JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 30, No. 2, March–April 1993

Pressurant Effects on Cryogenic Liquid Acquisition Devices

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On-orbit storage and resupply facilities for cryogenic liquids will likely require surface-tension liquid acquisition devices (LADs) in the storage tanks to provide reliable extraction and transfer of vapor-free liquid. The investigation reported in this paper comprised experiments with a screened-channel LAD in liquid hydrogen to measure the performance of the channel as a function of the type and temperature of the pressurant gas used to expel liquid from the test tank through the LAD. With cold pressurant (near the saturation temperature of hydrogen), vapor penetration of the LAD screen occurred at near the predicted pressure difference across the screen for both helium and hydrogen pressurant, although helium provided better results. With warm helium pressurant, there was no observable degradation in screen performance. With warm hydrogen there was a substantial degradation, and if the LAD outflow was interrupted, allowing the liquid in the LAD to stagnate, vapor penetrated the screen at very low differential pressures.

Introduction

MANAGING liquid propellants and other fluids in microgravity will be an essential element of the on-orbit facilities infrastructure needed to support future operations in space. Space transfer vehicles, Space Station Freedom, space-based defense systems, and serviceable satellites, for example, will require on-orbit servicing to replenish liquid propellants, fuels, coolants, commercial stocks, or life support fluids. Much of the technology required for storing and transferring significant amounts of these fluids in microgravity remains under development and is yet to be demonstrated. This is especially true regarding cryogenic liquids: For liquid hydrogen, oxygen, and nitrogen—which are important for in-space propulsion and life support systems—data describing the thermal and dynamic phenomena involved in storage and transfer in space are quite limited.

One important aspect of in-space fluid transfer is acquisition of vapor-free liquid from a storage tank. In the absence of gravity or acceleration forces to settle the liquid contents of a tank over the outlet, special devices must be used to transfer the liquid out of the tank. Bellows, bladders, and capillary (surface-tension) devices have been used effectively with non-cryogenic liquids. With cryogens, surface-tension devices (e.g., screen-covered channels) appear to be the best approach because heat conduction may form unwanted vapor bubbles within bellows and bladders. Further development followed by an in-space demonstration is necessary, however, for cryogenic applications. Liquid hydrogen in particular imposes potentially troublesome design constraints because of its low surface tension and ease of vaporization.

A liquid acquisition device (LAD) employing fine-mesh screen would usually be designed to serve either as a "total communication" LAD for withdrawing liquid from one tank for transfer into another or as a "start basket" in a propellant tank in an upper stage booster for providing vapor-free propellant during engine startup until the thrust settles all of the propellant. In either application, wherever vapor contacts the wetted screen, the surface tension at the liquid-vapor interface within the small pores in the screen inhibits the passage of vapor through the screen. Figure 1 shows a drawing of a total communication LAD in a spherical tank.

Although screen LADs are currently used routinely with ambient-temperature liquid propellants (for example, on the Space Shuttle orbiter[1]), it has been recognized that using them with cryogens entails special problems that must yet be fully understood before screen LADs are applied in cryogenic systems.[2-4] Foremost among these are the potential adverse effects of heat on the LAD: vapor penetration of the screen due to screen "dry out," and formation of vapor bubbles within the LAD by evaporation. Possible sources of heat are warm pressurant gas or heat leak into the tank from the environment. This paper discusses experiments conducted with screen samples and a screened-channel LAD to investigate the effects of pressurant temperature and species on the liquid retention capability of an LAD.

Prior Investigations

In the past two decades, several investigations of the application of LADs with screens to cryogenic liquids have been done. Among the earliest is one reported by Burge and Blackmon,[5] in which they tested the liquid-retention capabilities (i.e., ability to sustain a pressure difference across the screen by preventing vapor from passing through into the LAD) of samples of fine-mesh screens in liquid hydrogen (LH_2) when subjected to warm pressurant. In their experiments the pressurant was hydrogen vapor, which had been evaporated from the screen and was then blown by a small fan through a heater

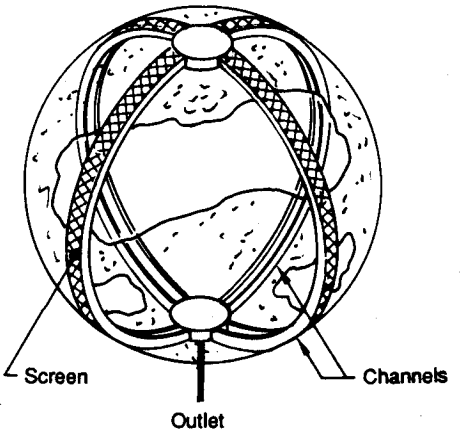

Fig. 1 Total communication LAD.

Presented as Paper 89-2844 at the AIAA/ASME/ASEE/SAE 25th Joint Propulsion Conference, Monterey, CA, July 10–12, 1989; received Nov. 28, 1989; revision received Dec. 3, 1991; accepted for publication Dec. 3, 1991.

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toward the screen. In contradiction to the results of previous experiments with LN_2 in the same apparatus, they found that warming the pressurant by only 5–10 K above the bulk liquid temperature caused premature breakdown of the screen. For gas temperatures above 30 K, the reduction in liquid-retention capability in the screens leveled out at a maximum reduction of about 70%.

Burge and Blackmon subsequently conducted two additional experiments and obtained seemingly conflicting results. Screen sample tests in a different apparatus designed to provide more accurate control of pressurization rate and heat flux showed no premature screen breakdown for pressurant temperatures up to 40 K, the maximum tested. In these tests the heater was placed just a short distance above the screen, but there was no fan and hence no forced convection. In another experiment, a screen basket was first submerged in LH_2 and then raised inverted into hydrogen gas of various temperatures. When the gas temperature was 40 K the gas soon broke through the screen and the basket drained, but in some cases (with the gas temperature 30 K or less) the basket retained the liquid until the gas pressure was allowed to drop below the vapor pressure of the liquid.

Blackmon[6] later tested a screen LAD in LH_2 in a "minus-1 g" configuration—that is, by withdrawing the liquid up through the LAD and out the top of the tank—and found that warm pressurant, whether hydrogen or helium, resulted in premature screen breakdown. The reduction in retention capability was as much as 70% with hydrogen pressurant, whereas with helium the reduction was only about 20%. Moreover, in some cases with warm pressurant there was sufficient heat conduction into the LAD through fittings and solid portions of the LAD that liquid inside the channel vaporized, resulting in almost no retention capability at all. Tests with cold pressurant—at close to the hydrogen saturation temperature—yielded generally better than predicted results with no premature screen breakdown. There was, however, more variability in the screen retention capability with hydrogen pressurant than with helium.

Using the same apparatus as Burge and Blackmon used for their second series of screen sample tests, Cady[7] later conducted additional heatload tests on several different screens in LH_2 to measure their bubble points when subjected to various calibrated heating rates. He found that, even at heating rates greatly exceeding the worst an LAD would be subjected to, the maximum reduction in screen bubble point was less than 15%—a result consistent with that of the less-extensive testing by Burge and Blackmon with that apparatus. Wicking through the screen and evaporation at the screen surface effectively absorbed the heat. This was in spite of the test conditions being deliberately established in many instances so the liquid beneath the screen was superheated with respect to the local liquid pressure.

Page et al.[4] and Warren et al.[8,9] conducted minus-1 g expulsion tests with LH_2 in a 63.5-cm-diam spherical tank fitted with a total communication LAD comprising eight screened channels. In tests during which the outflow was continuous, no instances of screen breakdown occurred, regardless of whether the pressurant was hydrogen or helium, or whether it was warm or cold. On the other hand, during tests in which the expulsion was done in stages, with hold periods alternating with periods of outflow, screen breakdown occurred repeatedly with warm hydrogen as the pressurant, but not at all with warm helium pressurant. The pressure difference across the screen imposed by hydrostatic head and screen flow-through loss, although not measured, was probably not more than 80% of the bubble point of the screens used in the LAD. Warren et al.[9] concluded that either hydrogen or helium may be used as pressurant as long as there are no stagnant regions within the LAD.

The most recent LAD experiments with LH_2 are tests reported by Bennett[10] of the liquid-retention capability of a 34-cm-high start basket. For each test the start basket was initially submerged in liquid, and then the liquid level was lowered to below the bottom of the basket and held there so that the basket was completely surrounded by the pressurant gas. The bubble point of the start basket screens was nearly twice the hydrostatic head of a 34-cm column of LH_2 in 1 g. Tests were conducted both with gaseous hydrogen and with helium as the pressurant. In all the tests with hydrogen pressurant—which was cooled to about 90 K prior to injection into the test Dewar—the screen failed even before the liquid level was lowered to the bottom of the basket. On average, the hydrostatic head at the point of failure was 50% of the normal bubble point of the screen in LH_2. With helium pressurant the liquid level could always be lowered below the basket, and subsequent retention of liquid in the basket was demonstrated for periods up to 3 h.

Objective

The purpose of the experiments reported in this paper was to obtain better quantitative measurements of the behavior of screened LADs in LH_2 under various pressurant conditions. Specifically, the objective was to measure the effects of the following factors on the breakdown pressure difference for a screened-channel LAD: 1) pressurant type—helium, normal hydrogen, or para-hydrogen; 2) pressurant temperature; and 3) degree of liquid stagnation in the LAD channel. One reason for making these measurements was to determine why the heatload tests on screen samples generally showed little degradation of screen performance, whereas LADs subjected to warm pressurant break down prematurely. A further motive was to quantify the differences in LAD performance that result from whether the pressurant is hydrogen or helium and to determine the reason for the difference. Also, we wished to determine if LAD performance with hydrogen pressurant depends on whether para-hydrogen or normal hydrogen (75% ortho-hydrogen and 25% para-hydrogen) is used. An on-orbit system could be designed for either one. Pressurant stored in high-pressure tanks at ambient temperature would have approximately the normal composition; pressurant generated by vaporizing stored liquid would be virtually all para-hydrogen.

Warm-Pressurant Tests with Screen Samples

Prior to fabricating an LAD channel for conducting experiments in LH_2, we conducted tests of the retention capability of several single- and double-screen configurations.[11] The purpose was to determine if using two slightly separated screen layers would provide increased liquid-retention capability in the presence of warm pressurant gas. The results showed that a double screen was no better than a single screen in this regard, and in one case was worse, even though with cool pressurant the double screen did show an increased breakdown pressure as expected.

We present a description of these screen tests because the results contribute to the discussion later in this paper of the factors relevant to premature screen breakdown with warm pressurant. Tests were conducted in Freon 113 with four 8-cm-diam test coupons, one with a single screen layer backed with perforated plate and the remainder with different arrangements of two screen layers. All of the test coupons were made with 325×2300 double dutch twill weave stainless steel screen, which has a pore size of approximately 10 μm.

Two of the double-screen coupons were made of two screen layers sintered to perforated backing plates and separated by a small gap. In one case the screens faced the gap, and in the other the screens faced outward. The third coupon was made by sintering two layers of 325×2300 screen to a pleated 22×22 square weave screen sandwiched between them.

Figure 2 shows a diagram of the test setup. The screen coupons were clamped and sealed to the face of a hemispherical Pyrex fixture, which was submerged in Freon. The fixture was gradually pressurized with filtered dry nitrogen. An electric heating element was used to heat the nitrogen, and radiation shields prevented direct radiation heating of the test coupons.

At the start of a test, the power to the heater coil was adjusted so that the desired steady-state temperatures were obtained at the thermocouples just below the screen surface. The pressure was raised slowly until the nitrogen broke through the test coupon.

Figure 3 shows a plot of the average values of the measured bubble points in Freon 113 vs pressurant temperature. Reduction of the bubble point of the single screen as the pressurant temperature was raised was minimal, similar to the results Cady[7] obtained with screen samples in LH_2. Because the pressurant was nitrogen, the partial pressure of Freon in the test fixture was well below the Freon saturation pressure; therefore, Freon was continuously evaporating from the liquid surface in the screen.

The retention capability of all of the double-screen coupons decreased with increasing pressurant temperature, and they essentially performed like a single screen when the pressurant temperature was above 100°F. This occurs because, as when the single-screen bubble point is reached, the pressurant penetrates the outer screen until all of the liquid is pushed out of the gap (thereby making the second screen share the pressure difference across the test coupon and permitting the first to reseal), and then the warm pressurant evaporates the liquid in the outer screen. This causes it to unseal, leaving only the inner screen as an effective barrier.

The bubble point of the pleated-screen sandwich dropped even below that of a single screen. With this configuration, when the outer screen dries out and heats up, the pleated screen conducts heat directly into the wires of the inner screen. This warms the wires sufficiently above the liquid surface temperature to degrade the bubble point, probably as a result of Freon vaporization at the junctions of the liquid-vapor interface with the screen wires.

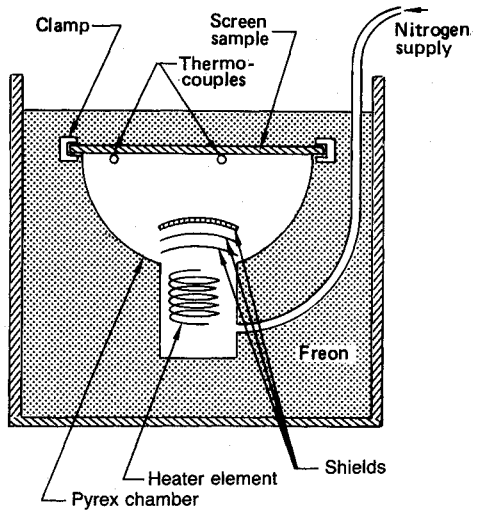


Fig. 2 Fixture for screen heatload tests.

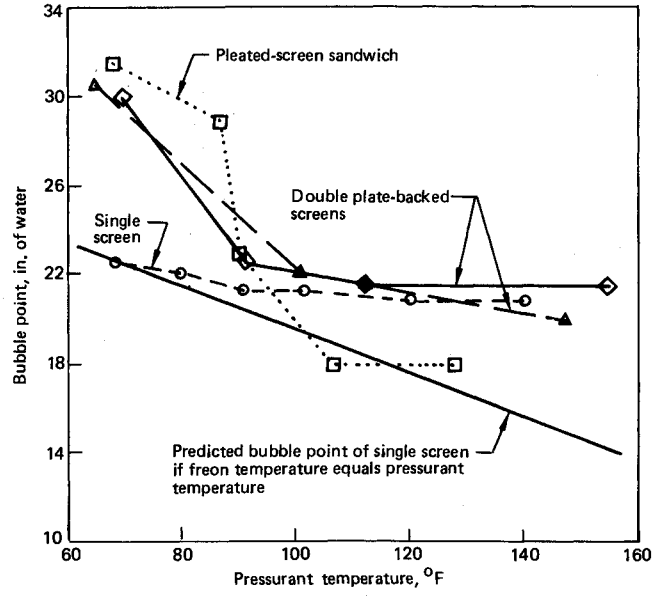


Fig. 3 Bubble point of screen samples in Freon as a function of pressurant temperature.

Experiment Apparatus and Procedure

Apparatus

The LAD channel fabricated for this experiment consists of a semicircular channel 1.7×7.4 cm in cross-section with a 15-cm radius of curvature. Figure 4 shows it installed in the experiment apparatus. The outer face of the channel is a 325×2300 double dutch twill weave screen bonded to a perforated plate having 58% open area. The channel, perforated plate, and screen are made of stainless steel.

Figure 5 is a schematic of the experiment. The LAD was mounted inverted in a cylindrical tank, with the outlet at the top of the tank. This tank, which is referred to as the LAD tank, was immersed in a vacuum-jacketed "guard" Dewar that was filled with LH_2 to provide a stable thermal environment for the LAD tank. The experiment involved pressurizing the LAD tank to expel the liquid in it up through the LAD and into an outlet in the guard Dewar, which provided a stable back pressure to the LAD outflow. The pressure difference ΔP_s across the LAD screen at the top of the channel was carefully controlled to enable us to determine its magnitude at the moment screen breakdown occurred.

The differential pressure at which a 325×2300 screen breaks down in liquid hydrogen is several times the hydrostatic pressure head obtained with the channel entirely uncovered. To produce a controlled ΔP_s large enough to cause screen breakdown, we attached a straw (stainless-steel tube) containing a small orifice to the lower end of the LAD and fitted a Viscojet in the LAD outflow line. The liquid outflow was continued through the straw after the liquid level dropped below the LAD screen. The pair of flow restrictions then created a pressure attenuator that permitted controlling ΔP_s between zero and the maximum LAD breakdown pressure (about 0.5 kPa, or 70 cm of hydrostatic head of LH_2) by

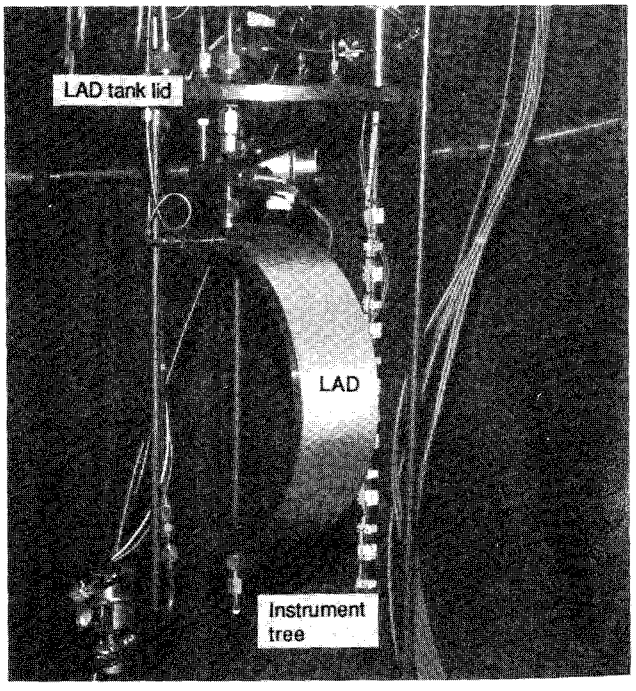


Fig. 4 LAD channel installed in experiment apparatus.

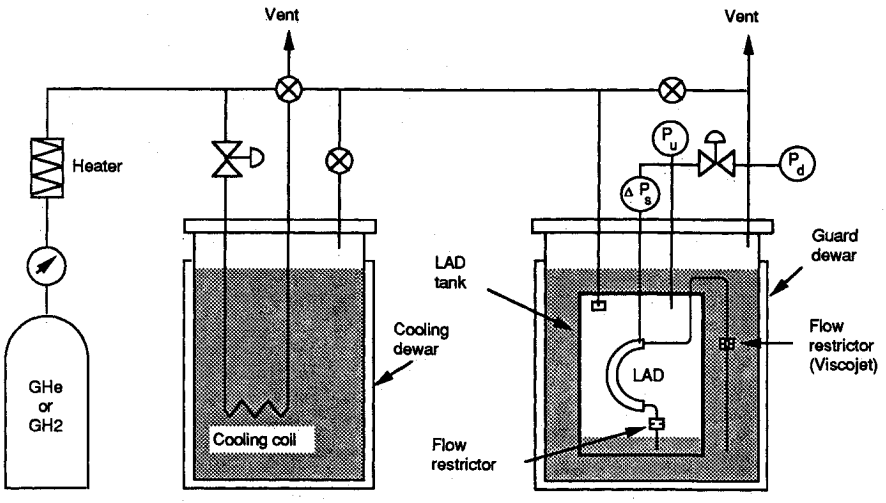


Fig. 5 Schematic of LAD experiment apparatus.

regulating the pressure in the LAD tank across the much wider range of 100–200 kPa.

To provide a direct measurement of ΔP_s, a differential pressure transducer with a range of ± 350 cm of LH_2 was connected between the LAD tank ullage and a pressure tap in the top of the LAD. This transducer had to be located outside of the guard Dewar to avoid cooling it below its normal operating temperature. To reduce the potential for pressure oscillations resulting from hydrogen condensing and evaporating in the 0.3-cm-diam line connecting the LAD pressure tap with the transducer, the line was filled with helium prior to the start of each test. A pair of absolute pressure transducers measured the ullage pressure P_u in the LAD tank and the guard Dewar pressure P_d.

The cylindrical tank containing the LAD was 48 cm long and 25 cm in diameter. The LAD with the attached tube at the bottom extended from 10 cm below the top of the tank to within 1.3 cm of the bottom, and an instrumentation tree with eight copper-constantan thermocouples and 15 platinum-resistor liquid level sensors spanned approximately the same distance.

The guard Dewar was a 130-l vacuum-jacketed vessel 68 cm long and 46 cm in diameter. The LAD tank was sealed and then suspended from the guard Dewar cover. In tests where relatively warm ullage conditions were desired, the liquid level in the guard Dewar was set so that a little more than half of the LAD tank was immersed (medium fill level in the guard Dewar), whereas in cold-temperature tests the tank was completely immersed (high fill level in the guard Dewar).

Three different gases were used as pressurant: helium, normal hydrogen, and para-hydrogen. The helium and normal hydrogen were supplied from high-pressure bottles. When it was necessary to chill either of these gases, the gas was routed through a copper coil immersed in a 75-l LH_2 Dewar. When warm pressurant was required, the gas was routed instead through a coil immersed in a 300 K water bath.

The 75-l Dewar also served as the para-hydrogen pressurant supply. Warm helium was passed through the coil in the Dewar, thereby evaporating the liquid hydrogen in the Dewar to produce the cold para-hydrogen gas used to pressurize the LAD tank.

Procedure

At the start of each test, the Dewars and LAD tank were filled to the desired levels, with the LAD tank always being filled to a liquid level above the top of the LAD so that any vapor trapped in the LAD during the fill process would be swept out when outflow was started. The LAD tank was generally filled through a line containing a 7-μm filter to ensure that no particulates large enough to clog the 10-μm screen pores entered the tank.

For the tests using bottled pressurant, a low-pressure regulator was manually set to a higher pressure than needed to exceed the LAD retention capability. For the tests using cold pressurant, the gas was first vented until the pressurant temperature just upstream of the LAD tank inlet had stabilized. Once the pressurant was thermally conditioned, the LAD tank was pressurized and liquid outflow was started.

In continuous expulsion tests, the LAD tank pressure was generally held constant until the liquid level had dropped below the bottom of the LAD screen. Then, with all of the flow going through the tube at the bottom of the LAD, the LAD tank pressure was ramped up until the screen broke down. Breakdown was indicated by a vapor sensor in the LAD outlet line and by a sharp drop in ΔP_s.

In stepped expulsion tests, the LAD outflow was stopped

Table 1 Summarized data for continuous expulsion tests done with modified experiment apparatus

Test no.	Pressurant	Outflow rate, l/min	T_{in}, K	T_u, K	Predicted ΔP_s, cm LH_2	Measured ΔP_s, cm LH_2
1A-1	Para-hydrogen	2.6	100–110	36	72[a]	67
1A-2	Para-hydrogen	3.0	100–115	31	72[a]	71
1A-3	Para-hydrogen	2.0	105–130	35	72[a]	70
1A-4	Para-hydrogen	3.9	80–90	38	72[a]	59
3A-1	Normal hydrogen	2.7	24–45	28	70[a]	80[c]
5A-1	Helium	2.8	25–35	22	75[a]	78
5A-3	Helium	2.3	30–50	29	75[b]	81
5A-10	Helium	2.5	90–110	32	75[b]	78
5A-11	Helium	2.2	80–105	35	75[b]	85
5A-13	Helium	2.2	65–95	33	75[b]	82

[a]Based on interface temperature corresponding to ullage pressure at breakdown.
[b]Based on interface temperature corresponding to initial ullage pressure (105 KPa).
[c]Screen partially blocked by frozen contaminants.

when the liquid level was halfway down the LAD. That condition was held for 5 to 10 min. If the screen did not break down during the hold time, outflow was restarted and the remainder of the outflow was done as in the continuous tests.

We conducted two sets of continuous expulsion tests and one set of stepped expulsion tests. For the first set of continuous expulsions and for the set of stepped expulsions, we filtered the ΔP_s signal with a low-pass filter that had a 10-Hz cutoff frequency. The recorded data were nonetheless quite noisy, presumably due to pressure oscillations induced by cavitation in the orifice in the inflow tube at the bottom of the LAD. For the second set of continuous expulsions, we installed a 0.5-Hz filter, which enabled considerably more accurate determination of the value of ΔP_s when screen breakdown occurred. We also changed the Viscojet in the outlet line to one with 50% lower flow resistance. The data from this last set of tests are presented first in the following discussion of the experiment results.

Results

Continuous Expulsions

The results for the continuous expulsions done with a 0.5-Hz filter on the ΔP_s signal are summarized in Table 1. The primary data in the table are the values of ΔP_s and the ullage temperature, T_u at the moment of LAD breakdown. Also given are the temperature of the pressurant upstream of the diffuser, the average outflow rate, and the predicted breakdown pressure based on the measured LAD bubble point.

The outflow rates listed are averages deduced from the total time required for the liquid level to fall from the uppermost liquid level sensor, located above the top of the LAD channel, to a lower one located approximately 3 cm above the bottom of the channel. For most tests the flow rate was steady during this portion of the test.

The predicted values of ΔP_s for LAD breakdown were calculated by correcting the previously measured (in isopropyl alcohol) LAD bubble point for the surface tension of para-hydrogen. Included in the correction was the strong functional dependence of the surface tension on the interface temperature (at 20 K the variation is 9%/deg). When the pressurant was hydrogen, the interface temperature had to equal the hydrogen saturation temperature at the LAD tank pressure. With helium pressurant, the interface temperature depended on the hydrogen partial pressure in the tank ullage near the screen, which could only be less than or equal to the vapor pressure corresponding to the temperature of the liquid within the LAD. In other words, the interface temperature had to be less than or equal to the bulk liquid temperature.

In the continuous expulsion tests with para-hydrogen pressurant the LAD behavior was consistent and repeatable, but breakdown occurred at relatively low pressures. In tests 1A-1 through 1A-4, ΔP_s at screen breakdown ranged from 71 to 59 cm of LH_2. In 1A-1 through 1A-3, the breakdown pressures nearly equaled the expected values, but in 1A-4 the result was almost 20% lower than expected. In 1A-4, however, the ullage was nearly 10 K warmer than in the other tests. The outflow rate was very high and the LAD tank wall was relatively warm due to a lower liquid level in the guard Dewar. Therefore, T_u was as high as 40–44 K during much of the expulsion, even though the pressurant came in relatively cold (at less than 90 K). In the other tests with para-hydrogen, the maximum T_u occurred at the end of the tests and ranged from 31–36 K.

The continuous expulsions using helium pressurant also yielded consistent and repeatable results, with clearly better LAD performance than with hydrogen pressurant. The breakdown pressures for the helium tests ranged from 85–78 cm of LH_2. The enhancement in retention for the helium tests can be explained by the depression of the partial pressure of hydrogen at the liquid-vapor interface. This results in a lower surface temperature and a higher surface tension. For test 5A-1, in which breakdown occurred at the lowest pressure for a test with helium, the breakdown pressure corresponds to a surface temperature 1.3 K lower than it would have been with hydrogen pressurant. The highest breakdown pressure obtained, which was in test 5A-11, corresponds to a surface temperature 2.5 K lower than it would have been with hydrogen pressurant.

Table 1 also shows the data for continuous expulsions with normal hydrogen used as the pressurant. The LAD behaved much differently with this pressurant. Except in test 3A-1, there was no clear indication that the LAD screen had broken down in any of the tests with cold normal hydrogen. Another characteristic of the normal hydrogen pressurant tests was that the ΔP_s transducer generally read a pressure difference that was progressively higher than usual during the time the liquid level was above the bottom of the screen. Usually the flow losses were negligible during that part of the expulsion, with the pressure difference entirely due to the height of the raised column of liquid in the LAD. We believe the anomalous behavior resulted from the supply of gaseous normal hydrogen containing small amounts of other gasses that froze on the screen and also froze into particulates that partially plugged the Viscojet and the orifice in the straw.

There is no apparent reason why the breakdown pressure with normal hydrogen pressurant should be noticeably higher than that with para-hydrogen. Differences in surface tension and saturation temperature between para-hydrogen and normal hydrogen, assuming that a layer of liquid normal hydrogen forms at the interface, might yield only a 1–2% higher retention capability with normal hydrogen pressurant.

Table 2 shows the data from the first set of continuous expulsions, which, as already noted, were done with a 10-Hz filter on the ΔP_s signal and with a higher-resistance Viscojet in the outflow line. Although the breakdown pressures could only be approximately determined, the results are consistent with those presented in Table 1. With normal hydrogen, we observed LAD breakdown during several tests in which the pressurant gas was warm. In two of these tests, 3-5 and 3-7, ΔP_s at breakdown appeared to average about 70 cm of hydro-

Table 2 Summarized data for continuous expulsion tests done with original experiment apparatus.

Test No.	Pressurant	Guard Dewar fill level	vented?	Ullage rate, l/min	Outflow T_{in}, K	at LAD breakdown T_u, K	at LAD breakdown Measured ΔP_s, cm LH_2
1-1	Para-hydrogen	High	No	2.6	>160	46	<30[a]
1-2	Para-hydrogen	High	No	2.8	115–180	41	<30[a]
1-3	Para-hydrogen	High	No	2.9	70–80	30	~70
1-4	Para-hydrogen	High	No	2.8	65–75	31	~70
1-5	Para-hydrogen	High	Yes	2.4	75–80	34	~70
3-1	Normal hydrogen	High	Yes	2.4	285–295	42	~30
3-5	Normal hydrogen	Medium	No	1.0	290–300	74	~70
3-7	Normal hydrogen	Medium	No	2.0	290–295	68	~70
5-3	Helium	High	Yes	2.9	75–80	26	~80
5-4	Helium	High	Yes	2.8	75–105	31	~80
5-5	Helium	Medium	No	2.7	290–300	43	~80

[a]LAD broke down before the liquid level was lowered below the LAD screen.

gen. Notably, the ullage gas was very warm in these tests: T_u at breakdown was 74 K in one and 68 K in the other. As a result, we would have expected a premature breakdown in both because in test 1A-4 premature breakdown occurred with para-hydrogen pressurant that was much cooler. Hence, contaminant gasses freezing on the screen probably affected these tests also.

There was one test with normal hydrogen, test 3-1, in which the LAD broke down at a low ΔP_s. In this instance, the LAD tank was vented during the expulsion to control the tank pressure, and the pressurant flow through the ullage increased the heat transfer from the ullage to the LAD screen. This was an unrealistically severe condition, so we did not vent the ullage in the other normal hydrogen tests.

The para-hydrogen tests listed in Table 2 exhibited premature breakdown on several occasions. In tests 1-1 and 1-2, the screen broke down before the liquid had dropped below the bottom of the screen, which means that they broke with ΔP_s less than about 30 cm of hydrogen. In these tests the para-hydrogen pressurant entered the LAD tank at well over 100 K, and T_u was over 40 K when the screen broke. In tests 1-3 through 1-5 the pressurant entered at much colder temperatures, and breakdown did not occur prematurely.

Test 5-5 is the only test in which warm helium pressurant was used, and breakdown occurred at essentially the same pressure difference as in tests 5-3 and 5-4 with cold helium.

Stepped Expulsions

Table 3 shows the results for tests in which the outflow was interrupted. In these tests the expulsion was stopped midway through, with the liquid level halfway down the LAD, and then held for several minutes before being restarted. Tests 2-1 and 2-2 were with para-hydrogen, 4-1 and 4-3 were with warm normal hydrogen, 4-4 was with cold normal hydrogen, and 6-1 and 6-2 were with helium. In test 2-1, during the hold period cold para-hydrogen pressurant was admitted into the LAD tank at a rate sufficient to maintain the pressure at 140 kPa (5 psig). The LAD did not break down during the hold, and the expulsion was restarted. The LAD broke down after the liquid level dropped below the bottom of the LAD, but before the pressure was ramped up. ΔP_s was about 35 cm of hydrogen.

Test 2-2 was similar to test 2-1 except that during the hold period the LAD tank vent was partially opened, so that more gas flow was required to maintain the pressure at 140 kPa. The LAD appeared to break down less than 1 min into the hold period, and the outflow could not be restarted.

In test 4-1 the pressurant was warm normal hydrogen, and T_u was 43 K when the liquid outflow was stopped. During the hold period, the LAD tank vent was opened sufficiently to require a pressurant flow rate of 1.2 g/s to maintain the pressure at 140 kPa. The LAD broke down within 10 s.

Test 4-3 was the same as test 4-1, except that the LAD tank was vented to 105 kPa (0.5 psig) when the outflow was stopped, and the pressurant flow through the tank and out the vent was set at 0.5 g/s. The vapor sensor indicated vapor in the outlet line almost immediately, but ΔP_s did not drop to zero until about a minute later. T_u was only 32 K when the flow was stopped, and it decreased during the hold. Since the pressure was allowed to drop to 105 kPa, it may be that the rapid vapor indication was due to boiling in the outlet line.

Test 4-4, with cold normal hydrogen, included two hold periods. First the outflow was stopped as usual when the liquid level was halfway down the LAD. The LAD tank inlet and vent were then closed, and the pressure subsequently fell to 105 kPa. The vapor sensor indicated vapor in the LAD outlet line immediately, and in less than a minute ΔP_s fell to zero. However, when the tank was repressurized to 140 kPa 5 min later to restart the expulsion, the LAD reseated and outflow was re-established. The outflow was stopped a second time after the liquid level had dropped 2.5 cm further. This time the vent was opened slightly to allow pressurant to pass through the ullage at 0.5 g/s, and the pressure was maintained at 115 kPa. Again the LAD broke down, and then reseated when the outflow was restarted 3 min later.

The last two tests, numbers 6-1 and 6-2, were done with helium pressurant. In 6-1, the interruption in the outflow was held for 9 min, during which the tank pressure was maintained at 140 kPa. During the hold the ullage temperature was uniformly about 20 K (during these tests the LAD tank was completely submerged in liquid hydrogen), and little helium had to be added to maintain the pressure. The LAD did not break down during the hold. Outflow was then restarted and, at the termination of the test, the usual value of ΔP_s (with helium) was achieved before breakdown occurred.

During the hold period in test 6-2, we opened the vent slightly and passed 0.5 g/s of helium through the ullage. The temperature of the helium as it entered the tank varied from 80 to 150 K. Again the LAD did not break down, and after 8 min the expulsion was resumed. As in the previous test, the ullage temperature was uniform at about 20 K, in spite of the continuous inflow of warmer gas.

Discussion

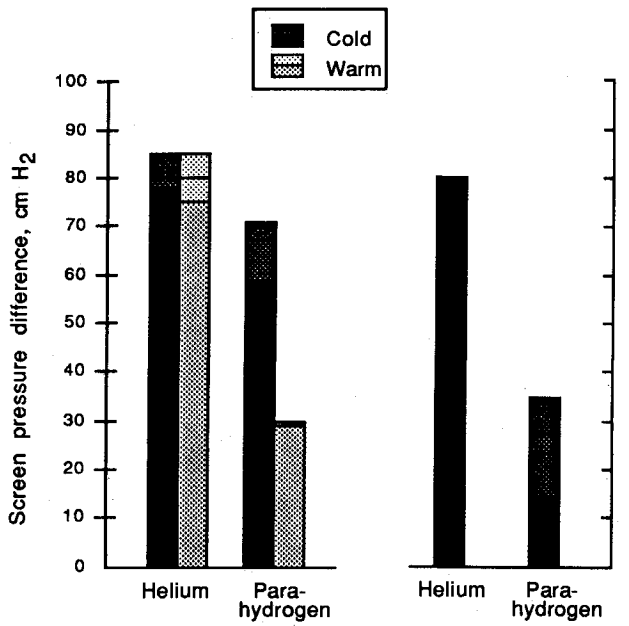
The experimental results are summarized by the bar graphs in Fig. 6. It is clear that with warm helium pressurant the retention capability of the LAD is much higher than with warm hydrogen. In fact, there were no tests with helium, either warm or cold, in which the screen broke down at a ΔP_s significantly less than predicted. With hydrogen pressurant, however, ullage temperatures of 40 K or higher caused premature breakdown in the continuous expulsion tests, and stagnant liquid in the LAD caused premature breakdown in the stepped expulsion tests.

Figure 7a is an illustration of the LAD screen and the liquid-vapor interface showing the heat and mass transfer that occurs when the pressurant is hydrogen. A heat balance at the interface indicates that condensation will occur there when liquid is flowing through the LAD. The flowing liquid is cooler than the interface, and it continuously carries away the latent heat of condensation deposited at the interface. The

Table 3 Summarized data for stepped expulsion tests

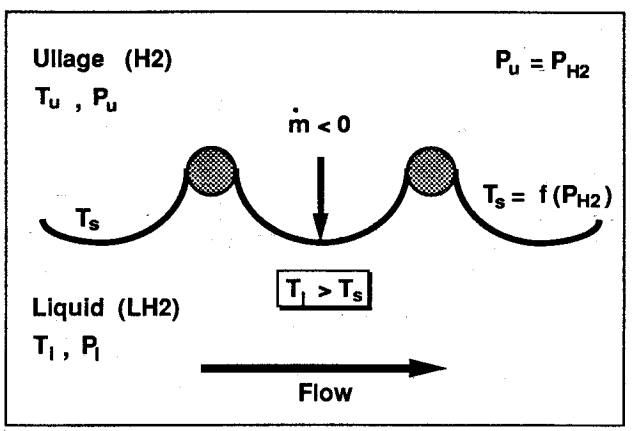
Test No.	Pressurant	Guard Dewar fill level	During hold period: Ullage vented?	P_u, kPa	Pressurant rate, g/s	T_{in}, K	T_u, K	at LAD breakdown: Measured ΔP_s, cm LH_2
2-1	Para-hydrogen	High	No	140	N/A	65–70	24–28	~35
2-2	Para-hydrogen	High	Yes	140	N/A	60–65	23–25	14[a]
4-1	Normal hydrogen	Medium	Yes	115–145	1.1–1.5	290	40–54	14[a]
4-3	Normal hydrogen	Medium	Yes	105	0.3–0.5	295	28	14[a]
4-4a	Normal hydrogen	High	No	105	N/A	N/A	22	14[a]
4-4b	Normal hydrogen	High	Yes	115	0.28	115–140	22	14[a]
6-1	Helium	High	No	135	N/A	100–120	20	~80
6-2	Helium	High	Yes	125–135	0.28	80–150	20	~80

[a]LAD broke down during hold.

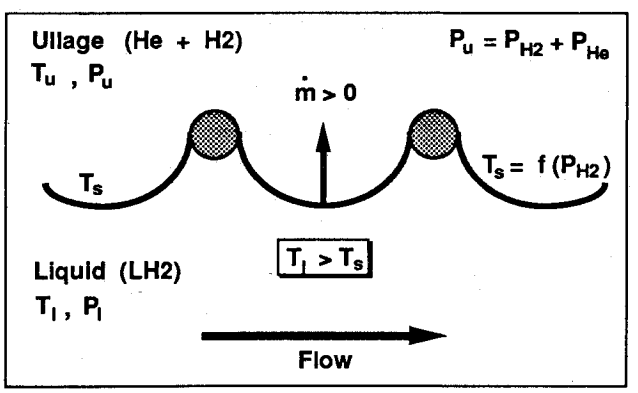


a) Continuous expulsion b) Stepped expulsion

Fig. 6 Summary of test results.



a) Hydrogen pressurant (condensation)



b) Helium pressurant (evaporation)

$$\dot{m} = K_1(T_l - T_s) - K_2(T_u - T_s), \text{ where } K_1 >> K_2$$

Fig. 7 Energy balance at screen surface.

liquid-side heat transfer term is so much larger than the gas-side term that it dominates in this case. The liquid directly behind the screen wires will be warmed to near or above the surface temperature by heat conduction through the wires. Since the liquid pressure behind the interface will be lower than the ullage pressure, due to the pressure difference across the screen, there is a good possibility that the liquid close behind the wires will be in a slightly superheated state.

In this condition the stability of the interface is quite sensitive to changes in the rates of heat transfer to and from the interface and the screen. A slight increase in the temperature of the screen wires could cause bubbles to form on the liquid side of the screen and thereby detach the liquid surface from the wires. The results of our single- and double-screen coupon tests in Freon lend support to this contention. A heat balance on the wire shows that an increase in the gas-side heat transfer or a decrease in the liquid-side heat transfer could each cause the wire temperature to increase. In our experiment, when we increased the gas-side heat transfer coefficient by flowing additional gas through the ullage, the screen broke down earlier; when we decreased the liquid-side heat transfer coefficient by stopping the liquid flow through the LAD—in the stepped expulsion tests—the screen also broke down early.

Figure 7b illustrates the conditions at the screen and liquid-vapor interface when the pressurant is helium. The difference from the situation shown in Fig. 7a is that the helium in the ullage will lower the partial pressure of the hydrogen at the interface and thus lower the interface temperature. If the partial pressure is below the saturation pressure of the bulk liquid, then evaporation will occur at the interface. Increasing the ullage temperature will increase the evaporation rate. The evaporation at the interface will cool the liquid near the screen wires, tending to make it slightly subcooled instead of superheated.

Conclusions

We conducted a series of tests on a single semicircular LAD channel with 325 × 2300 fine-mesh screen to measure how the breakdown pressure across the screen is affected by the temperature and type of the pressurant gas. The tests were conducted in LH_2 with the channel inverted so that the liquid flowed upward through the channel and out the top of the test vessel, against the hydrostatic pressure gradient. Tests were made with both continuous and intermittent outflow. The pressurants tested were helium, normal hydrogen, and para-hydrogen.

With helium, no measureable variation in the LAD performance was observed as the pressurant conditions were changed. In every test, the breakdown pressure was close to the value predicted from the screen bubble point previously measured in alcohol.

With hydrogen, however, the LAD exhibited strong sensitivity to pressurant temperature. With a cold ullage the breakdown pressure was about as predicted, which is slightly less than with helium. This difference is due to the higher liquid surface temperature (and consequently lower surface tension) that occurs to maintain thermodynamic equilibrium with the hydrogen pressure in the ullage. With a warm ullage, the breakdown pressure was significantly reduced; ullage temperatures as little as 15–20 K above saturation caused sharp reductions in the LAD liquid-retention capability. Measurement of the LAD performance with normal hydrogen pressurant was inconclusive due the presence of contaminant gases in our normal hydrogen supply. Nevertheless, we observed no evidence of heating of the LAD screen due to conversion of ortho-hydrogen to para-hydrogen on the screen.

Evaporative cooling appears to be the mechanism underlying the high tolerance to heated hydrogen pressurant observed by other investigators in experiments conducted with individual screen samples. Those observations contrast with the results of actual LAD tests with hydrogen pressurant, in which

low tolerance is observed, but are similar to LAD test results with helium. During liquid expulsion using an LAD, condensation occurs on the LAD screen when hydrogen is the pressurant, whereas evaporation was occurring in the screen sample experiments. Evaporation from the LAD screen does take place, on the other hand, when the pressurant is helium. This provides cooling that significantly moderates the heating of the screen by the warm pressurant; condensation produces the opposite effect.

When the pressurant was hydrogen, interrupting the liquid outflow and stagnating the liquid in the LAD caused a severe reduction in liquid retention capability, even with the ullage temperature only a few degrees above the bulk liquid temperature. Breakdown repeatedly occurred shortly after the outflow was interrupted, when the differential pressure was just 20% of the usual breakdown pressure with cold pressurant. In some cases, it appears that vaporization within the LAD channel was inducing the breakdown.

The results from these tests help to clarify the reasons for the differences in LAD behavior observed under various pressurant conditions. An issue requiring further investigation is how screen heating alters the attachment of the liquid surface to the screen wires and induces premature breakdown.

Acknowledgment

We would like to express our thanks to Al Kacaroski, Bill Hadley, and Al Quant of the Boeing Tulalip Test Site for their help in performing the liquid hydrogen testing.

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