Cryogenics 74 (2016) 95–105

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Screen channel liquid acquisition device bubble point tests in liquid nitrogen

J.W. Hartwig *

Cryogenic and Fluid Systems Branch, NASA Glenn Research Center, USA

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 22 September 2015
Accepted 27 September 2015
Available online 9 October 2015

Keywords:
Liquid acquisition devices
Liquid nitrogen
Cryogenic fluid management
Subcooled liquid
Fuel depot

ABSTRACT

The primary parameter for gauging performance of a liquid acquisition device (LAD) is the bubble point pressure, or differential pressure across a screen pore that overcomes the surface tension of the liquid at that pore. Recently, cryogenic bubble point tests were conducted in liquid nitrogen across a parametric trade space to examine the influential factors that govern LAD performance, and 1873 data points were collected. Three fine mesh screen samples (325 × 2300, 450 × 2750, 510 × 3600) were tested over a wide range of liquid temperatures (67–114 K) and pressures (0.032–1.83 MPa), using both autogenous (gaseous nitrogen) and non-condensable (gaseous helium) pressurization schemes. Experimental results in liquid nitrogen are compared to recently reported results in liquid hydrogen, oxygen, and methane. Results indicate a significant gain in performance is achievable over the baseline 325 × 2300 reference bubble point by using a finer mesh, operating at a colder liquid temperature, and pressurizing and subcooling the liquid with the noncondensable pressurant. Results also show that the cryogenic bubble point is heavily affected by enhanced heating and cooling at the screen liquid/vapor interface by evaporation and condensation.

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1. Introduction

Future long duration human and robotic space exploration missions will require efficient methods to transfer high performance cryogenic propellants from a storage tank to a transfer line despite the varying thermal and gravitational conditions of space. Depending on the specific mission requirements, which include acceleration level, direction, and spin, mass flow rate, thermal environment, tank pressure, and desired expulsion efficiency, multiple cryogenic fluid management (CFM) technologies will be required to ensure efficient long term storage and transfer of cryogenic propellants. The two primary customers for integrating advanced CFM technologies are in-space cryogenic engines and future in-space cryogenic fuel depots. A fuel depot is defined as an Earth-orbiting propellant storage vessel which would house cryogenic propellants such as liquid hydrogen (LH_2) or liquid oxygen (LOX) in Low Earth Orbit (LEO) indefinitely [1]. A customer spacecraft could launch from Earth, rendezvous and dock with the depot, and extract propellant en route to the final destination. Fuel depots would therefore allow spacecraft to either reach destinations faster, or allow more of the original launch vehicle mass to be reserved for payload instead of fuel. A depot must be designed to ensure minimal propellant consumption during chilldown of the connecting transfer line and customer spacecraft receiver tank, as well as to achieve a very high final liquid volume fill fraction in the receiver tank. An in-space cryogenic engine requires vapor-free liquid to avoid combustion instabilities during restart and continuous operation, and the future cryogenic depots will require vapor-free liquid due to the high cost of launching and storing propellant in LEO, therefore necessitating the use of propellant management devices (PMDs) in the storage tank upstream.

The purpose of this paper is to present the liquid nitrogen (LN_2) bubble point data, to examine the effect of varying the screen type, thermodynamic state of the liquid (saturated or subcooled), and pressurant gas type and temperature on liquid acquisition device (LAD) performance, and to compare trends here with data collected in liquid methane (LCH_4), LOX, and LH_2. An outline of the paper is as follows: First, a background is given into PMDs, how to gauge performance of PMDs, as well as previously reported bubble point data. Next the experimental design for conducting bubble point tests is presented for both the low and high pressure rigs. Then, instrumentation, data acquisition, uncertainty analysis, and the test conditions are presented. Finally, the LN_2 bubble point data is systematically analyzed and comparisons are made to the different cryogens.

* Address: M/S: 301/3, NASA Glenn Research Center, Cleveland, OH 44135, USA. Tel.: +1 216 433 3979.

E-mail address: Jason.W.Hartwig@nasa.gov

http://dx.doi.org/10.1016/j.cryogenics.2015.09.008
0011-2275/Published by Elsevier Ltd.

Nomenclature

b_0	fitting parameter for temperature dependent pore diameter
c	fitting parameters in the coefficient of thermal contraction
D_P	pore diameter (m)
DPT	raw differential pressure across the screen (Pa)
EE	expulsion efficiency
g	gravity (m/s^2)
L_T	length of a material at temperature (T) (m)
L_{293}	length of a material at 293 K (m)
P	pressure (Pa)
P_{sat}	saturation pressure (Pa)
T	temperature (K)
T_{sat}	saturation temperature (K)
$V_{residuals}$	residual liquid volume at LAD breakdown (m^3)
V_{tank}	volume of tank (m^3)
γ	surface tension (N/m)
ΔP_{BP}	bubble point pressure (Pa)
$\Delta P_{BP,NBP}$	bubble point pressure at normally saturated conditions (Pa)
ΔP_{total}	total pressure drop in LAD system (Pa)
ξ	coefficient of thermal contraction
ρ_{LN2}	liquid density (kg/m^3)
θ_C	contact angle

2. Background

The separation of liquid and vapor phases within a propellant tank is governed by the lowest achievable potential energy state. In 1-g, density of the fluid dictates the location of the vapor and liquid phases because the heavier liquid settles to the bottom and the lighter vapor rises to the top, but in microgravity, surface tension becomes the controlling mechanism because the liquid tends to adhere to the tank walls, leaving a gaseous core in the center of the tank. To ensure the tank outlet is sufficiently covered with liquid during all phases of a mission, multiple PMDs may be required in the storage tank. Of the available types of PMDs [2–4], screen channel liquid acquisition devices (LADs) are by far the most robust and flexible in that they can be designed to sustain any flow rate and supply liquid against any adverse acceleration level at the cost of having the lowest reliability (due to complexity in design) and highest cost and mass.

The purpose of a LAD is threefold [5]: to separate and control liquid and vapor phases within a propellant tank, to maintain communication between liquid and tank outlet during all phases of the mission, and to wick liquid to areas of the screen that dry out due to evaporation. LADs rely on surface tension forces and capillary flow to ensure vapor-free liquid is transferred from a propellant storage tank to the transfer line, despite varying thermal and gravitational conditions of LEO. Depending on mission requirements, multiple LADs may be required to ensure the tank outlet is always covered with liquid. A representative screen channel LAD is depicted in Figs. 1 and 2. Fig. 1 shows a LAD channel used in laboratory scale experiments, and Fig. 2 shows a total communication, full scale assembly of LAD channels. In flight applications, screen channel LADs are designed to closely follow the contours of the propellant tank. Channels are typically composed of three solid walls and one porous side composed of a fine mesh screen with <100 μm sized pores which faces the propellant tank wall. Screen selection for a particular mission [6] is dictated by the desired mass flow rate, maximum adverse acceleration level, and desired expulsion efficiency, defined as:

$$EE = \frac{V_{residuals}}{V_{\tan k}} \quad (1)$$

where $V_{residuals}$ is the residual liquid propellant left in the tank when the LAD breaks down and admits vapor into the transfer line, and $V_{\tan k}$ is the internal volume of the tank. Therefore EE is a measure of how much of the tank is drained through the LAD before the LAD breaks down. The channels converge to a common point over the tank outlet. The tank is drained through the LAD; as the liquid level drops, surface tension forces at the screen generate a localized area of high pressure differential that blocks vapor entrance into the channel, but allow the liquid to flow freely. As long as the pressure differential across the screen does not exceed the bubble point pressure, vapor-free liquid will be extracted from the storage tank. While screen channel LADs have been used in many flight storable propulsion systems (propellants are liquids at room temperature) in Geostationary Operational Environmental Satellites weather monitoring systems, [7], Intel satellites [8] for phones, Miltar satellites [9] for military communication, and most notably in Shuttle Orbital Maneuvering System and Reaction Control Systems [10–13], they have not been used in space flight systems employing LOX or LH_2. Screen channel LADs however have flight heritage in inert cryogens in the Superfluid Helium On-Orbit Transfer (SHOOT) experiment employing Liquid Helium (LHe) [14,15].

Fig. 1. Laboratory scale screen channel liquid acquisition device.

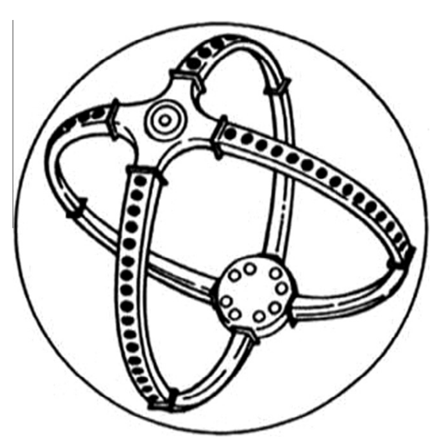

Fig. 2. Total communication screen channel gallery arm.