Screen Channel Liquid Acquisition Devices for Cryogenic Propellants

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Abstract

This paper describes an on-going project to study the application screen channel liquid acquisition devices to cryogenic propellant systems. The literature of screen liquid acquisition devices is reviewed for prior cryogenic experience. Test programs and apparatus are presented to study these devices. Preliminary results are shown demonstrating bubble points for 200x1400 wires per inch and 325x2300 wires per inch Dutch twill screens. The 200x1400 screen has a bubble point of 15.8 inches of water in isopropyl alcohol and 6.6 inches of water in liquid nitrogen. The 325x2300 screen has a bubble point of 24.5 inches of water in isopropyl alcohol, 10.7 inches of water in liquid nitrogen and 1.83 inches of water in liquid hydrogen. These values are found to be in good agreement with the results reported in the literature.

Background

Under the influence of earth's gravity, buoyancy normally dominates the separation of liquid and vapor inside a container, that is, the liquid (heavier fluid) settles to the bottom while the vapor (lighter fluid) rises to the top. In the reduced acceleration or gravity environment of space surface tension, rather than buoyancy, can become dominant in determining the relative positions of liquid and vapor propellants. In low gravity, as the liquid-vapor interface shape assumes the minimum surface and potential energy position, the liquid tends to wet or migrate along the walls or interior structures within the tank. In a cylindrical tank the liquid-vapor interface assumes the shape of a half-sphere in zero gravity; whereas, in the case of a spherical container, liquid-vapor interface becomes spherical, that is, the liquid actually encapsulates the vapor.

The propulsion systems of most vehicles require single-phase propellant delivery since two-phase flow in the propulsion system leads to cavitation and engine damage. During the high acceleration engine thrust periods, single-phase expulsion is accomplished simply by withdrawing liquid from the bottom of the tank and utilizing an anti-vortex baffle over the tank outlet. However, in low gravity where fluid is not centered over the tank outlet, withdrawing single-phase fluid becomes a challenge. On current upper stages such as the Centaur, small storable propellant thrusters are used to create acceleration and position the fluid over the tank outlet for second or third main engine firings. The Space Transportation System (STS) or Space Shuttle auxiliary propulsion system utilizes a bipropellant system (N2O4 and MMH) for orbital maneuvering (Orbital Maneuvering System or OMS) and for attitude control (Reaction Control System or RCS). Capillary liquid acquisition devices (LADs) within the Shuttle OMS and RCS tanks have proven quite successful in assuring delivery of single-phase propellant to the engine. Considerable experience exists with LADs for storable propellants and a variety of shapes, sizes, and combinations can be used, depending on the mission application.

One type of LAD, referred to as a vane, is a lightweight structure with high surface area. Multiple vanes are located in a central region of the tank and are configured such that the vapor is positioned, by capillary action, in preferable positions. Liquid is wicked down the vane and into a capillary trap that supplies liquid for engine restart. Another, more prevalent type LAD is a screen channel device (used on the Shuttle for auxiliary propulsion). Screen channel devices closely follow the contour of the propellant tank wall (typically within 0.25 inches) and can be of either a rectangular or triangular cross-section. Usually, four channel legs (one per tank quadrant) are used and manifolded together over the tank outlet or feed-line entrance. The channels are positioned such that one or more channels are always in contact with the liquid along the tank wall, independent of the liquid-vapor positions. This property of always being in contact with the liquid is called "total communication." The channel side that faces the tank wall has multiple openings that are covered with tightly woven screen. As pressurized outflow or expulsion begins in reduced gravity, surface tension forces within the screen weave tend to block the outflow of vapor and allow the passage of liquid as propellant. As discussed later, wicking action assures that the screens surfaces remain wetted and that the vapor blocking effect is sustained provided other conditions are satisfied.

Through previous and current applications, analysis and design techniques for storable propellant screen channel LADs have been well established (see references 15 and 16). The resistance to vapor passage is dependent on the surface tension retention ability of the screen. The

capillary pressure resistance to vapor passage, or delta P, is described in terms of the well-known equation $\Delta P = 2 \times$ surface tension divided by pore radius. Thus, the smaller the effective pore size of the screen, the greater the surface tension retention capability. The capillary retention capability is also termed the "bubble point." Bubble point is property of the screen/fluid combination. It is defined as the pressure differential across the screen at which a bubble breaks through when one side of the screen has liquid against the surface and the vapor side of the screen is pressurized with vapor. (The gas pressure on the gas side of the screen is higher than the liquid pressure on the other side). The larger the bubble point, the better a screen-channel LAD can withstand vapor penetration or spillage of liquid due to acceleration perturbations. Also, the finer mesh or high bubble point screens tend to wick more readily. The mesh weave refers to the number of wires per inch in each direction. The weave pattern, the over/under pattern used in manufacturing the screen, is an important parameter affecting the choice of screen; that is, certain weaves are capable of producing much finer pore sizes than other weaves. Joining the screen to the channel without damaging it or leaving a larger pore size gap along the edge can be challenging. However, several manufacturers have developed techniques to do so. Also, it should be noted that screen materials, upon manufacturer delivery, are typically lot checked for bubble point performance with isopropyl alcohol (IPA) as opposed to using the hazardous storable propellants directly. Relationships on the behavior of LADs in storable propellants and isopropyl alcohol (IPA) are sufficiently understood that the bubble point data can be reliably scaled to the storable propellants. Hence, comparisons with historical IPA data is a convenient means for calibrating one's bubble point measurement technique and for assessing the capillary retention capability of various screen samples.

It is important to note that bubble point is not the only characteristic that must be considered when choosing a screen and LAD configuration. If the cumulative flow resistance (across the screen, along and through the feed system) exceeds the bubble point, breakdown and vapor ingestion can occur. Thus, screen small screen pores improve the bubble point but increase the pressure drop during outflow.

Environmental concerns over the use of storables are leading to examination of non-toxic cryogenic propellants for on-orbit propulsion on reusable launch vehicles. Additionally, cryogenic upper stages offer the advantages of higher performance as compared with storable or solid propellant propulsion systems. Therefore, the application of capillary LADs to cryogenic propellants has become highly desirable. However, the application of LADs to cryogenics is complicated by the reduced gravity interaction of internal tank thermodynamics with capillary retention. Pressurization gases, liquid saturation conditions, vapor entrapment, tank pressure control/venting, and heat transfer are issues/conditions that must be addressed. Compared with storable propellants, the experience level with LADs for cryogenic applications is indeed meager. The experience and database is primarily limited to bench testing with screen samples, i.e., no flight experience exists. Historically, ground-testing emphasis has been on liquid hydrogen and some of the data is conflicting. Very little data exists with liquid oxygen or a simulant, liquid nitrogen. Therefore, the need for additional cryogenic data is apparent.

Review of the Literature

Early Work

The need for a device to separate liquid and gas in zero-g was recognized early on in the space program. Radcliffe and Transue[1] discuss its importance in restarting an engine in low gravity. Unterberg and Congelliere[2] address the problem with regards to construction of space nuclear power plants but provide a good overview of issues applicable to all applications. Hall[3] discusses in detail a design concept for providing liquid hydrogen for fuel cells in zero-g and shows a drawing remarkably similar to modern total communications screen channel designs although the porous barrier material used to separate liquid and gas is never clearly identified. Many proposed solutions looked at the use of capillary forces including standpipes vanes, and perforated plates. Screens were often considered as weight saving devices capable of replacing a solid surface. Clodfelter and Lewis[4] investigated their effectiveness in this role via zero gravity test. Clodfelter[5] summarizes early air force work and discusses its application to electric propulsion feed systems. Reynolds[6] in his early work on low gravity behavior discusses the theory of capillary restraint of liquids and uses the example of floating a screen on a body of liquid as an example (this experiment can be easily repeated with the correct screen sample and a glass of water). He also includes a photo of a screen acting as a barrier to liquid motion in zero-g from KC-135 testing. Paynter et al.[7] review the extensive research of the Martin-Marietta Company on low-gravity fluid behavior culminating in the design of an engine restart sump for the Titan Transtage. Work on an attitude control system for the transtage resulted in a patented design very similar to modern total communication screen devices. Borass et al.[8] describe an elaborate design capable of restraining liquid during a gaseous vent, but discuss more general design concepts as well. Barksdale and Paynter[9] explored the effectiveness of perforated plates instead of screens. The Agena stage also contains a sump protected by screens and represents an early use of Dutch twill (a fabric weave

capable of producing a very fine pore size) screens. Morgan et al.[10] in their orbital tanker design consider a screen concept to control cryogenic liquids in very large tanks, but find the uncertainty in screen performance too high to risk committing it to the baseline design. Blatt et al.[11] continue the analysis designing a hydrogen trap for Saturn IV engine restart and a total communication LAD for a liquid oxygen resupply tanker. The lessons learned from this study are also collected into a design handbook.

Shuttle Era

Desire for an all-cryogenic space shuttle design and space tug led to extensive work in the '70s on cryogenic screens for liquid acquisition devices. Paynter[12] documents extensive development testing of his acquisition system for earth orbital propulsion systems. Burge and Blackmon[13] study screen channel designs to support shuttle auxiliary propulsion and a space tug like vehicle. Cady[14] expands on the work of Burge and Blackmon to include fuel reactant storage. He also includes some of the first data on the bubble point of fine mesh Dutch twill screens in liquid hydrogen. As budget and schedule pressures increased cryogenic options for the space shuttle were abandoned in favor of storables. The storable systems designed still make extensive use of screen channels (see Gaines and Orton,[15] Fester[16] for final shuttle designs). Blatt and Walter[17] examine the use of screens for the Shuttle based Centaur upper stage. The trap design selected is continued in Blatt and Riseberg.[18] Liquid hydrogen testing was attempted. Unfortunately facility and funding problems prevented this test from obtaining conclusive results.

Non-Toxic OMS/RCS

As the space shuttle continues to operate system trades have identified the continued use of toxic storable propellants as one of the major cost drivers for the shuttle program as well as a major safety risk. Hurlbert et al.[19] summarizes the results of many trade studies from 1980 to 1996 and identifies a liquid oxygen and ethanol propulsion system as the leading replacement. Return to a liquid oxygen system has renewed interest in cryogenic screen performance. Two major aerospace contractors conducted preliminary design trades. Results of these studies are reported in Bailey and Uney[20] and Lak et al.[21] Both designs include liquid oxygen LADs. This paper's authors personal discussions with the design teams indicated that there was almost no data on screen performance with liquid oxygen. Furthermore the size and scope of the systems were not considered in prior work (The early shuttle designs are close but their use of a hydrogen/oxygen propellant combination put a different demands on the oxygen flow rate). As a result of these discussions it was decided to reestablish a program to evaluate LAD and screen performance characteristics.

Approach

Experimental Set-Up

The LAD test hardware consists of a tank within a tank arrangement. The test hardware is installed inside the vacuum chamber at NASA Glenn Research Center's (GRC) Small Multipurpose Research Facility (SMIRF). The vacuum chamber is used to increase the test safety during IPA testing. (The chamber is evacuated and back filled with GN2 to provide an inert atmosphere around the test article during IPA tests.) The vacuum chamber also provides insulation to reduce heat leak during cryogenic tests.

The outer tank (test tank) is a pressure vessel designed to hold the test liquid. The outer tank penetrations provide instrument feed-throughs and pressurant gas and vent connections for both the inner and outer tank. There are two windows in the outer tank. One window provides illumination and the other window is for visual observation with a camera. Fluid level is monitored using a silicon diode rake with the diodes operating either as point or temperature sensing devices (see Dempsey and Fabik[22]). A differential pressure sensor is also used to measure the quantity of fluid in the tank.

The inner tank is cylindrical tank with a flanged lid. The lid consists of a screen sample attached to the sealing flange. Figure 1 shows the inner tank hanging on rods from the lid of the outer tank. The pressurant gas for the inner tank is supplied from a commercial pressure controller. The controller is set up in differential control mode. Supply pressure can be increased or decreased in 12.34 Pa (0.05 inch of water) steps.

During a test, the outer tank is filled with fluid until the lid of the inner tank is covered with fluid. The surface of the inner tank lid (screen) is observed using a camera. A mirror has been positioned in such a way that it is possible to obtain both a side view and top view from a single camera. (See Figure 2.) The pressurant is gradually added underneath the screen in the inner tank until bubbles appear on the surface of the screen.

Control

The initial test plan called for acquiring data at 15 and 45 psia saturated liquid conditions. A pressurant gas control system for the test article that had the ability to provide controlled repeatable pressure steps of 25 Pa (0.1 inches of water) or better was required. In order to obtain accuracy at both pressure levels, a differential

pressure controller was used. The reference port of the differential pressure controller was attached to the tank vent. A commercially marketed pressure control system with a user-friendly interface was purchased for the application.

Instrumentation

The bubble point of the screen must be measured at the screen surface. At first it was thought that a submersible differential pressure transducer was required. The transducer was installed such that the high side of the transducer was plumbed to the gas side of the sample holder and the low side of the transducer was plumbed to the liquid outside the sample holder at the screen surface. The physical geometry of the sample holder and inner tank necessitated locating the pressure tap below the screen surface. Corrections were made to the differential pressure reading to account for the difference in liquid head between the screen surface and the measurement location. The accuracy on the differential pressure transducer had to be 24.6 Pa (0.1 inch of water) or better. The submersible transducer was calibrated at multiple temperatures in order to correct for thermal shifts at cryogenic temperatures. The submersible transducer performed satisfactorily for baseline IPA testing. Despite calibration at with the working fluid at temperature failure of the transducer due to leakage around the diaphragm plagued the program. The transducer was moved outside of the vacuum chamber for subsequent tests.

Results

Screen samples for 325x2300 and 200x1400 Dutch twill screens were prepared and tested. They were tested with isopropyl alcohol, then nitrogen and finally hydrogen. Good results for IPA were obtained after some initial chamber setup problems were resolved. After several false starts mainly having to do with sealing the edge of the screen (epoxy and solder were tried prior to going to an all welded construction) good results for liquid nitrogen were also obtained. Figure 3 shows the screen at the time of breakthrough. A couple of streams of small bubbles can be seen in the upper right portion of the screen at the two o'clock position.

Liquid hydrogen testing proved the most challenging. Unfortunately the liquid hydrogen bubble point is so low maintaining a constant pressure is difficult. Overshoots in pressure on the gas side would result in swarms of bubbles being released through the screen. Careful observation of repeated test was able to isolate the bubble swarm phenomena from the core screen breakdown and estimate a bubble point for the 325x2300 in liquid

hydrogen. Unfortunately for 200x1400 and its lower bubble point pressure this proved impossible.

Preliminary estimates of screen bubble points in all three liquids are shown in table 1. These estimates are based on hand-logged times of events observed during the test. More accurate values will available once the videotape data from the test is synchronized with the pressure data. Reseal pressure is also given; this is the pressure which the chamber had to drop to after the screen had broken through to get the bubble streams to stop. As can be seen from the table there is some hysteresis involved in the reseal process. Usually the pressure had to drop several inches of water before the screen would reseal. Average values are the average of all test performed typically about 30 values (although the hydrogen data is based on only 3 tests). After initial filling the screen pressure would be cycled between breakthrough and reseal resulting in about 15 values per run. Runs with IPA and Nitrogen were repeated. The IPA includes runs before and after cold shocking the screen with liquid nitrogen. The minimum, maximum and standard deviation columns should give the reader a feel for the spread of the data. The authors are quite pleased with the spread of most of the data. The one exception is some of the reseal data. Since our primary interest was breakthrough some of the reseal event times were not recorded as accurately as they should have been leading to a large spread in the pressure data. Review of the video should improve the accuracy of reseal times. Comparison of our results to those reported in Cady[14] show very similar values.

Overall the breakthrough and reseal pressures seem very repeatable and reliable. Test values for IPA and hydrogen are in good agreement with prior work. Liquid nitrogen data represents a new contribution to the open literature. The reseal pressure measurements are also new.

Future Work

The test hardware discussed in this work has shown a good capability for repeatedly and reliably determining screen bubble points. Although NASA has moved from examining shuttle upgrades to designing new vehicles as shuttle replacements, the forces that led to the selection of non-toxic cryogenic propellants for on-orbit operations for shuttle still remain. As a consequence LAD test data still remains important. Our future research plans are focused in two directions. First to rework the facility so that bubble point testing can be conducted with liquid oxygen rather than using nitrogen as a simulant. Second to conduct test on LAD assemblies rather than screen samples. Future papers will report the fruits of these efforts.

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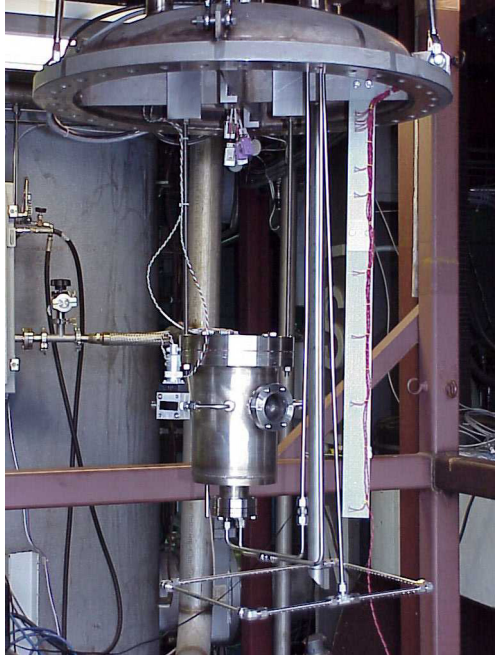
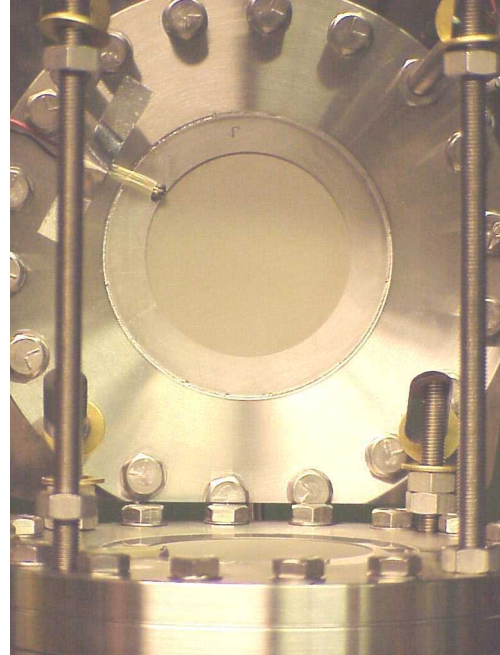Figure 1.—Inner Test Chamber Suspended from Outer Chamber Lid.
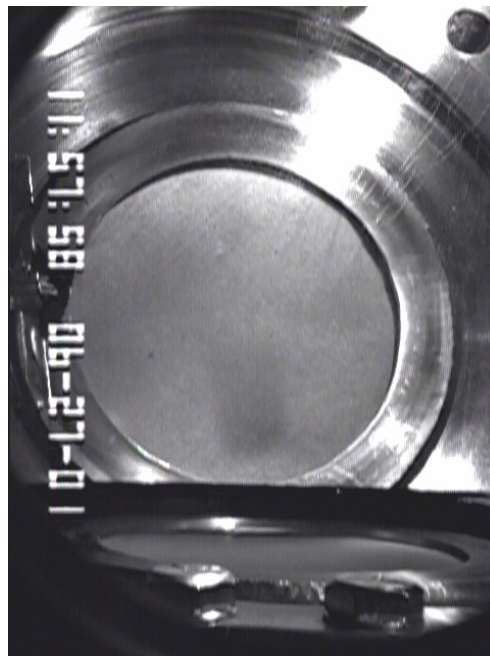

Figure 2.—Screen and Mirror Assembly View.

Figure 3.—Screen Breakthrough During Liquid Nitrogen Test Series 2.

TABLE 1.—SCREEN CHARACTERISTIC PRESSURES (INCHES OF WATER)							
	Bubble Point					Reseal	
Screen mesh	Average	Min	Max	Standard Deviation	Value from Cady[14]	Average	Standard Deviation
IPA							
200x1400	15.78	14.38	17.06	0.55	14.5	13.14	1.58
325x2300	24.54	23.96	25.01	0.24	24.0	17.08	1.96
Liquid Nitrogen							
200x1400	6.63	5.75	7.18	0.34	Not Tested	4.45	0.33
325x2300	10.67	10.00	11.38	0.30	Not Tested	6.62	0.82
Liquid Hydrogen							
325x2300	1.83	1.75	1.91	0.08	1.77	1.03	0.04

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