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Screen channel liquid acquisition device outflow tests in liquid hydrogen

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ABSTRACT

This paper presents experimental design and test results of the recently concluded 1-g inverted vertical outflow testing of two 325 × 2300 full scale liquid acquisition device (LAD) channels in liquid hydrogen (LH_2). One of the channels had a perforated plate and internal cooling from a thermodynamic vent system (TVS) to enhance performance. The LADs were mounted in a tank to simulate 1-g outflow over a wide range of LH_2 temperatures (20.3–24.2 K), pressures (100–350 kPa), and flow rates (0.010–0.055 kg/s). Results indicate that the breakdown point is dominated by liquid temperature, with a second order dependence on mass flow rate through the LAD. The best performance is always achieved in the coldest liquid states for both channels, consistent with bubble point theory. Higher flow rates cause the standard channel to break down relatively earlier than the TVS cooled channel. Both the internal TVS heat exchanger and subcooling the liquid in the propellant tank are shown to significantly improve LAD performance.

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1. Introduction

The enabling of all future in-space cryogenic engines and cryogenic fuel depots for long duration human and robotic space exploration missions begins with technology development of cryogenic fluid management (CFM) systems upstream in the propellant tank. Depending on the mission requirements, which include acceleration level, direction, and spin, mass flow rate, thermal environment, tank pressure, and desired expulsion efficiency, multiple CFM technologies will be required to ensure efficient long term storage and transfer of cryogenic propellants. There are two primary customers or applications for CFM technology. In-space cryogenic engines will require vapor free propellant transfer over a wide range of flow rates in milli- and microgravity environments over a wide range of thermal environments. Future in-space cryogenic fuel depots, which are of particular interest in the current work, will also require efficient methods to store (in excess of one year) and transfer liquid hydrogen (LH_2) and liquid oxygen (LOX) from a depot storage tank to a customer receiver tank due to the projected overwhelming cost to launch and store propellant in Low Earth Orbit (LEO).

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2. Background

Gravity affects many fluidic processes, such as the separation of liquid and vapor phases within a propellant tank. In Earth's standard 1-g environment, 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. In microgravity however, 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. In-space transfer of cryogenic propellants begins with extraction of vapor free liquid from the storage tank. In normal gravity, liquid is easily removed from the bottom of the tank. In the reduced gravity of space however, liquid may not sufficiently cover the tank outlet, and so a variety of propellant management devices (PMDs) or liquid acquisition devices (LADs) may be required to favorably position liquid and ullage within the tank.

2.1. Propellant management devices

The primary purpose of a PMD is to transfer vapor free liquid from a propellant tank to a transfer line en route to an engine or receiver tank. The secondary purpose of a PMD is to feed a mixing pump inside a storage tank in order to de-stratify the liquid and provide adequate mixing and pressure control of the bulk propellant. All PMDs rely on surface tension forces and capillary flow to

Nomenclature

C_{min}	minimum heat capacity rate of the hot and cold fluids (W/K)
$c_{p,LAD}$	specific heat of liquid inside LAD channel (J/kg K)
D_p	screen pore diameter (μm)
ε	efficiency of TVS heat exchanger
F	two phase multiplier
h_i	heat transfer coefficient of cold TVS fluid (W/m^2 K)
h_L	heat transfer coefficient assuming all liquid flow (W/m^2 K)
h_{NB}	heat transfer coefficient for nucleate boiling (W/m^2 K)
$\dot{m}_{LAD}$	outflow rate through the LAD channel (kg/s)
NTU	number of heat transfer units
P	tank pressure (kPa)
P_{SAT}	saturation pressure based on the temperature of the liquid at the screen (kPa)
$\dot{Q}$	heat transfer rate between cold TVS fluid and warm LAD fluid (W)
S	nucleate boiling suppression factor
$T_{c,in}$	temperature of the cold liquid inside TVS coil (K)
$T_{h,in}$	temperature of incoming liquid into LAD channel (K)
ΔP_{BP}	bubble point pressure (Pa)
$\Delta P_{BP,NBP}$	bubble point pressure at normally saturated conditions (Pa)
$\Delta P_{dynamic}$	dynamic pressure loss inside LAD channel (Pa)
ΔP_{FTS}	flow through screen pressure drop (Pa)
$\Delta P_{frictional}$	frictional pressure loss inside LAD channel (Pa)
$\Delta P_{hydrostatic}$	hydrostatic pressure drop (Pa)
ΔP_{other}	transient pressure drop terms (Pa)
ΔP_{total}	total pressure loss for LAD system (Pa)
ε	heat exchanger effectiveness
γ	surface tension (mN/m)
θ_C	contact angle

maintain communication between liquid, PMD, and tank outlet. PMDs must be specifically designed for each mission.

PMDs are broken down into three types, namely screen channel gallery arms, vanes, and sponges [1–3]. Screen channel LADs are designed and manufactured in a variety of styles, sizes, and geometries. As shown in Fig. 1, gallery arms tend to closely follow the contour of the propellant tank wall and can have different cross section geometries (typically a triangular or rectangular shape) [1]. The channel side that faces the wall has openings covered with a tightly woven fine mesh screen. The screen has micron sized pores which are used to wick liquid into the channel, prevent pores from drying out during tank drain, and also act as a barrier to vapor ingestion. As liquid is withdrawn from the tank and vapor approaches the screen, 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. Liquid is wicked along the screen and prevents the pores from drying out if they come into contact with vapor. Full communication screen channel LADs (i.e. LADs that extend the entire length of the tank wall to maintain communication with the liquid at all time) have demonstrated flight heritage in storable propulsion (fluids that exist as liquids at room temperature) systems such as the STS Reaction Control System (RCS) and Orbital Maneuvering System (OMS) [4,5], and the design of LADs for storables is well understood [6,7].

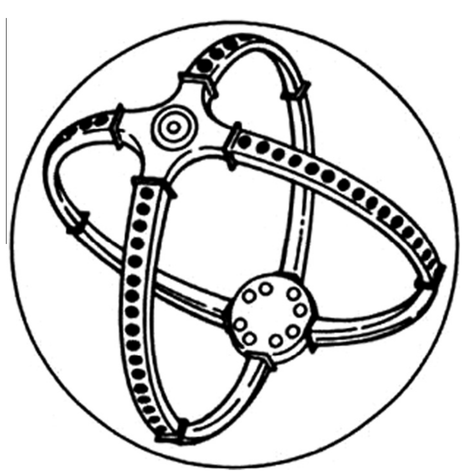

Fig. 1. Full communication screen channel gallery arm.

Although screen channel LADs have been used in a small scale liquid helium experiment in microgravity [8], they have not been used with LH_2 in low gravity. Screen channel LADs are the recommended technology approach for the future cryogenic depots due to a rich technology development program, flight heritage in storable propellants, and higher performance, flexibility, and robustness relative to vanes and sponges [9].

2.2. Screen channel liquid acquisition devices

For flight systems, screen channel LAD usage is broken into two categories [10,11]. Start baskets, traps, and start tanks are considered small liquid acquisition devices that confine sufficient liquid to start engines until the relatively large accelerations can adequately reorient the liquid for the large flow rates required for continuous engine operation. Meanwhile full communication channels, distributers, or tank liners are used in systems with small accelerations and small flows rates. Start baskets are used in systems that experience high flow rate demands over small time scales in milli- to microgravity while full communication gallery arms are implemented in systems with smaller flow rate demands over longer time scales in microgravity.

The choice of screen for the LAD is dictated by the gravitational environment and desired maximum flow rate, which can be estimated through knowledge of the bubble point pressure. Screens are characterized by the screen weave, which refers to the number of wires per inch in each direction, and the specific weave pattern used during manufacturing. For example, the 325 × 2300 Dutch Twill mesh screen displayed in Fig. 2 has 325 warp wires and 2300 shute wires per square inch of the screen. For a Dutch Twill, each shute wire passes under two warp wires before traveling over the next warp wire. Fine mesh Dutch Twill screens create very small pores and provide a tortuous path and good resistance against gas ingestion, and provide more margin in system design, which make them popular candidates for low surface tension cryogenic liquids. However, they may generate large hydraulic pressure losses during outflow and may become clogged by particulate matter.

2.3. The bubble point

The primary performance parameter characterizing LADs is the bubble point, which is defined as the differential pressure required to overcome the liquid surface tension force at the screen pore.