.9 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

9.10 Label Mini DVCAM Tape: CFE-Vane Gap 2 CCW Wet Test Three and include GPS time.

9.11 Tmpry stow : Mini DVCAM Tape (used)

10. **VANE GAP 2 GAP STABILITY TEST**

10.1 √ #10 fastener is securely tightened

10.2 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

CAUTION

The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

10.3 √ PD100 Camcorder for CFE Vane Gap 2 entire Field of View

Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW
√ REC Lamp → Off
√ Sony emblem is covered
√ Vane position → 0 degrees
√ PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.
10.4 Use tape or paper to mark the location of the Vane Gap 2 vessel on the MWA surface so that it can easily be returned to approximately the same position.

NOTE
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

10.5 PD100 Camcorder → On

10.6 Voice into the PD100 Camcorder GPS time, "Gap Stability Test", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

10.7 Allow 1 minute for camcorder to record baseline condition.

10.8 Slowly rotate the vane CW to 90 degrees at approximately 3 degrees per second for a total movement duration of approximately 30 seconds.

10.9 Remove #10 Fastener and Tmpry stow.

10.10 Remove the vessel from the MWA and use a “soft” centrifuge method to relocate most of the fluid from the base to the lid. The goal is approximately two thirds of the fluid at the lid. This will provide enough fluid to bridge the gaps between the base and the vane, and between the lid and the vane.

As gently as possible, return the vessel to the MWA within five seconds and reattach using the #10 fastener. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.
10.11 Inspect test chamber interior surface for fluid film.

If present
\[ \sqrt{\text{POIC}} \] and wait for fluid film breakage

10.12 Wait 10 minutes to allow the fluid to reach its equilibrium condition.

10.13 Per the table below, slowly rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time. The gaps mentioned in this step are between the vane and the test chamber walls.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>3 minutes</td>
<td>Slow turn desired ~20 second movement duration</td>
</tr>
<tr>
<td>50</td>
<td>10 minutes</td>
<td>Possible large gap de-wetting</td>
</tr>
<tr>
<td>45</td>
<td>10 minutes</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>10 minutes</td>
<td>Possible small gap de-wetting</td>
</tr>
<tr>
<td>20</td>
<td>10 minutes</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10 minutes</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>10 minutes</td>
<td></td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times until both gaps have de-wetted (it is possible that they won’t de-wet).

If both gaps have de-wetted,

Proceed to the next step

10.14 Rotate vane CCW to 0 degrees if not already there.
10.16 Label Mini DVCAM Tape: CFE Vane Gap 2 Gap Stability Test and include GPS time.

10.17 Tmpry stow: Mini DVCAM Tape (used)

11. VANE GAP 2 ASYMMETRIC INTERFACE TEST 90

11.1 #10 fastener is securely tightened

11.2 Retrieve: Mini DVCAM Tape (new)  
Install Mini DVCAM Tape (new) in PD100 Camcorder 

CAUTION  
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

11.3 PD100 Camcorder for CFE Vane Gap 2 entire Field of View 
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW  
REC Lamp – Off  
Sony emblem is covered  
Vane position – 0 degrees  
PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

11.4 Use tape or paper to mark the location of the Vane Gap 2 vessel on the MWA surface so that it can easily be returned to approximately the same position.

NOTE  
1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.
NOTE
3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

11.5 PD100 Camcorder → On

11.6 Voice into the PD100 Camcorder GPS time, "Asymmetric Interface Test 90", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

11.7 Allow 1 minute for camcorder to record baseline condition.

11.8 Slowly rotate the vane CW to 90 degrees at approximately 3 degrees per second for a total movement duration of approximately 30 seconds.

11.9 Remove #10 Fastener and Tmpry stow.

11.10 Remove the vessel from the MWA and use a centrifuge method to move most of the fluid from the base to the left side of the test chamber. Fluid will likely bridge the gaps between the vane and the test chamber walls.

As gently as possible, return the vessel to the MWA within five seconds and reattach using the #10 fastener. Minor bumps on contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

11.11 Inspect test chamber interior surface for fluid film.

If present

√POIC and wait for fluid film breakage

11.12 Allow 2 minutes to allow the fluid to reach its equilibrium condition.

11.13 Per the table below, slowly rotate Vane Position Indicator CCW to the Vane Position listed and wait the prescribed time. The gaps mentioned in this step are between the vane and the test chamber walls
Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2 minutes</td>
<td></td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times until a familiar (i.e. more symmetric) interface configuration is established.

When a familiar interface configuration is established
Proceed to the next step

11.14 Rotate vane to 0 degrees if not already there.

End Video Activity

PD100 Camcorder

11.15 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)

sw Mini DVCAM Tape → Save

11.16 Label Mini DVCAM Tape: CFE Vane Gap 2 Asymmetric Test 90 and include GPS time.

11.17 Tmpry stow : Mini DVCAM Tape (used)

12. VANE GAP 2 ASYMMETRIC INTERFACE TEST 0

12.1 √#10 fastener is securely tightened

12.2 Retrieve: Mini DVCAM Tape (new)
Install Mini DVCAM Tape (new) in PD100 Camcorder

**CAUTION**
The camera view and the front face of the Vane Gap 2 vessel should be orthogonal or loss of science may occur.

12.3 √PD100 Camcorder for CFE Vane Gap 2 entire Field of View
Refer to 5.010 CFE VANE GAP CHAMBER FIELD OF VIEW

√REC Lamp – Off
√Sony emblem is covered
√Vane position – 0 degrees
√PD100 Camcorder view is orthogonal to the front face of the CFE Vane Gap 2 vessel. Gauge by eye checking both the top view and the side view.

12.4 Use tape or paper to mark the location of the Vane Gap 2 vessel on the MWA surface so that it can easily be returned to approximately the same position.

**NOTE**

1. This test does not require any tapping to aid in fluid redistribution. The operator only needs to adjust the vane position and wait the prescribed time for each step without disturbing the vessel for each setpoint.

2. Vane angle adjustments are made by smoothly turning the Vane Position Indicator. An approximate 2 degree backlash is present on the Vane Position Indicator and it may be necessary to overturn the Vane Position Indicator approximately 2 degrees to establish the desired angle once the Vane Position Indicator is released.

3. When rotating Vane Position Indicator, care should be taken to keep the Vane Position Indicator visible and unobstructed in the camera Field of View.

4. VALVE 1 remains open (extended) during all the CFE Vane Gap 2 tests.

12.5 PD100 Camcorder → On

12.6 Voice into the PD100 Camcorder GPS time, "Asymmetric Interface Test 0", "CFE Vane Gap 2", and the module temperature from the PCS ECLSS page.

12.7 Allow 1 minute for camcorder to record baseline condition.

12.8 Remove #10 Fastener and Tmpry stow.

12.9 Remove the vessel from the MWA and use a centrifuge method to move most of the fluid from the base to the left side of the test chamber. Fluid should bridge the base and lid along the left side of the test chamber, but may not cover the lid and/or base.

As gently as possible, return the vessel to the MWA within five seconds and reattach using the #10 fastener. Minor bumps on
contact are acceptable. Try to place the vessel back to its original position when reattaching to the MWA. Do not adjust the vessel position after placement back onto the MWA.

12.10 Inspect test chamber interior surface for fluid film.

If present

\[ \text{POIC} \]

and wait for fluid film breakage

12.11 Allow 2 minutes to allow the fluid to reach its equilibrium condition.

12.12 Per the table below, slowly rotate Vane Position Indicator CW to the Vane Position listed and wait the prescribed time. The gaps mentioned in this step are between the vane and the test chamber walls.

Using the PD100 Camcorder, voice observations of the fluid response.

<table>
<thead>
<tr>
<th>Vane Position</th>
<th>Wait Time</th>
<th>Setpoint Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2 minutes</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1 minute</td>
<td>Slow CCW turn ~30 second movement duration</td>
</tr>
</tbody>
</table>

Repeat for the remaining vane positions and wait times until a familiar (i.e. more symmetric) interface configuration is established.

When a familiar interface configuration is established

Proceed to the next step

12.13 Move vane to 0 degrees if not already there.

End Video Activity

PD100 Camcorder

12.14 PD100 Camcorder → Off
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save
12.15 Label Mini DVCAM Tape: CFE Vane Gap 2 Asymmetric Test 0 and include GPS time.

12.16 Tmpy stow : Mini DVCAM Tape (used)

13. **VANE GAP 2 POST TEST FLUID WITHDRAWAL**

13.1 Visually inspect the fluid in the vessel. There should not be any liquid in contact with the lid of the test chamber. In general, the fluid should cover the base and rise partially up the walls of the test chamber forming a rather large meniscus.

If at any time during this step the fluid configuration departs from this state,

Perform 4.001 CFE VANE GAP FLUID RELOCATION all, then:

13.2 √#10 fastener is securely tightened

CFE Vane Gap

13.3 Position vane angle to 0 degrees.

13.4 Slowly turn KNOB 1 CW initially at approximately 1/4 to 1/2 turn per second to stop (approx. 46 revolutions), retracting as much fluid into reservoir without ingesting bubbles. Withdrawal rate must be reduced significantly to avoid ingestion of air bubbles during the final stages of the drain procedure (complete drain could take up to 5 minutes). Not all fluid will be removed from container. Remove only as much as is possible without ingesting bubbles beyond VALVE 1.

13.5 With one hand supporting CFE Vane Gap 2, gently push VALVE 1 to hard stop.

13.6 Notify POIC of tape serial number and/or sequence number for each used tape.

13.7 Stow:

- Mini DVCAM Tapes (per execution note, used)
- Gray Tape
- CFE Vane Gap
- 1/8” L-Wrench (2 1/4” length)

RESTOW TOOLS, PARTS, MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS EXCEPT FOR:

Mini DVCAM Tape [per execution note] P/N SED33111489-305 TO: For return to Houston
2.007  CFE CONTACT LINE TEST OPERATIONS - INCREMENT 13

OBJECTIVE:
Capillary Flow Experiment (CFE). During this procedure the data for the CFE Contact Line tests is recorded via Camcorder video and sound. The CFE tests are titled Axial, Slide, Multi-Slide and Drainage.

STATION PARTS:
CFE Contact Line 2 P/N 60083MA00200
Mini DVCAM Tape [3] P/N SED33111489-305

STATION TOOLS:
MWA Work Surface Area P/N SEG33110270-301
MWA Utility Kit P/N SJG33110310-301
Fine Point Sharpie P/N 528-40674-1
PD100 Camcorder P/N SEZ16103293-301

STATION MATERIALS:
Dry Wipe P/N SEG33107170-306

NOTE
1. This procedure contains Near Real - Time video downlink or LAB VTR recording requirements.
2. AOS may be required for POIC to configure on board system for downlink of science or LAB VTR recording.

1. CFE TEST CHAMBER FILL

1.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Refer to 5.013 CFE PINNING LIP COMPARISON
If the pinning lip needs to be cleared of fluid at any time during this step, perform step 6 and then resume this step where exited.

1.2 #10 fastener is securely tightened

1.3 Unstow: Mini DVCAM Tapes (3)
Temporarily close to PD100 Camcorder
Insert Mini DVCAM Tape into PD100 Camcorder.

1.4 PD100 Camcorder for CFE Contact Line 2 entire Field of View
REC Lamp – OFF
Sony emblem is covered
Refer to Figure 5.005 CFE CONTACT LINE CHAMBER FIELD OF VIEW

CAUTION
1. Once fluid dispensing into the test chambers has begun, the process for turning the knob needs to be consistent or a loss of science will occur.
CAUTION
2. The smooth cylinder fluid will be dispensed before the pinning cylinder in order to reduce disturbances that could impact science associated with the pinning lip.

NOTE
1. Valve 2 and Knob 2 are associated with the smooth cylinder. Refer to 5.001 CFE CONTACT LINE. Valve 2 remains open during all subsequent operations.

2. Valve 1 and Knob 1 are associated with the pinning cylinder. Refer to 5.001 CFE CONTACT LINE. Valve 1 remains open during all subsequent operations.

3. Bubbles in the fluid reservoirs are expected and a normal occurrence. No action is necessary other than fluid deployment as described below. Once deployed, the bubbles will find their way to the surface and pop.

1.5 PD100 Camcorder → ON

CFE Contact Line 1.6 With one hand supporting CFE Contact Line 2, gently pull Valve 2 to hard stop. High resistance may be encountered.

1.7 Slowly Turn Knob 2 CCW to stop at approximately 1/4 to 1/2 turn per second (approx. 40 revolutions, requires up to 2 to 3 minutes).

1.8 √CFE Contact Line 2 fluid has been fully dispensed into the smooth cylinder.

CAUTION
CFE Contact Line 2 fluid leakage may occur around the valves, and/or the piston.

1.9 √CFE Contact Line 2 for visible leakage

**************************************************************************
If leakage
Wipe with Dry Wipes.
If leakage continues,
√ POIC to report leakage
**************************************************************************

CFE Contact Line 1.10 With one hand supporting CFE Contact Line 2, gently pull Valve 1 to hard stop. High resistance may be encountered.
1.11 Slowly Turn Knob 1 CCW to stop at approximately 1/4 to 1/2 turn per second (approx. 40 revolutions, requires up to 2 to 3 minutes).

1.12 √CFE Contact Line 2 fluid has been fully dispensed into the pinning cylinder.

**CAUTION**

CFE Contact Line 2 fluid leakage may occur around the valves, and/or the piston.

1.13 √CFE Contact Line 2 for visible leakage

*************************************************************************
If leakage

   Wipe with Dry Wipes.

   If leakage continues,

   √POIC to report leakage

*************************************************************************

1.14 Zoom in the PD100 Camcorder so that the small Field of View is recorded. Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW

1.15 Voice observations (into recording PD100 Camcorder) concerning symmetry of interface on pinning lip of pinning cylinder and presence and approximate size of any bubbles.

1.16 PD100 Camcorder → OFF

End Video Activity

2. CFE AXIAL TEST

2.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Refer to 5.013 CFE PINNING LIP COMPARISON

   If the pinning lip needs to be cleared of fluid at any time during this step,

   Perform step 6 and then resume this step where exited.

2.2 √#10 fastener is securely tightened.

2.3 √PD100 Camcorder viewing CFE Contact Line 2 small Field of View

√Sony emblem is covered
√REC Lamp – Off
√Camera view in front face of CFE Contact Line vessel is orthogonal
Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW

**CAUTION**

1. The Axial disturbances should be very small to start and increase gradually with each disturbance. The disturbance should never be large enough to destabilize the pinning cylinder interface, form bubbles, or break-up the fluid interfaces. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Axial disturbance for the fluid motion to fully decay (damp out, settle, etc.) or science will be lost.

**NOTE**

1. An axial mode disturbance is created by deflecting and releasing the MWA much like a diver on a spring board. The disturbance will excite axial oscillation modes on the liquid surfaces in the cylinders.

2. Special care must be taken to impart the disturbance quickly. The action should be to depress the MWA with an immediate release to avoid seeing one disturbance from deflecting the MWA and another disturbance when releasing it.

3. Valve 1 and Valve 2 remain open (extended) during the CFE test.

---

2.4 PD100 Camcorder → ON

2.5 Voice into the PD100 Camcorder GMT, "Axial Test", "CFE Contact Line 2", and the module temperature from the PCS ECLSS page.

2.6 Beginning with extremely weak deflections, using finger, depress and release the MWA (using MWA as cantilever) to impart an axial mode disturbance to the interfaces (much like a diver on a diving board). Operator must wait at least 15 seconds after each axial disturbance.

Repeat disturbance with approximately same deflection.

2.7 Repeat step 2.6 with increased disturbance amplitude until it is perceived that further increases in disturbance amplitude will de-pin interface or eject liquid droplets from surface.

---

2.8 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

2.9 Label Mini DVCAM Tape FILL and AXIAL TEST and include approximate GMT.
2.10 Tmpry stow:
Mini DVCAM Tape (used)

3. CFE SLIDE TEST

3.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip.
Refer to 5.013 CFE PINNING LIP COMPARISON
If the pinning lip needs to be cleared of fluid at any time during this step, Perform step 6 and then resume this step where exited.

3.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 2 to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 2 may slide smoothly left to right in field of view without excess slop.

3.3 Retrieve:
Mini DVCAM Tape (new)
Install a Mini DVCAM Tape (new) in PD100 Camcorder

3.4 PD100 Camcorder viewing CFE Contact Line 2 small Field of View has been zoomed out slightly to show the entire range of motion.
Sony emblem is covered
REC Lamp – Off
Camera view in front face of CFE Contact Line vessel is orthogonal
Refer to 5.002 CFE CONTACT LINE SMALL FIELD OF VIEW

<table>
<thead>
<tr>
<th>CAUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Begin with a weak Slide. The Slides should not increase to the point the pinning cylinder interface is de-pinned or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.</td>
</tr>
<tr>
<td>2. Time must be allowed after each Slide test for the fluid motion to fully decay or science will be lost.</td>
</tr>
</tbody>
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<table>
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<tbody>
<tr>
<td>1. A Slide is a one period lateral oscillation, (back and forth), completed within the Field of View at the approximate natural frequency of the interface (predicted to be approximately 1.5-2 Hz). Crew must identify the approximate natural frequency during operations.</td>
</tr>
<tr>
<td>2. Valve 1 and Valve 2 remain open (extended) during the CFE test.</td>
</tr>
<tr>
<td>3. It is desirable to avoid hitting the ends of the slot to reduce the risk of depinning the interface.</td>
</tr>
<tr>
<td>4. Drift after a slide can be minimized by readjusting the #10 fastener prior to each slide as necessary.</td>
</tr>
</tbody>
</table>
NOTE

5. Each Slide applied to the CFE Contact Line 2 must be in same orientation (left to right) across the FIELD OF VIEW, with the same grip on the CFE Contact Line 2.

3.5 PD100 Camcorder → ON

3.6 Voice into the PD100 Camcorder GMT, "Slide Test", "CFE Contact Line 2", and the module temperature from the PCS ECLSS page.

3.7 Very slowly slide the CFE Contact Line 2 right, close to the end of the mounting slot. Avoid abrupt impact with slot end. Do not disturb the interface. Operator must wait at least 15 seconds before proceeding.

3.8 Lightly Slide CFE Contact Line 2 in Field of View laterally (left to right) one period a distance of about 10mm (peak to peak amplitude). Avoid abrupt impact with slot ends. Using the PD100 Camcorder, voice the event. Using the PD100 Camcorder, voice observations of the fluid response. Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay. Operator must wait at least 15 seconds after each slide disturbance.

Repeat one time. If interesting or noticeably different behavior between cylinders results, Repeat Slide up to two times.

3.9 Repeat step 3.8 moving 15 mm each time

3.10 Repeat step 3.8 moving 20 mm each time

3.11 Repeat step 3.8 moving 25 mm each time

3.12 Repeat step 3.8 moving 30 mm each time

4. CFE MULTI-SLIDE TEST

4.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Isolated drops in the pinning lip may be tolerated if they do not touch surfaces of the cylinder below the pinning lip. Refer to 5.013 CFE PINNING LIP COMPARISON
If the pinning lip needs to be cleared of fluid at any time during this step, perform step 6 and then resume this step where exited.

4.2 Loosen, but do not remove, the #10 Fastener that secures the CFE Contact Line 2 to the Maintenance Work Area through the slot in the base plate, such that the CFE Contact Line 2 may slide smoothly left to right in field of view without excess slop.

**CAUTION**

1. Begin with a weak multiple, lateral oscillation, (back and forth). The Slides should not increase to the point the pinning cylinder interface is de-pinned or the fluid interfaces break up or bubbles form. Clearing the pinning edge takes considerable time and will reduce time for operations.

2. Time must be allowed after each Multi-Slide Test for the fluid motion to fully decay or science will be lost.

**NOTE**

1. A Slide is now defined as multiple (2, 3, 4) period lateral oscillations completed within the Field of View, at the approximate natural frequency of the interface (predicted to be approximately 1.5-2 Hz). Crew must identify the approximate natural frequency during operations.

2. Valve 1 and Valve 2 remain open (extended) during the CFE test.

3. It is desirable to avoid hitting the ends of the mounting slot to avoid the risk of de-pinning the interface.

4. Drift after a multi-slide can be minimized by readjusting the #10 fastener prior to each multi-slide as necessary.

5. Each multiple oscillation Slide applied to the CFE Contact Line 2 must be in same orientation (left to right) across the FIELD OF VIEW, with the same grip on the CFE Contact Line 2.

4.3 Voice into the PD100 Camcorder GMT, "Multi-Slide Test", "CFE Contact Line 2", and the module temperature from the PCS ECLSS page.

4.4 Slide CFE Contact Line 2 two full cycles with a peak to peak distance of about 10mm in the Field of View. Avoid abrupt impact with slot ends.

   Using the PD100 Camcorder, voice the event.
   Using the PD100 Camcorder, voice observations of the fluid response.
   Drift and/or rotation may occur at the end of motion and is acceptable and should remain untouched for the prescribed time delay.
Operator must wait at least 15 seconds after each slide disturbance.

Repeat Multi-Slide one time.
If interesting or noticeably different behavior between cylinders results,
Repeat multiple Slide up to two times.

4.5 Repeat step 4.4 moving 15 mm each time.

4.6 Repeat step 4.4 moving 20 mm each time.

4.7 Repeat step 4.4 moving 25 mm each time.

4.8 Repeat step 4.4 moving 30 mm each time.

4.9 As video tape allows, continue Slides of increasing number of oscillations (3, 4), being careful to avoid depinning the interface.

4.10 PD100 Camcorder → OFF
Eject Mini DVCAM Tape (used)
sw Mini DVCAM Tape → Save

4.11 Label Mini DVCAM Tape SLIDE and include approximate GMT.

4.12 Tmpry stow:
Mini DVCAM Tape (used)

5. CFE DRAINAGE

5.1 Visually inspect the vessel to determine if the pinning lip is dry. In general, a dry pinning lip diffracts light in such a manner that it is not possible to clearly see through the pinning lip in profile. Refer to 5.013 CFE PINNING LIP COMPARISON
If the pinning lip needs to be cleared of fluid at any time during this step,
Perform step 6 and then resume this step where exited.

5.2 √#10 fastener is securely tightened

5.3 √CFE Contact Line 2 Valve 2 is open, (valve pulled out to hard stop)

5.4 Remove the fluid as fast as possible by turning Knob 2 CW without ingesting air into the reservoir. Retraction of the fluid at the end of the process should be very slow, to avoid ingesting air into the fluid reservoir. Not all of the fluid will be removed.

5.5 With one hand supporting CFE Contact Line 2, gently push Valve 2 to overcome high resistance to hard stop (closed).
5.6 CFE Contact Line 2 Valve 1 is open, valve pulled out to hard stop

5.7 Remove the fluid as fast as possible by turning Knob 1 CW without ingesting air into the reservoir. Retraction of the fluid at the end of the process should be very slow, to avoid ingesting air into the fluid reservoir. Not all of the fluid will be removed.

5.8 With one hand supporting CFE Contact Line 2, Gently push Valve 1 to overcome high resistance to hard stop (closed).

6. CFE DRYING THE PINNING LIP

<table>
<thead>
<tr>
<th>NOTE</th>
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<tbody>
<tr>
<td>1. This process could take up to 15 minutes per attempt and may take several tries to get right, but is critical to achieving the science goals.</td>
</tr>
<tr>
<td>2. The most challenging aspect of the centrifuge method is slowing down smoothly without disturbing the pinning lip.</td>
</tr>
<tr>
<td>3. Liquid remaining in the groove serving as the pinning lip of the pinning cylinder should be cleared as needed. It is preferred that this liquid be moved to the base of the cylinder, clearing it by any force deemed acceptable.</td>
</tr>
<tr>
<td>4. Drops of fluid on the test chamber wall above the pinning lip are not a problem and may be ignored.</td>
</tr>
<tr>
<td>5. Small isolated drops residing in the pinning lip are also not a problem if they are clearly not touching the pinning cylinder walls below the pinning lip.</td>
</tr>
</tbody>
</table>

6.1 Remove test vessel from MWA and use centrifuge method (see movie clip for Mike Fincke’s method). A higher angular velocity will likely be required to clear the pinning lip.

6.2 If the previous effort does not clear the pinning lip perform the following:

6.3 Drain the pinning cylinder by turning Knob 1 CW, without ingesting air bubbles into the reservoir.

6.4 With one hand supporting CFE Contact Line 2, gently push Valve 1 to overcome high resistance to hard stop (closed).

6.5 Remove #10 Fastener from Maintenance Work Area and try pry stow to allow the CFE Contact Line 2 to be held in hand(s).

6.6 Use impulse type disturbances to the vessel (jerks, ‘bonks’, whatever, etc.) to clear the fluid in the pinning lip and hopefully move it below the pinning lip.
6.7 A combination of centrifugal force with impulse disturbances may be required to clear the pinning lip.

6.8 Use something like the Fincke centrifuge method to return the fluid in the Smooth cylinder to the base of the cylinder.

6.9 Gently re-secure CFE vessel to the MWA using the #10 fastener.

6.10 Visually inspect the test chambers for any fingerprints. Use a dry wipe to remove any if found.

6.11 With one hand supporting CFE Contact Line 2, gently pull Valve 1 to hard stop. High resistance may be encountered.

6.12 Slowly Turn Knob 1 CCW to stop at approximately 1/4 to 1/2 turn per second (approx. 40 revolutions, requires up to 2 to 3 minutes).

6.13 CFE Contact Line 2 fluid has been fully dispensed into the pinning cylinder.

6.14 Continue operations.

RESTOW TOOLS, PARTS, MATERIALS AS REQUIRED TO ORIGINAL LOCATIONS, EXCEPT FOR:
Mini DVCAM Tape [3] P/N SED33111489-305 TO: CTB, for return to Houston
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**13. SUPPLEMENTARY NOTES**  
**14. ABSTRACT**  
This report provides a summary of the experimental, analytical, and numerical results of the Capillary Flow Experiment (CFE) performed aboard the International Space Station (ISS). The experiments were conducted in space beginning with Increment 9 through Increment 16, beginning August 2004 and ending December 2007. Both ‘primary’ and ‘extra science’ experiments were conducted during 19 operations performed by 7 astronauts including: M. Fincke, W. McArthur, J. Williams, S. Williams, M. Lopez-Alegria, C. Anderson, and P. Whitson. CFE consists of 6 approximately 1 to 2 kg handheld experiment units designed to investigate a selection of capillary phenomena of fundamental and applied importance, such as large length scale contact line dynamics (CFE-Contact Line), critical wetting in discontinuous structures (CFE-Vane Gap), and capillary flows and passive phase separations in complex containers (CFE-Interior Corner Flow). Highly quantitative video from the simply performed flight experiments provide data helpful in benchmarking numerical methods, confirming theoretical models, and guiding new model development. In an extensive executive summary, a brief history of the experiment is reviewed before introducing the science investigated. A selection of experimental results and comparisons with both analytic and numerical predictions is given. The subsequent chapters provide additional details of the experimental and analytical methods developed and employed. These include current presentations of the state of the data reduction which we anticipate will continue throughout the year and culminate in several more publications. An extensive appendix is used to provide support material such as an experiment history, dissemination items to date (CFE publication, etc.), detailed design drawings, and crew procedures. Despite the simple nature of the experiments and procedures, many of the experimental results may be practically employed to enhance the design of spacecraft engineering systems involving capillary interface dynamics.  
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