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Thermal analysis of a cryogenic liquid acquisition device under autogenous and non-condensable pressurization schemes

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ABSTRACT

This paper presents thermal analysis of a 325 × 2300 mesh LAD sample that was tested over a wide range of liquid methane temperatures (106–160 K) and pressures (0.0618–1.78 MPa) for a LAD using both autogenous (gaseous methane) and noncondensible (gaseous helium or nitrogen) pressurization schemes. To compare between schemes, screen interfacial temperatures, screen Reynolds numbers, condensation and/or evaporation mass flow rates at breakdown, and heat fluxes produced at the screen are computed as a function of liquid temperature and pressure. Condensation and evaporation rates are also computed using kinetic theory to allow comparison. Each parameter has a profound impact on surface tension and thus the performance of the LAD screen. The understanding gained here will be used to determine optimal propellant pressure and temperature operating regimes and will help mission designers determine whether autogenous pressurization is feasible for future space missions.

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1. Introduction

All in-space cryogenic propulsion systems require single phase liquid to be delivered to the engine from the storage tank. In the microgravity environment of space, the driving force for phase separation is surface tension. The denser liquid tends to wrap the walls of the storage tank and the lighter vapor tends to reside in an annular core along the centerline. This introduces complications for propellant transfer to the engine because the tank outlet may not be sufficiently covered by liquid. Propellant management devices (PMDs) must be employed to correct for this issue, with one such device being the screen channel liquid acquisition device (LAD). Full communication LADs follow the contours of the tank and have channels which extend along the entirety of the tank walls, enabling liquid propellant to always have a path to the tank outlet. A schematic of such a LAD system is shown in Fig. 1. The principal fluid design goal for propellant transfer applications is for the LAD to have continuous contact with the liquid for any type of vehicle acceleration, all the way to tank depletion [1]. LADs are designed to provide a physical barrier to vapor ingestion into the liquid due to surface tension forces within the micron-sized pores.

LADs are said to have failed when vapor is ingested into the channel, since the purpose of the LAD is to maintain phase separation. Therefore the primary performance parameter for assessing LAD performance is the bubble point or breakdown point. It is the differential pressure across a screen pore required to overcome the surface tension of the liquid at that pore. For cryogenic liquids, a simplified version of the bubble point equation from [2,3] describes the relationship:

$$\Delta P_{BP} = \frac{4\gamma(T)}{D_P} \quad (1)$$

where $\gamma(T)$ is the temperature-dependent surface tension and D_P is the average pore diameter. The LAD screen used in this study was a 325 × 2300 Dutch Twill weave with 325 warp wires per inch and 2300 shute wires per inch of screen material (128 warp and 905 shute per square centimeter).

Recently, liquid methane has received serious consideration for propulsion systems because of its high performance relative to storable propellants (fluids that exist as liquids at room temperature), and because of its lower susceptibility to parasitic heat leak relative to liquid hydrogen (LH_2). Liquid oxygen/liquid methane (LOX/LCH_4) propulsion systems may one day replace toxic storable propulsion systems for in-space systems, such as the proposed Ascent Main Engine Stage (AME) [4] and Reaction Control Systems (RCS) [5], and LADs will be required to extract single phase liquid

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Nomenclature

A	area
B	screen thickness
CV	control volume
D	diameter
f	arbitrary function
g	gravitational acceleration
GCH_4	gaseous methane
GHe	gaseous helium
GN2	gaseous nitrogen
h	enthalpy
J	mass flux
k	fitting parameter for surface tension
LCH_4	liquid methane
l	distance between consecutive wires
m	mass
$\dot{m}$	mass flow rate
n	number of wires per length scale
P	pressure
Q	volumetric flow rate
R	individual gas constant
Ra	radius
Re	Reynolds number
S	characteristic screen length
T	temperature
t	time
U	velocity
V	volume
Z	compressibility factor

Greek letters

γ	surface tension
Δ	change in a parameter
ε	porosity
μ	dynamic viscosity
ρ	density
σ	Schrage model coefficient
Φ	heat flux

Subscripts

0	reference value
bubb	outside bubble
BP	bubble point
C	condensation
ch	chamber
crit	critical
E	evaporation
F	FRITZ
fg	fluid-to-gas
G	gas
I	interface
IN	mass inflow into cup
inert	inertial
P	pore
S	screen
SAT	saturation
SH	shute wire
W	warp wire

in both milli and micro-g environments. In microgravity applications, specifically loitering maneuvers [6], there will be a great need for a full communication LAD which will extend around the entire circumference of the tank.

Previous work has found that autogenous pressurization, or pressurization with the liquid's own vapor, of cryogenic liquids leads to a significant amount of liquid heating [7–9]. Increasing the interfacial temperature lowers the surface tension, which lowers the bubble point pressure, lowering the performance of the LAD. Meanwhile, noncondensible pressurization may evaporate liquid away from the screen, cooling the screen, reducing the interfacial temperature, increasing the surface tension and thus bubble point [10,11]. Studies investigating the effects of autogenously pressurizing a liquid hydrogen system found that the changes in surface tension may be due to thermocapillary flows which affect the meniscus within the screen pore [12,13]. Pressurizing liquid hydrogen with heated hydrogen vapor lead to condensation and induced temperature gradients along the liquid surface. The ensuing thermocapillary flow established a pressure distribution within the interface which deformed the center of the surface into the liquid. The meniscus expanded into the liquid and eventually detached from the screen wires. Similarly, it was observed in [12,13] that pressurizing liquid hydrogen with heated helium lead to evaporation and a thermocapillary flow structure which was opposite to that seen with autogenous pressurization. Autogenous pressurization may carry with it increased efficiency with regard to hardware and mass considerations, and so it is very important to determine if an ideal operating regime exists in which autogenous pressurization is feasible.

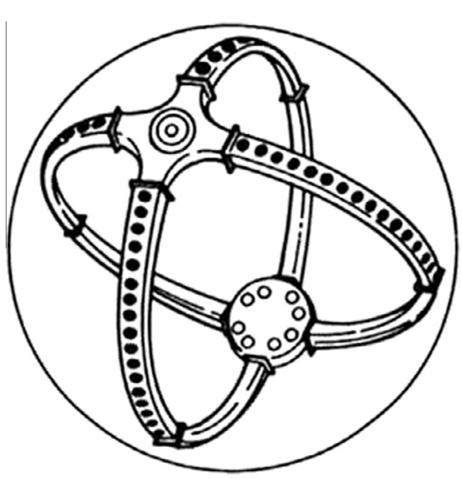

Fig. 1. Full communication LAD.

This study looks at LCH_4 being pressurized autogenously with gaseous methane (GCH_4) as well as using noncondensibles such as gaseous helium (GHe) and gaseous nitrogen (GN_2). While GN_2 is known to be more soluble in LCH_4 than GHe [14], both gases can sufficiently be considered noncondensible over the timescales involved in this experiment. To compare between pressurization schemes, screen interfacial temperatures, screen Reynolds numbers, condensation and evaporation mass flow rates at breakdown, and heat fluxes produced at the screen are computed as a function of liquid temperature and pressure. All of these parameters affect the bubble point pressure and therefore have a marked impact on the effectiveness of the LAD and pressurization system.

2. Test hardware and data acquisition

Thermal analysis in this work is based on previously reported methane bubble point tests from [7], which outlines the bubble