Bubble Point Measurements With Liquid Methane of a Screen Channel Capillary Liquid Acquisition Device

*John M. Jurns*
ASRC Aerospace Corporation, Cleveland, Ohio

*John B. McQuillen*
Glenn Research Center, Cleveland, Ohio

*Joseph D. Gaby, Jr.*
ASRC Aerospace Corporation, Cleveland, Ohio

*Steven A. Sinacore, Jr.*
Glenn Research Center, Cleveland, Ohio

March 2009
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at [http://www.sti.nasa.gov](http://www.sti.nasa.gov)
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 301–621–0134
- Telephone the NASA STI Help Desk at 301–621–0390
- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320
Bubble Point Measurements With Liquid Methane of a Screen Channel Capillary Liquid Acquisition Device

John M. Jurns
ASRC Aerospace Corporation, Cleveland, Ohio

John B. McQuillen
Glenn Research Center, Cleveland, Ohio

Joseph D. Gaby, Jr.
ASRC Aerospace Corporation, Cleveland, Ohio

Steven A. Sinacore, Jr.
Glenn Research Center, Cleveland, Ohio

Prepared for the
54th Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting
sponsored by the JANNAF Interagency Propulsion Committee
Denver, Colorado, May 14–17, 2007
Level of Review: This material has been technically reviewed by technical management.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.
Bubble Point Measurements With Liquid Methane of a Screen Channel Capillary Liquid Acquisition Device

John M. Jurns
ASRC Aerospace Corporation
Cleveland, Ohio 44135

John B. McQuillen
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Joseph D. Gaby, Jr.
ASRC Aerospace Corporation
Cleveland, Ohio 44135

Steven A. Sinacore, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Liquid acquisition devices (LADs) can be utilized within a propellant tank in space to deliver single-phase liquid to the engine in low gravity. One type of liquid acquisition device is a screened gallery whereby a fine mesh screen acts as a “bubble filter” and prevents the gas bubbles from passing through until a crucial pressure differential condition across the screen, called the bubble point, is reached. This paper presents data for LAD bubble point data in liquid methane (LCH₄) for stainless steel Dutch twill screens with mesh sizes of 325 by 2300. These tests represent the first known nonproprietary effort to collect bubble point data for LCH₄.

Introduction

Multiple propellant management devices (PMD) can be utilized within the propellant tank in space to deliver single-phase fluid to the engine in low gravity. Varying acceleration and gravity regimes will probably lead to a system design using multiple varieties of PMDs. One type of PMD, a liquid acquisition device (LAD) uses capillary flow and surface tension to acquire liquid.

Capillary flows LADs have been well characterized for storable propellants (Ref. 1). In recent years, on-going research has evaluated LADs in liquid oxygen (LO₂), liquid nitrogen (LN₂) and liquid hydrogen (LH₂). NASA has determined that liquid methane (LCH₄) is also a promising propellant option for future exploration missions. Understanding LCH₄ characteristics and how it performs in cryogenic fluid systems (including LADs) is critical to advancing technology that would utilize LCH₄ as a propellant.

A number of screen weaves are suitable for use in LADs. The weave pattern, which refers to the over/under pattern used in manufacturing the screen, is an important parameter affecting the choice of screen; certain weaves of wires produce much finer pore sizes than other weaves. The tightness of the weave (mesh) and the weave pattern determine the geometry of the pores in the screen. A given mesh screen is designated by two numbers; the first number refers to the number of shute wires and the second number refers to the number of warp wires. In a Dutch twill screen, each shute wire travels over two warp wires before going under a warp wire. Figure 1 provides detail on the Dutch twill weave pattern. Figure 2 shows a scanning electron microscope (SEM) photograph of a 325 by 2300 mesh Dutch twill screen.
The geometry of the pore and the fluid surface tension determine the bubble point of the screen. “Bubble Point” is defined as the differential pressure across the screen that overcomes the surface tension of the liquid on the screen. A high bubble point (fine screen mesh) is desirable to ensure single phase (liquid) fluid delivery and good wicking of fluid into the screen pores. Fine mesh screens, however, tend to generate a large pressure loss during outflow through the screen. The total pressure loss in the system must be less than the bubble point pressure to prevent vapor ingestion into a LAD channel.

NASA Glenn Research Center has an on-going test program to develop data for LAD performance for a variety of cryogenic propellants (Refs. 2 to 4). This paper presents new bubble point data in LCH₄ for stainless steel Dutch Twill Screens with a mesh size of 325 by 2300. Testing was conducted in 2006 and 2007 at Glenn Research Center’s Creek Road Complex in the Cryogenic Components Lab 7 (CCL-7). It is a small scale cryogenic fuel test stand designed for component screening (Ref. 5).

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>Capillary number = ( \frac{\mu U}{\sigma} )</td>
</tr>
<tr>
<td>( D_p )</td>
<td>Effective pore diameter of the screen weave</td>
</tr>
<tr>
<td>( D_h )</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>NBP</td>
<td>Normal Boiling Point</td>
</tr>
<tr>
<td>( \Delta P_{bp} )</td>
<td>Bubble Point pressure</td>
</tr>
<tr>
<td>( r )</td>
<td>Bubble radius</td>
</tr>
<tr>
<td>( U )</td>
<td>Bubble velocity</td>
</tr>
</tbody>
</table>
Liquid Methane Bubble Point Tests

Test Hardware Design

Figure 3 shows the cylindrical test article used for bubble point testing. A screen sample is welded into the flanged top of the test article. The flanged design allows for rapid change out of various screen samples. A mirror aids in viewing the screen surface. Positioning the mirror over the screen surface provides both a side view and top view from a single camera to allow observation of gas bubbles passing through the screen. Instrument taps on the test article connect to pressure transducers external to the dewar and measure differential pressure across the LAD screen as shown in Figure 4. The assembled test article is shown installed inside the dewar in Figure 5.

Screen Size

The LAD screen used for these tests is a 325 by 2300 mesh Dutch Twill screen. The screen is welded to the top flange of the test article shown in Figure 3. The screen itself has a diameter of 2.5 in. (6.25 cm) and a surface area exposed to the liquid of 4.91 in.² (31.7 cm²).
Figure 4.—LAD test article shown inside dewar.

Figure 5.—Test article installed inside the cryogenic dewar.
Test Facility

CCL-7 is a small scale screening facility for concept and component testing. In addition to component screening, the facility can perform propellant transfer, propellant conditioning (warming and subcooling), and vent flow tests. CCL-7 safely handles 300 gal (1130 liter) of both LH₂ and LN₂, and 120 gal (450 liter) of LCH₄. Gaseous helium (GHe) and gaseous nitrogen (GN₂) are available on-site.

Tests can be performed in either a “Supply” or “Receiver” vacuum jacketed Dewar at the facility; although the Supply Dewar is generally used for propellant conditioning. The Supply Dewar is a vertical cylinder with a 22 in. (0.55 m) diameter and 54 in. (1.36 m) height. It has an 11 ft³ (0.32 m³) internal volume and an operating pressure of 40 psia (274 KPa). An instrument rake equipped with silicon diodes provides temperature measurements and liquid level indication. A simplified schematic of the CCL-7 test facility showing Supply and Receiver Dewars at CCL-7 is shown in Figure 6.

For this test program, the LAD hardware shown in Figure 4 was installed in the Receiver Dewar. Fluid supply and vent piping, and instrumentation lines pass through the lid of this Dewar. The diameter of the Receiver Dewar is 22 in. (0.55 m). An instrument rake equipped with silicon diodes provides temperature measurements and liquid level indication. The Receiver Dewar is 42 in. (1.07 m) deep, has an internal volume of 8.1 ft³ (0.23 m³), and has a working pressure of 25 psia (170 KPa). A window in the sidewall is located 22 in. (0.55 m) from the bottom of the dewar.

LCH₄ is transferred to the test facility through a 0.75 in. (20 mm) diameter vacuum jacketed hose and piping from a portable 450 liter liquid methane vacuum jacketed Dewar. The cryogen is transferred either into the Supply Dewar and from there to the Receiver Dewar, or directly into the Receiver Dewar. The Supply and Receiver Dewars can vent either directly to atmosphere or through a series of air ejectors. The ejectors allow the dewars to operate at a minimum pressure of approximately 2.5 psia (17 KPa). The Receiver Dewar vent valve is operated either open loop, or with a proportional—integral—derivative

![Simplified test facility schematic diagram.](image-url)
(PID) loop in the programmable logic controller (PLC) control system, and can control backpressure in the Receiver Dewar to within ±0.05 psi (±0.34 KPa). A separate vent line with an open loop proportional valve is available for test articles installed inside the Receiver Dewar. Gasses evolved during testing from the dewars and test articles can vent directly to atmosphere, or through a series of four mass flow meters. The LAD test article installed inside the Receiver tank has an independently controlled pressurization system. Figure 5 shows a simplified schematic of the LAD hardware installed in the Receiver Dewar.

Instrumentation/Data Acquisition

CCL-7 utilizes a LabView (National Instruments) based data collection system. Up to 320 channels of data can be collected at a nominal rate of 1 Hz. Many of the facility channels are pre-configured for standard instruments including thermocouples, pressure transducers, and silicon diodes. Interlocks, alarms and shutdowns protect the research hardware and the facility. Operator controlled open-loop processes are used to provide flexibility.

Video

It is necessary to observe the LAD screen during test to determine at what differential pressure bubbles break through the screen in order to determine the bubble point pressure. A CCD video camera located in the test facility views the LAD screen through the view port on the side of the Receiver Dewar. The video signal is transmitted to a monitor in the test facility control room, and is recorded on a VHS format video tape. The video data is time stamped and synchronized with the data collected to aid in post test data processing.

Test Objectives/Overview

The purpose of this experimental program was to determine bubble point characteristics of a 325 by 2300 mesh screen LAD by performing bubble point tests in LCH₄. A wealth of data exists for isopropyl alcohol (IPA) that can be correlated to storable propellants, but the database needs to be extended to cryogenic propellants. Bubble point data has been collected for LN₂, LO₂, and LH₂. This is the first known effort to collect LAD bubble point data for LCH₄. Data was collected for both normal boiling point (NBP) and sub-cooled LCH₄. Bubble point was determined by observing the LAD screen via a CCD video camera and correlating the observed bubble breakthrough with concurrently collected sensor data.

Initial check-out tests were performed at the facility using LN₂. Following those tests, LCH₄ was transported on site and connected to the test facility dewars. The LCH₄ was supplied in portable 450 liter dewars filled by an industrial gas supplier. Each shipment of LCH₄ was supplied with a chemical analysis. Details of the LCH₄ specification, supplier, and analysis of a typical delivery are given in Appendix A.

Test Procedure

LAD Screen Bubble Point Tests

For bubble point testing, the LAD test article was placed inside the Receiver Dewar as shown in Figure 5. A precision differential pressure controller was used to pressurize the LAD test article to determine bubble point. The pressure controller was referenced to the dewar ullage pressure. This allowed the controller to set the pressure inside the LAD test article from 0 to 50 in. H₂O (12.44 KPa) above ullage pressure. During fill, the pressure inside the LAD test article was set at approximately 30 in. H₂O (7.47 KPa) above dewar ullage pressure to prevent the test article from flooding. As the dewar filled and the entire screen surface became wetted, surface tension forces also helped to prevent flooding of the LAD test article. The dewar was filled with LCH₄ to approximately 8 in. (20 cm) above the top of the LAD screen. After the fill was complete, the pressure in the dewar was increased from atmospheric pressure to approximately 20 psia (138 KPa) to suppress any boiling of LCH₄. The pressure controller was then used to gradually ramp down the pressure inside the test article until gas bubbles were no longer...
seen coming through the screen. This reseal pressure was noted, and the pressure decreased by several more inches H₂O. The pressure was then gradually increased inside the test article in 0.1 in. of water (0.28 KPa) increments until gas bubbles broke through the screen surface. This bubble point pressure was noted, and the pressurization/depressurization cycle repeated a number of times to obtain additional data. Pressure across the screen surface was measured using sensitive differential pressure transducers.

Fluid Conditioning

Tests were conducted with LCH₄ at two different fluid conditions. For the first series of tests, the Receiver Dewar was filled with LCH₄ from the portable liquid cylinder while the Receiver Dewar was vented to atmospheric pressure, essentially saturating the fluid at NBP conditions. The dewar was then pressurized with GHe for bubble point tests. A second series of tests was performed with subcooled liquid. For these tests, the LCH₄ was transferred to the Supply Dewar. The pressure in the Supply Dewar was reduced using the facility ejectors. This subcooled the LCH₄ to approximately 175 °R (97 K). The Supply Dewar was then pressurized with GHe, and the subcooled LCH₄ transferred to the Receiver Dewar for bubble point testing. The LCH₄ did absorb some heat during transfer, and final liquid temperatures were 186 to 188 °R (103 to 104 K) for subcooled tests.

Test Results/Observations

Eighteen tests were performed with warm LCH₄ saturated near NBP conditions (LCH₄ temperature 201 to 206 °R (112 to 114 K)). Twelve tests were performed using subcooled LCH₄ (temperature 186 to 188 °R (103 to 104 K)). Tests were performed at these two different fluid conditions to evaluate bubble point pressures at several values of surface tension.

Bubble point pressure is calculated using Equation (1) (Ref. 6)

\[
\Delta P_{BP} = \frac{4\sigma \cos \theta_c}{D_p}
\]  

Here, \(\sigma\) is the surface tension of the liquid and \(\theta_c\) is the contact angle of the liquid on the screen material. For LCH₄, \(\theta_c \approx 0\) so \(\cos \theta_c = 1\). The effective pore diameter of the screen weave is \(D_p\). Note that the standard practice for determining the effective pore diameter for a particular screen is to measure \(\Delta P_{BP}\) with a special bubble-point apparatus using IPA as a reference liquid and calculating \(D_p\) for the screen weave from Equation (1). This value of \(D_p\) was used to compute the bubble-point pressure for the 325 by 2300 screen weave and LCH₄. IPA bubble point tests were performed on the identical screen used for this test series (Ref. 7). The \(D_p\) based on that data was determined to be 0.000567 in. (0.0144 mm).

Table 1 shows average values of predicted and measured bubble point pressures from tests.

<table>
<thead>
<tr>
<th>LCH₄ Temperature, °R</th>
<th>Surface tension, (lb/in.)</th>
<th>(\Delta P_{BP}) Measured, (in. H₂O)</th>
<th>Std Dev., (in. H₂O)</th>
<th>(\Delta P_{BP}) Predicted, (in. H₂O)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>204±2</td>
<td>7.463×10⁻³</td>
<td>14.11</td>
<td>0.38</td>
<td>14.59</td>
<td>-3.3</td>
</tr>
<tr>
<td>187±1</td>
<td>8.525×10⁻³</td>
<td>17.37</td>
<td>0.36</td>
<td>16.66</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Comparison With Historical Data

Bubble point data has previously been reported for IPA (Refs. 2, 4, 7, and 8), LH2 (Refs. 2, 4, and 8), LN2 (Refs. 2 and 7), and LO2 (Ref. 7). Predicted values for bubble point pressure were calculated using Equation (1). Cady (Ref. 8) reported bubble point values for LH2 based on liquid saturated at 50 psia (344.7 KPa). Kudlac (Ref. 7) reported bubble point predictions for LO2 and LN2 were based on saturated liquid at NBP. Chato (Ref. 2) did not report fluid conditions, but a review of data from the Chato tests indicated that LN2 temperature was 142.5 °R (79.2 K), and LH2 temperature was 39.6 °R (21.9 K). Using surface tension values for these conditions, predicted bubble point values were calculated using Equation (1). A plot of predicted and measured bubble points versus surface tension for a 325 by 2300 LAD screen is shown in Figure 7. The data are shown in tabular form in Table 2.

Table 2.—Predicted and Measured Bubble Point Pressures

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface tension, (lb/in.)</th>
<th>ΔP_{BP} measured, (in. H₂O)</th>
<th>ΔP_{BP} Predicted, (in. H₂O)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH₂</td>
<td>6.526E-06</td>
<td>1.216</td>
<td>1.285</td>
<td>Cady, 1973</td>
</tr>
<tr>
<td>IPA</td>
<td>1.359E-04</td>
<td>23.9</td>
<td>-----</td>
<td>Cady, 1973</td>
</tr>
<tr>
<td>LH₂</td>
<td>1.087E-05</td>
<td>1.44</td>
<td>2.14</td>
<td>Cady, 1977</td>
</tr>
<tr>
<td>IPA</td>
<td>1.359E-04</td>
<td>24.8</td>
<td>26.75</td>
<td>Cady, 1977</td>
</tr>
<tr>
<td>IPA</td>
<td>1.256E-04</td>
<td>24.54</td>
<td>24.73</td>
<td>Chato, 2002</td>
</tr>
<tr>
<td>LN₂</td>
<td>4.888E-05</td>
<td>10.67</td>
<td>9.62</td>
<td>Chato, 2002</td>
</tr>
<tr>
<td>LH₂</td>
<td>1.028E-05</td>
<td>1.83</td>
<td>2.02</td>
<td>Chato, 2002</td>
</tr>
<tr>
<td>LN₂</td>
<td>4.996E-05</td>
<td>9.6</td>
<td>10.7</td>
<td>Kudlac, 2005</td>
</tr>
<tr>
<td>LO₂</td>
<td>7.537E-05</td>
<td>14.5</td>
<td>14.11</td>
<td>Kudlac, 2005</td>
</tr>
<tr>
<td>IPA</td>
<td>1.256E-04</td>
<td>24.18</td>
<td>-----</td>
<td>Kudlac, 2005</td>
</tr>
</tbody>
</table>

Surface tension values for the current LCH₄ tests were obtained from the NIST thermodynamic fluid property software program GASPAK (Ref. 9). The source in this program for surface tension properties is Sprow & Prausnitz (Ref. 10). In the course of analyzing data from the LCH₄ tests, surface tension values as defined by Fuks & Bellemans (Ref. 11) were also considered. A comparison of these two sources indicates that the Fuks & Bellemans values for surface tension were approximately 3 to 4 percent lower than the Sprow & Prausnitz values. From Equation (1), it is apparent that the predicted values for bubble point pressure would be correspondingly 3 to 4 percent lower.
LCH₄ ΔPₓᵧ Predictions Based on Surface Tension

Equation (1) predicts bubble point reasonably well for NBP liquid. However, as can be seen for the LCH₄ test data summarized in Figure 8, it under-predicts bubble point pressure for subcooled liquid. Although Equation (1) calculates bubble point only as a function of screen pore diameter and surface tension, both Kudlac (Ref. 7) and Dodge (Ref. 6) state that bubble point is also influenced by liquid viscosity and density. However, neither of these terms is included in Equation (1).

In an attempt to improve the correlation for bubble point, we considered other treatments of pressure drop of a bubble through a screen. The bubble point is the maximum pressure that surface tension forces can prevent a gas bubble from flowing through the screen or, viewed differently, the pressure difference at which gas flow through the screen is initiated.

Bretherton (Ref. 12) related the pressure drop for a long bubble through a tube as

\[ \Delta P = 3.58 \left( \frac{3 \mu U}{\sigma} \right)^{\frac{2}{3}} \frac{\sigma}{r} \]  

(2)

Where \( U \) is the bubble velocity, albeit very slow. The value inside the parenthesis of Equation (2) is three times the Capillary Number (Ca). Gauglitz and Radke (Ref. 13) used a similar relationship for bubble traversing through constricted capillaries, similar to those found in porous media. If we view LAD screens as thin porous media and utilize this relationship to evaluate bubble point measurements considering liquid viscosity and surface tension, the result correlates well with data. This is plotted in Figure 8. Note that we did not measure the bubble velocity, but determined it from Equation (2). We note that rather than using the Capillary number (and hence the viscosity) raised to the 2/3 power, if we consider the Kudlac (Ref. 7) and Dodge (Ref. 6) statement that bubble point is also influenced by liquid viscosity and density, and multiply Equation (1) by a normalized kinematic viscosity raised to the 1/3 power as shown in Equation (3), we achieve similarly good results. The advantage of Equation (3) is that it provides good correlation with the data without having to consider bubble velocity \( U \). Resolution of this behavior is ongoing.
\[
\Delta P_{BP} = \frac{4\sigma \cos \theta_p}{D_p} \left( \frac{\nu}{\nu_{NBP}} \right)^{1/3}
\]  

(3)

**LAD Screen Characteristics**

Data presented is from different tests with different screens. Cady tests from the 1970’s report for 325 by 2300 mesh screens with warp and shute wire diameters of 0.0015 and 0.001 in. (0.038 and 0.024 mm) respectively. Cady reports pore diameter = 0.00039 in. (0.0099 mm) absolute, 0.00047 to 0.00049 in. (0.0119 to 0.0124 mm) experimental equivalent pore diameter, where the absolute pore diameter is given by the manufacturer, and the experimental equivalent pore diameter is calculated using Equation (1). Manufacturers’ data from 325 by 2300 screen mesh LAD screens used for NASA GRC tests list the warp and shute wire diameters as 0.0014 and 0.0011 in. (0.0355 and 0.0279 mm) respectively. Kudlac does not report \( D_P \), but it was calculated to be 0.000567 in. (0.0144 mm) based on IPA tests and Equation (1). This same value of \( D_p \) was used in this report. SEM images were taken of the screen used for the LCH4 tests as shown in Figure 2. Scaled measurements from these photographs indicated warp and shute wire diameters of 0.00165 and 0.00098 in. (0.0419 and 0.0249 mm) respectively. Of course, the SEM photograph is only calculated for one small area and cannot be construed as accurate for the entire screen, considering variations in the manufacturing and fabrication of the screen. However, it does corroborate the manufacturers’ data.

In an effort to understand the relationship between \( D_p \) and the physical characteristics of the LAD screen, we examined screen geometry configuration to see if they can be utilized to predict the measured bubble points associated with these screens. The analysis was based on the physical dimensions of the openings or gaps through the screen and the fact that gas phase must constrict to a certain size in order to be able to enter the hole. Three types of holes or gaps were considered: (1) Projections into the top surface of the screen, (2) gaps between two adjacent shute wires at the warp wire and (3) gaps among four adjacent shute wires. Method (1) yields an equivalent diameter of 0.00065 in. (0.0165 mm). Method (2) yields an equivalent diameter of 0.0003 in. (0.0076 mm). Method (3) yields an equivalent diameter of 0.0004 in. (0.0102 mm). Note that method (3) yields a similar value as the 0.00039 in. absolute pore diameter reported by Cady. Details of this analysis are given in Appendix B.

It is apparent that there are variations in screen dimensions between manufacturers and between different batches from the same manufacturer. Although values for \( D_p \) may be inferred from the physical dimensions, the standard method of calculating \( D_p \) using Equation (1) and IPA should be used with the specific screen under consideration when designing LADs.

**Conclusions**

We have shown in this series of LAD tests that LCH4 bubble point data is repeatable and consistent with pre-test predictions for NBP liquid. We also note that Equation (1) appears to under-predict \( \Delta P_{BP} \) for subcooled LCH4. The prediction may be improved by including a kinematic viscosity term as per Equation (3). However, this needs to be evaluated with other cryogenic fluids. Future work may include reanalyzing existing data for LO2, LN2, and LH2 to include this factor. We have investigated the geometry of LAD screens, and agree that screen design parameters should be determined experimentally when designing a LAD for a specific application. LCH4 joins the list of cryogenic fluids that have been characterized with LAD screen channel devices to show that they can consistently deliver single phase cryogenic fluid with system pressure losses less than bubble point pressure for the fluid/screen combination.
References

Appendix A—Liquid Methane Supply

Specifications and Supplier

At the onset of this test program, there was no agreed upon LCH₄ purity specification. Liquefied natural gas (LNG) consists largely of LCH₄, with a number of other hydrocarbon constituents and impurities. Although LNG is widely available throughout the world, NASA had determined that it would be unsuitable for use as a propellant due to variations in properties making predictions of accurate performance impossible. NASA worked with several suppliers to determine what higher purity sources of LCH₄ were available, and to what specification it could be produced and delivered. The LCH₄ supplier worked with NASA to develop the purity specification shown in Table 3. The last column shows the analysis of a typical delivery of LCH₄.

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Specification</th>
<th>Typical Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&lt;2 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>&lt;500 ppm</td>
<td>29 ppm</td>
</tr>
<tr>
<td>Total Atmospheric Gases</td>
<td>--------------</td>
<td>&lt;125 ppm</td>
</tr>
<tr>
<td>Ethane</td>
<td>&lt;30 ppm</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>&lt;50 ppm</td>
<td>&lt;50 ppm</td>
</tr>
<tr>
<td>Propylene</td>
<td>&lt;1 ppm</td>
<td>Other total hydrocarbons</td>
</tr>
<tr>
<td>Ethylene</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Propane</td>
<td>&lt;5 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Sulfur</td>
<td>&lt;0.5 ppm</td>
<td>&lt;0.1 ppm</td>
</tr>
<tr>
<td>Moisture</td>
<td>&lt;1 ppm</td>
<td>&lt;0.05 ppm</td>
</tr>
</tbody>
</table>

Subsequent to the start of this test program, MIL SPEC MIL-PRF-32207 “Performance Specification Propellant Methane” was issued. This specification is shown in Table 4 for comparison. Note that the LCH₄ used for this test most closely matches Grade “C” product.

<table>
<thead>
<tr>
<th>Property</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity (CH₄), % volume, min</td>
<td>A</td>
</tr>
<tr>
<td>Water, ppm by volume, max</td>
<td>B</td>
</tr>
<tr>
<td>Oxygen, ppm by volume, max</td>
<td>C</td>
</tr>
<tr>
<td>Nitrogen, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Carbon Dioxide, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Total atmospheric gases, ppm by volume, max (Ar, O₂, N₂, He, Ne)</td>
<td></td>
</tr>
<tr>
<td>Ethane (C₂H₆), ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Propane (C₃H₈), ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Other hydrocarbons, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Total Sulfur, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Non-volatile residue, mg/L, max</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 4.—MIL-PRF-32207 PERFORMANCE SPECIFICATION PROPELLANT METHANE

<table>
<thead>
<tr>
<th>Property</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity (CH₄), % volume, min</td>
<td>A</td>
</tr>
<tr>
<td>Water, ppm by volume, max</td>
<td>B</td>
</tr>
<tr>
<td>Oxygen, ppm by volume, max</td>
<td>C</td>
</tr>
<tr>
<td>Nitrogen, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Carbon Dioxide, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Total atmospheric gases, ppm by volume, max (Ar, O₂, N₂, He, Ne)</td>
<td></td>
</tr>
<tr>
<td>Ethane (C₂H₆), ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Propane (C₃H₈), ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Other hydrocarbons, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Total Sulfur, ppm by volume, max</td>
<td></td>
</tr>
<tr>
<td>Non-volatile residue, mg/L, max</td>
<td></td>
</tr>
</tbody>
</table>
LCH$_4$ Containers and Delivery

Product produced to this specification was delivered to the NASA Glenn Research Center in 450 liter portable cryogenic dewars. DOT restrictions limited filling of the containers to 360 liter of product. Product was produced near Toledo, Ohio and trucked to NASA Glenn in Cleveland.

Product Purity

Early on in the test program, we noticed some problems transferring liquid between test dewars. We suspected that this may be due to plugging of a filter located in the transfer line between the test dewars. The system was emptied and purged, and the filter was removed. The filter was then washed with a solvent, and the filtrate examined visually and using Energy Dispersive X-ray Spectroscopy (EDS). Visual examination of the filtrate indicated some small metallic particles, and the EDS analysis indicated presence of silicon, aluminum and iron (other elements were detected, but were discounted as being components of the filter paper). We also took SEM photographs of the 10 $\mu$m filter before and after it was cleaned with solvent. Figures 9 and 10 show the filter in the pre-cleaned and post-cleaned condition. After the filters were cleaned, the test system performed well with no further issues.

Figure 9.—10 $\mu$m filter screen before cleaning.

Figure 10.—10 $\mu$m filter screen before cleaning.
Appendix B—LAD Screen Pore Diameter Analysis

Introduction

The purpose of this analysis is to examine if there is the screen geometry configuration can be utilized to predict the measured bubble points associated with these screens. The analysis is based on the physical dimensions of the openings or gaps through the screen and the fact that gas phase must constrict to a certain size in order to be able to enter the hole. Three types of holes or gaps are considered: (1) projections into the top surface of the screen, (2) gaps between two adjacent shute wires at the warp wire, and (3) gaps among four adjacent shute wires.

Bubble Point Calculation

The bubble point is defined as the pressure difference necessary for a gas bubble to overcome the pressure difference imposed by surface tension forces in order for the bubble to enter/pass through an orifice. Mathematically,

\[ \Delta P_{BP} = \frac{4 \sigma}{D_P} \]  

Generally, IPA is used as the fluid of choice to characterize screens by determining the pore size. For the 325 by 2300 mesh, bubble point testing with IPA yielded a \( \Delta P_{BP} = 24.2 \) in H\(_2\)O (6.02 KPa). The resulting pore diameter is 0.000567 in. (0.0144 mm).

Physical Characteristics of 325 by 2300 Screen

The diameter of the “shute” wires is 0.001 in. (0.0254 mm). The diameter of the “warp” wires is 0.0015 in. (0.0381 mm). The configuration of the Dutch Twill wiring is that the “shute” wires are raveled and grouped in combinations of four. Two of these wires are on the top of the screen and two are below. Alternating top and bottom shute wires and redirected towards the other side at alternating warp wires.

Image Analysis for Pore Diameter

A scanning electron microscope image of 325 by 2300 mesh was obtained and is shown in Figure 11. Assuming that the pores are triangular in nature and the projection on the top surface is consistent through the thickness of the screen material, a triangle with the following dimensions are obtained by applying the scaling factor on the SEM image.

Hydraulic Diameter

In order to calculate the “area” of the triangular hole, it is necessary to split the triangle into two triangles that are separated by a line that forms a right angle with the “base” or the side that is 0.00249 in. (0.0632 mm) long. Two equations are then defined using the Pythagorean theorem:

\[ h^2 + b^2 = L_2^2 \]

\[ h^2 + (L_1 - b)^2 = L_3^2 \]
TABLE 5.—325 BY 2300 MESH SCREEN DIMENSIONS FOR CALCULATING HYDRAULIC DIAMETER

<table>
<thead>
<tr>
<th>Side</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>0.00249 in. (0.0632 mm)</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.00221 in. (0.0561 mm)</td>
</tr>
<tr>
<td>$L_3$</td>
<td>0.00083 in. (0.0211 mm)</td>
</tr>
</tbody>
</table>

Where $h$ and $b$ are the height of the triangle and $b$ is the one of the lengths along the base side where the height line intersected the base. The area of the triangle was determined to be $8.99\times10^{-7}$ in.$^2$ ($5.8\times10^{-4}$ mm$^2$). Hydraulic diameter is defined as 4 times the cross-sectional area divided by the wetted perimeter or:

$$D_H = \frac{4 \cdot A}{(L_1 + L_2 + L_3)}$$

For this screen, the resulting value is 0.00065 in. (0.0165 mm)

**Inscribed Circle**

The formula for the radius of a circle inscribe inscribed in triangle as

$$r = \sqrt{\frac{(s-a)(s-b)(s-c)}{s}}$$

Where $s = (a+b+c)/2$ and $a$, $b$, and $c$ are lengths of the triangle legs. $s$ is calculated to be 0.00276 in. (0.0678 mm) leading to an inscribed circle diameter of 0.00065 in. (0.0165 mm) as well.

**Other Geometrical Configurations**

Other geometries were analyzed as well including the gap between shute wires as they pass around a warp wire as shown in Figure 12, and between the four shute wires in the interval between warp wires as shown in Figure 13.
Three diameter “definitions” were analyzed for both cases: Inscribed circle, hydraulic diameter and “equivalent” diameter where the area available for flow was substituted into the definition for area of a circle. The “equivalent” diameter calculated for the case considered in Figure 13 yielded the correlation with historical data.
14. ABSTRACT

Liquid acquisition devices (LADs) can be utilized within a propellant tank in space to deliver single-phase liquid to the engine in low gravity. One type of liquid acquisition device is a screened gallery whereby a fine mesh screen acts as a “bubble filter” and prevents the gas bubbles from passing through until a crucial pressure differential condition across the screen, called the bubble point, is reached. This paper presents data for LAD bubble point data in liquid methane (LCH₄) for stainless steel Dutch twill screens with mesh sizes of 325 by 2300. These tests represent the first known nonproprietary effort to collect bubble point data for LCH₄.

15. SUBJECT TERMS

Cryogenic fluids; Methane; Fluid management; Cryogenic fluid storage; Liquefied gases