ABSTRACT

During Lunar missions, NASA’s new Orion Crew Exploration Vehicle (CEV) may benefit from mass savings and increased reliability by the use of a passive, capillary-driven Static Phase Separator (SPS) for urine collection, containment, and disposal in place of a rotary-fan separator and wastewater storage tank. The design of a capillary separator addresses unique challenges for microgravity fluid management for liquids with a wide range of possible contact angles and high air-to-liquid flow ratio. This paper presents the iterative process leading to a successful test in a reduced gravity aircraft of the SPS concept. Using appropriately scaled test conditions, the resulting prototype allows for a range of wetting properties (0 < θ < 90º) with complete separation of liquid from gas.

INTRODUCTION

The SPS project was started during the earliest stages of the CEV program prior to the establishment of a vehicle baseline design. During this period, NASA conducted a survey of current and historical waste management systems and identified some specific engineering concerns with these systems. Diaper-type systems, considered for contingency use in many programs, are unacceptable to the user and prohibitively large as crew size and mission duration increase. Airflow assisted systems such as those used by the Shuttle and Station, are not desirable because they require rotary equipment that is subject to failure from precipitates, particles, and slug flow.

Therefore, for the Constellation Program, replacement of the rotary-fan separator and associated wastewater storage tank with a passive capillary-driven, two-phase separator with direct overboard dump may offer a comparable user interface, systems mass savings, and greater reliability. This paper reviews the design and development of a Static Phase Separator for urine collection that meets the requirements for the CEV with the objective to return dry air to the cabin and vent the urine overboard1.

MICROGRAVITY FLUID MANAGEMENT

On Earth, gravity provides for natural separation of fluids. However, pouring water down a drain becomes a complex process in space where microgravity effectively eliminates buoyancy, and instead surface tension and wetting forces dominate liquid configurations. A particular liquid-gas-solid system will have specific characteristics based on the fluids and solids selected. Three general kinds of wetting for a liquid drop on a substrate are shown in Figure 1: spreading, partial wetting, and non-wetting interactions.

A hydrophilic system consists of a liquid with higher affinity for the surface than itself. In a hydrophobic system, the converse is true. In partial wetting and spreading systems, wetting can occur spontaneously as does dewetting in many nonwetting systems. This is known as capillary action2. Capillary systems can be designed for a range of expected contact angles (a
frequently-used parameter for characterizing wetting conditions) based on the selected materials and liquids.

Systems in microgravity, such as propellant tanks, are often designed to take advantage of capillary forces and passively drive fluids in desired directions. For example, Figure 2 shows a sketch of a liquid in a wedge where the pressure drop across the fluid surface can drive the fluid along the corner. The pressure drop can be represented as

\[ P_\infty - P_2 = \frac{\sigma}{R} \left( \frac{\cos \theta}{\sin \alpha} - 1 \right), \]

where \( P_\infty \) is the atmospheric pressure, \( P_2 \) the pressure at the interface, \( \sigma \) the surface tension of the liquid, \( R \) the principle interface radius of curvature, \( \theta \) the contact angle of the liquid with the solid, \( \alpha \) the half-angle of the interior corner, and \( h \) the height of the liquid as measured from the corner vertex. In Equation 1 when \( \alpha < 90^\circ - \theta \) (and in the absence of significant body forces such as gravity, vehicle acceleration, vibrations or inertia) an under-pressure (\( P_\infty > P_2 \)) in the liquid arises such that any gradients in the meniscus height along the corner will result in a spontaneous redistribution of fluid along the corner until such gradients are eliminated. Similarly, a corner channel with a changing \( \alpha \) will ensure that the liquid will pump along the corner in the direction of decreasing capillary pressure.

Therefore, the critical Bond number must be met to ensure that background accelerations do not destabilize the liquid system. The Bond number is a dimensionless comparison of the relative magnitude of gravitational and capillary forces. When \( Bo > 1 \) gravitational forces dominate. When \( Bo << 1 \), capillary forces dominate. Adapting the Bond number for the SPS design

\[ Bo_{cr} = \frac{\Delta \rho g R L}{\sigma} < 1, \]

where \( \Delta \rho \) is the difference in the density between the gas and liquid, and \( R \) and \( L \) are the radius and length of the SPS test article. In a similar way, a critical Weber number condition must also be met to reduce the confounding effects of inertia,

\[ We_{cr} = \frac{\Delta \rho V^2 R}{\sigma} < 3, \]

where \( V \) is a characteristic velocity of the flow. An experimental reduced-gravity apparatus was developed that allowed for circulation of a test liquid with air through a sequence of test articles. All tests were conducted with DI water as an ersatz for wastewater with contact angle \( \theta > 80^\circ \). Some test articles also used 200 proof Ethanol as an ersatz for urine with \( \theta \sim 10^\circ \), and 3M Fluorinert FC-72 as a perfectly wetting fluid. The sub-scale flow rates used to approximate the 100:1 air to liquid flow rate ratio anticipated with a 340 l/min fan were 3.9-7.8 l/min air flow and 20-60 ml/min liquid. The air loop was closed with air recycling through the system, and liquid carryover was retained in a buffer volume that served as a temporary separator. The liquid line was fed by graduated syringes, and the liquid drained and carried over was collected at the end of each test point in separate syringes.

**STATIC PHASE SEPARATOR IERATIONS**

The proposed Static Phase Separator utilizes capillary and centripetal force to separate urine and air streams. Elements of the SPS designs are based on the capillary wedge concept presented in Figure 2. The iterative designs and test results that led to a successful sub-scale SPS test article are presented herein.

**TEST ARTICLE REV A: INITIAL DEMONSTRATION OF CAPILLARY RETENTION**

The objective of the first test article (shown in Figure 3) was to experimentally establish four essential elements of the design concept:

1) a coil to collect free droplets into a guided continuous liquid stream, or rivulet, along the outside edge of the coil,
2) an expanding region to slow the air flow velocity reducing air drag and shear on the liquid surface,
3) a set of capillary wedges that hold the fluid and move it to regions of increasing fin density, and
4) an air exit port that requires the air to make a sharp change in direction, increasing the opportunities for liquid droplets to penetrate into the fluid retention section and gas to exit without liquid carryover.

The evaluation of Rev A on the C-9 microgravity research aircraft in June 2006 demonstrated the four essential design fundamentals of capillary fluid management stated previously, as well as some unexpected behavior.

One unexpected result was identified before the flight tests began. The fin section was made using stereolithography (SLA) from a nominally transparent resin that tended to warp after repeated exposure to water. It would also warp at temperatures as low as 95°F (common in Houston in summer). Although SLA allowed the rapid manufacture of complex shapes and visual observation of the interior dynamics during testing, the warpage was deemed unacceptable and alternate methods were sought.

Three other unexpected results experienced during the flight had a more significant impact on the design. First, the liquid rivulet flow meandered all around the circular cross-sectional area of the coil, making fluid introduction into the fin section unpredictable. Second, while the coil section had a circular cross section, the fin section had a square cross section, and the design failed to account for the subtleties of the transition. Finally, the air outlet of Rev A had a stove pipe fitting—where the exiting cylindrical tube protruded into the fin section. Due to its placement, this design attracted stray droplets that became entrained in the gas stream contributing to carryover. Ultimately, the unexpected results proved to be more helpful in focusing redesign than the demonstrations of intended effects.

TEST ARTICLE REV B: ACHIEVING GUIDED RIVULET FLOW

The Rev A inlet supplied meandering and time varying rivulet flow. To achieve greater control (i.e. guided rivulet flow), we exploit the interior corner geometry in an otherwise circular tube in a similar manner to the capillary wedge concept shown in Figure 2. The result is an ice-cream-cone-shaped cross section conduit.

In an attempt to combine both the centripetal and capillary functions into one test article, the design concept for Rev B began with a cylinder. The two-phase flow would move through a helical ice-cream-cone shaped channel. Ideally, fins would be positioned within the wedge portion, leaving a gap at the tip and allowing the water to communicate between fins. The channel would possess a variable-shaped cross section with a vane structure growing in width along the conduit length.

However, since manufacturing such a complex geometry with intricate and delicate fins was difficult and costly, the fin concept was abandoned and the cross section of the Rev B test article was simply ice-cream-cone-shaped with the “tip” of the cone radially outward and the semi-circular “ice cream” section of the cone radially inward. The test article, shown in Figure 4, was constructed of acrylic to allow visual observation during testing and to provide a more sturdy structure than the previous SLA test article. To simplify manufacturing, the acrylic cylinder was cut into two pieces—a core and an annulus. The semi-circular portion of the channel was cut into the external surface of the core, and the variable-depth wedge shape was cut into the inner surface of the annulus. The two pieces were then press-fit together, and the junction on the top and bottom surfaces were sealed with a silicone adhesive. The sealant was not applied between the core and annulus surfaces due to a concern that the adhesive would migrate into the channel area.
While there was some very minor leaking between the interior surfaces of the annulus and core, the July and August 2006 flight tests with the Rev B design showed that the ice-cream cone shape was extremely successful in achieving guided rivulet flow. Fluid moved to the tip within the first turn of the coil and stayed in the tip across a wide range of air flow velocities and fluid injection conditions. Droplets exiting the inlet to the device quickly coalesced to form a continuous rivulet. It is important to note that centripetal forces do not hold the liquid in place, but rather capillary forces. The centripetal forces are exploited only to bring free droplets to the outer race of the cone and to create a force with which to coalesce with the rivulet.

TEST ARTICLE REV C: BISECTING FLUID STORAGE VANES

The Rev B test article successfully achieved every fluid management challenge but one: fluid storage. If vertical vanes bisecting the capillary wedge could wick fluid from the tip of the ice cream cone and hold the fluid in a large-capacity reservoir, a single device that separates and retains fluid could be manufactured. The Rev C design shown in Figure 5 and Figure 6, attempted to combine both the separation and storage functions.

For Rev C, the ice-cream-cone-shaped helix from the Rev B design was retained, and this coil area now transitioned into a cylindrical finned section. The August 2006 C-9 test results showed that the Rev C test article stored fluid too well. By design, liquid moved to the outside wall of the finned section, but this obscured the ability to observe the liquid behavior at the exit of the helix and among the fins. Additionally, the test article was not properly scaled for the C-9, holding over a liter of water and it could not be conclusively demonstrated that the air phase of the flow was separating completely.

Therefore, because the Rev C test article was a significant departure from the original design approach, was difficult to manufacture, and the initial flight tests were not encouraging, the next iteration of the SPS design returned to the original concept with a helix venting into a low flow, capillary dominated fin section.

TEST ARTICLE REV D: HELIX WITH FLOW ALIGNED VANES

The Rev D test article had both a coil and separator section as with the Rev A design, but the coil was comprised of a core and annular section with the ice-cream shaped helix similar to the Rev B design. Unlike Rev B, the helix had only one and a quarter turns since the Rev B flight tests showed the helix was effective in a short distance. Thus, the coil and fin sections could be successfully evaluated together despite the limited time (~20s) afforded by the low-g aircraft. The coil was manufactured of clear acrylic, and the core and annulus were again press fit together and sealed on the outer surfaces with an adhesive.

The fin section had a similar shape to the Rev A test article but the expansion region did not use a small diameter “stove pipe” for the air outlet as in Rev A. The fin section was also manufactured from clear acrylic, machined as a separate block to smoothly and continuously join with the helix and fin section. A photo of test article Rev D is shown in Figure 7, with a solid model shown in Figure 8.
When Rev D was tested on the C-9 in October 2006, fluid was successfully separated in the helix and provided as a single continuous rivulet flow to the fin section; however the high contact angle liquid did not transfer quickly and uniformly through the expansion region to the fins as anticipated. Instead, the fluid pinned and accumulated at the front of the fins in the low velocity region (represented in blue in Figure 8), forming an undulating blob. The accumulation grew in size leading to acceleration of the bypassing air stream to the point liquid droplets were entrained into the exiting air (i.e. carryover).

Interestingly, when the finned section was perturbed by manually tapping the test article, the water globule was pulled down into the fins and water progressed toward the liquid outlet by capillary forces. Also, when there was a continuous path of water connecting the helix to the fin section, Rev D successfully separated the fluid from the air stream and contained the liquid in the fin section.

The formation of the liquid blob was attributed to finite thickness vanes, edge pinning, and surface roughness resulting in contact line pinning requiring advancing contact angles to be exceeded before the liquid interface would move along the solid surfaces. When the vessel was perturbed by tapping or shaking, the fluid interface would depin and the liquid would behave as intended.

The fluid buildup observed in the flight tests showed that in shear-dominated sections of the helix where gas velocities are high surface roughness was less important, and when there was fluid continuity along the length of the device, the system performed as predicted. But if ever in the expanding region there was low flow and/or fluid discontinuity, the system was prone to suffer the effects of contact line pinning leading to significant carryover by air shear and entrainment.

TEST ARTICLE REV E: IMPROVED WETTING ATTEMPT WITH TITANIUM

Rev E set out to address the pinning effects by changing construction materials from clear acrylic to titanium (Ti-64), and to demonstrate a system with flight-like materials. Titanium has good corrosion resistance to urine, more favorable wetting characteristics and can be polished to a very smooth surface, which would presumably be less prone to pinning. Since the use of titanium precludes flow visualization within the fin section, the acrylic core was retained to allow observation of the fluid flow to ensure the two-phase flow was entering the test article properly, and to provide a nearly hydrophobic surface. Without visual access determination of separation was limited to checking the air outlet for liquid carryover. The Ti-64 helix was manufactured using an electron beam powder metallurgy process. The expansion and fin portions of the device were machined from sheet stock and Ti-64 block, respectively. Rev E is shown in Figure 9.

The C-9 tests of Rev E in March 2007 used fluids with very different characteristics: de-ionized (DI) water and Fluorinert Electronic Fluid FC72. Using water, the primary focus was on managing fluids under poor wetting conditions. As in previous tests, the flight tests with the Rev E design still suffered from high contact angle pinning, a problem the change to Titanium did not solve satisfactorily.

Fluorinert is a non-hazardous, highly wetting low surface tension dielectric liquid manufactured by 3M. The flight tests with Fluorinert demonstrated that when surface pinning effects were negligible and the systems performs generally as expected. However, the Fluorinert also exhibited some undesirable film-spreading behavior that led to liquid carryover. Because it is an ideally wetting liquid on the selected test materials it was readily driven by air shear to cover all internal surfaces eventually leading to carryover. Observations of such flows illuminated simple design techniques to manage such highly wetting systems, particularly for wetting films near the air exit.

TEST ARTICLE F: A FUNDAMENTAL RESOLUTION TO POST COIL TRANSITION PROBLEMS

The simple approach of changing material type and surface finish did not solve the problem of achieving a smooth liquid-pinning-free transition from the coil section to the fin section. The ultimate solution to the transition problem was geometric.
Test articles A, D, and E align both the orientation of the fin section and the fins within the fin section along the same line as the two-phase flow leaving the coil section. Because of this, the air flow tries to drag the fluid along the length of the fin section, and the thickness of the fins themselves block the fluid flow. However, the Rev F test article, as depicted in Figure 10, rotates the fin section such that the fins are perpendicular to the flow coming from the coil section. This change in orientation dramatically changed the capillary pumping direction as the two-phase flow departs the coil. The liquid exiting the ice-cream-cone-shaped helix is directed onto the side of the fins in the fin section, causing the liquid to be driven further into the corners of the vanes by the air.

Several changes were also made to the air outlet. First, the air exit was moved downstream of the liquid drain port to move it to a region beyond the liquid containment section. Second, two air outlet ports were employed to slow the airflow and reduce the likelihood of entraining shear. Third, the air exit ports were ‘stove-piped’ into the cavity to create a sharp ledge and form a geometric pinning barrier further resisting liquid carryover at the air exit. Wetting barriers such as surface coatings could also have been employed but were not. The final design also added a third, opposing capillary vane to direct liquid back toward the liquid drain port and re-adhere spurious rogue droplets that manage to escape past the capillary vanes.

Rev F was tested in July and August 2007 over a wider range of flow conditions than previous test articles, using DI water, Ethanol and FC-72. The helix of the test article holds approximately 12ml of liquid, while the vanes store approximately 15ml. The liquid priming line of the test stand held up to 9ml.

Test results representative of the performance during the flight week with all three liquids are presented in Table 1. As is shown, complete separation was achieved regularly with all three liquids. Two-phase behaviors for the liquids during stable reduced gravity flight are shown in Figure 11, Figure 12 and Figure 13. Mirror images are shown to match the sketch in Figure 10.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Air flow (l/min)</th>
<th>Liq. flow (ml/min)</th>
<th>Flow ratio</th>
<th>Liq. injected (ml)</th>
<th>Liq. drained (ml)</th>
<th>Carryover (ml)</th>
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<tr>
<td>DI Water</td>
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<td>7</td>
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<tr>
<td></td>
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<td>40</td>
<td>98</td>
<td>12</td>
<td>9</td>
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</tr>
<tr>
<td></td>
<td>5.2</td>
<td>30</td>
<td>173</td>
<td>9</td>
<td>8</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Ethanol</td>
<td>5.2</td>
<td>30</td>
<td>173</td>
<td>10</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.9</td>
<td>20</td>
<td>195</td>
<td>6</td>
<td>5</td>
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<tr>
<td></td>
<td>3.9</td>
<td>20</td>
<td>195</td>
<td>6</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>FC-72</td>
<td>3.9</td>
<td>50</td>
<td>78</td>
<td>12</td>
<td>6</td>
<td>&lt;1</td>
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<tr>
<td></td>
<td>3.9</td>
<td>40</td>
<td>98</td>
<td>12</td>
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</tr>
</tbody>
</table>

As the liquid exited the helix, it formed blobs that built up until the air shear pulled the liquid away from the surface and drove it into the capillary storage vanes. Both figures show that the majority of the liquid is contained at the ‘base’ of the test article (as oriented in the photos), but a small portion of the liquid would travel along the length of the vanes. Nearly all of the liquid remained connected and would drain nominally. On occasions where slight carryover was detected it could be confirmed by observations that it was attributable to isolated drops uncharacteristically entrained into the air flow in the finned section, or from liquid drops adhering around the stove-piped exit ports.
The C-9 flight campaigns have shown that a Static Phase Separator can be designed to accommodate both the high contact angle pinning effects and the low contact angle spreading effects. The design elements required to achieve separation include:

1) a helix with an ice-cream-cone-shaped cross section to remove free liquid droplets and generate a continuous guided rivulet flow,
2) a seamlessly joined expansion section to reduce air flow velocities and connect the helix with the capillary collection and containment section,
3) a set of capillary vanes that hold the fluid and move the fluid passively to regions of increasing fin density near the fluid exit port,
4) an orientation of the fin section relative to the coil section that causes the air flow to push the fluid into the tips of the fin section, requiring that the air flow make at least two full 90° turns.

The sub-scale test article will be further developed to achieve robust, total air and liquid separation. The first improvement will be to increase the size of the sub-scale test article vane region such that the air volume is greater while at the same time maintaining the volume occupied by the liquid vanes. This will also serve to locate the air exit ports further away from the capillary vanes, helping to decrease further the probability of carryover. Additionally, the capillary pumping geometry of the liquid drain will be improved to reduce residual liquid hold-up. Finally, urine fouling studies will be continued to characterize the nature of urine fouling and the subsequent impact on contact angle. Then appropriate solutions to any negative impacts will be determined, including design rules for similar hardware, and procedures for pretreatments, usage, flushing and other maintenance. A full-scale test article has been proposed for an early CEV flight as a Detailed Test Objective experiment.

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**CONTACTS**

Evan Thomas: evan.a.thomas@nasa.gov
John Graf: john.c.graf@nasa.gov
Jeff Sweterlitsch: jeffrey.j.sweterlitsch@nasa.gov
Mark Weislogel: mmw@cecs.pdx.edu