Cryogenics 87 (2017) 85–95

Contents lists available at ScienceDirect

Cryogenics

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

Research paper

EDU liquid acquisition device outflow tests in liquid hydrogen: Experiments and analytical modeling

J.W. Hartwig [a,*], S.R. Darr [b], P. Meyerhofer [c], R. Garces [d]

[a] Cryogenic and Fluid Systems Branch, NASA Glenn Research Center, USA
[b] The Aerospace Corporation, USA
[c] Department of Mechanical and Aerospace Engineering, Case Western Reserve University, USA
[d] NASA Marshall Space Flight Center, USA

ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 24 August 2017
Accepted 6 September 2017
Available online 9 September 2017

Keywords:
Liquid hydrogen
Liquid acquisition device
Engineering development unit
Outflow
Analytical model

ABSTRACT

This paper presents experiments and modeling of the most recent set of liquid acquisition device (LAD) vertical outflow tests conducted in liquid hydrogen. The Engineering Development Unit (EDU) was a relatively large tank (4.25 m^3) used to mimic a storage tank for a cryogenic storage and transfer flight demonstration test. Six 1-g propellant tank outflow tests were conducted with a standard 325 $\times$ 2300 rectangular cross-section curved LAD channel conformal to the tank walls over a range of tank pressure (158–221 kPa), ullage temperature (22–39 K), and mass flow rate (0.0103–0.0187 kg/s) per arm. An analytical LAD channel solver, an exact solution to the Navier-Stokes equations, is used to model propellant outflow for the LAD channel. Results shows that the breakdown height of the LAD is dominated by liquid and ullage gas temperatures, with a secondary effect of flow rate. The best performance is always obtained by exposing the channel to cold pressurant gas and low flow rates, consistent with the cryogenic bubble point model. The model tracks the trends in the data and shows that the contribution of flow-through-screen pressure drop is minimized for bottom outflow in 1-g, versus the standard inverted outflow.

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. The purpose of one such CFM technology, a propellant management device (PMD), is to separate liquid and vapor phases within a propellant tank such that the tank outlet is always sufficiently covered in liquid to ensure vapor-free liquid is transferred from the tank to the transfer line. In Earth's standard 1-g environment, the 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. However, in microgravity, surface tension forces dominate causing liquid to adhere to the tank walls and interior structures, leaving a gaseous core in the center of the tank. Therefore, in the reduced gravity of space, multiple PMDs may be required to sufficiently cover the outlet with liquid during all phases of a mission. While cryogenic propellants offer significant improvements in performance, the goal of ensuring vapor-free liquid for liquid hydrogen (LH_2) and liquid oxygen (LOX) is exacerbated by numerous issues such as low surface tension (relative to propellants that exist as liquids at room temperature) and high susceptibility to heat leak, which causes unwanted evaporation and condensation [1].

PMDs are broken down into three types, vanes, sponges, and screen channel liquid acquisition devices (LADs) or gallery arms [2–4], each with advantages and disadvantages in implementation. For example, vanes are the simplest, lowest mass, lowest cost, and highest reliable PMD at the cost of an open flow path to the tank outlet; vanes cannot sustain medium or large demand flows and cannot supply liquid against large adverse acceleration levels. Meanwhile, gallery arms provide the highest flexibility since they can sustain any flow rate and supply liquid against any adverse acceleration level. However, screen channel LADs have the highest complexity, mass, and cost, and the lowest reliability of the three.

* Corresponding author at: M/S: 86-12, NASA Glenn Research Center, Cleveland, OH 44135, USA.
E-mail address: Jason.W.Hartwig@nasa.gov (J.W. Hartwig).

http://dx.doi.org/10.1016/j.cryogenics.2017.09.001
0011-2275/Published by Elsevier Ltd.

Nomenclature

a	surface area to volume ratio [1/m]
B	screen thickness [m]
C_{lam}	laminar coefficient
C_{turb}	turbulent coefficient
D_p	pore diameter [μ m]
g	gravity [m/s^2]
H	height [cm]
L	length [m]
P	pressure [Pa]
Q	tortuosity
Re	Reynolds number
$\bar{u}_e$	exit velocity [m/s]
v	velocity [m/s]
W	width [cm]
Subscripts	
fr	frictional
FTS	flow - through - screen
inj	injection
L	liquid
v	vapor
x	x direction
y	y direction
Greek	
α	laminar FTS Coefficient
β	turbulent FTS Coefficient
ΔP_{BP}	bubble point pressure [Pa]
ΔP_{total}	total pressure drop [Pa]
ε	surface area to volume ratio
μ	viscosity [Pa$*$s]
ρ	density, [kg/m^3]

Gallery arm performance can, however, be tested on the ground prior to flight whereas implementation of vanes and sponges relies on flight tests or analysis. Unfortunately, solvers routinely used in PMD design do not account for many issues that arise when using cryogenic propellants, making it inherently dangerous to rely solely on analysis.

The PMD style that is the focus of the current work is the screen channel LAD. Screen channels are divided into start baskets or traps used in high-g, high flow rate, short duration liquid acquisition where settling thrusting maneuvers can be used to favorably maintain liquid over the tank outlet after a restart, and full communication gallery arms, used in low-g, lower outflow (relative to start baskets, but still considerably higher than vanes and sponges), long duration liquid acquisition. Screen channels tend to closely follow the contour of the walls where the channels are composed of three solid walls and one porous wall usually facing the inner tank wall. The channels connect to a common location over the tank outlet.

The screen serves three purposes. When liquid approaches the screen, it allows liquid to flow into the channel and to the outlet. When vapor approaches the screen, surface tension forces of the liquid in the screen generate a localized area of high pressure differential that blocks vapor entrance into the channel. Third, the screen can wick liquid along the screen to prevent dry-out due to evaporation. This is especially useful when implementing galleries in cryogenic propellant tanks. The choice of screen for the LAD is dictated by the mission requirements [1]. 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 $\times$ 2300 Dutch Twill mesh screen has 325 warp wires and 2300 shute wires per square inch of the screen. Fine mesh screens are advantageous due to the small pore sizes and good resistance to gas ingestion, but they may generate large hydraulic pressure losses during outflow and become clogged by particulate matter. Screen selection is generally a trade between the five influential factors that govern LAD performance, including bubble point pressure, flow-through-screen pressure drop, wicking rate, screen compatibility, and screen compliance [5].

See [6] for the most recent and comprehensive review of where all PMD styles have been implemented in ground tests, space experiments, and missions. Screen channel LADs have enjoyed a rich flight heritage with storable propellants systems such as the Shuttle Reaction Control System and Orbital Maneuvering System [7–9], space experiments such as the Fluid Acquisition and Resupply Experiment (FARE-1) [10], and satellites such as Intelsat [11] and Geostationary Operational Environmental Satellites [12]. While screen channel LADs have been used in a small scale liquid helium experiment in microgravity [13–16], and while they are the only PMD type with flight heritage with a cryogen, they have not been used with LH_2 or LOX in low gravity.

The purpose of this paper is to present experimental results and model predictions for the most recent set of vertical outflow LAD tests conducted on the Engineering Development Unit (EDU) LH_2 propellant tank. The outline of the paper is as follows: first a description of the LAD channels and manufacturing process is given, along with the facility and test tank. Experimental methodology for how to performance test full scale LAD channels is also discussed. Next, the LAD channel analytical model is outlined, along with basic model performance. Then vertical outflow test data is compared with corresponding model predictions along with discussion of results. Finally, implications and conclusions are given.

2. Test description

2.1. Facility and EDU test tank

EDU testing was performed at Marshall Space Flight Center (MSFC) Test Stand 300 (TS-300). Tests were conducted between 6/2014 and 7/2014. Details of the facility and its capabilities are available in [17]. As part of the Cryogenic Propellant Storage and Transfer project and mission, the EDU tank was designed and built with the purpose of conducting ground testing to simulate flight testing. The EDU was sized to mimic the flight system storage tank, which was used to house and transfer LH_2 to a receiver tank to simulate a fuel depot propellant transfer. While the flight test article never came to fruition [1], ground based testing was successful at obtaining some CFM data for propellant storage and transfer. Specifically, the purpose of the EDU LAD outflow test series was threefold: to complement the recent set of tests performed on a smaller tank [18], to test a different channel manufacturing technique as well as different method to cool liquid in the channel from [18], and to add to the outflow database. What made the EDU test tank and test series especially valuable to the cryogenics commu-