Cryogenics 64 (2014) 260–271

Contents lists available at ScienceDirect

Cryogenics

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

A steady state pressure drop model for screen channel liquid acquisition devices

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ARTICLE INFO

Article history:
Available online 20 March 2014

Keywords:
Liquid acquisition devices
Liquid hydrogen
Cryogenic fluid management
Porous screen
Thermodynamic vent heat exchanger
Fuel depot

ABSTRACT

This paper presents the derivation of a simplified one dimensional (1D) steady state pressure drop model for flow through a porous liquid acquisition device (LAD) inside a cryogenic propellant tank. Experimental data is also presented from cryogenic LAD tests in liquid hydrogen (LH_2) and liquid oxygen (LOX) to compare against the simplified model and to validate the model at cryogenic temperatures. The purpose of the experiments was to identify the various pressure drop contributions in the analytical model which govern LAD channel behavior during dynamic, steady state outflow. LH_2 pipe flow of LAD screen samples measured the second order flow-through-screen (FTS) pressure drop, horizontal LOX LAD outflow tests determined the relative magnitude of the third order frictional and dynamic losses within the channel, while LH_2 inverted vertical outflow tests determined the magnitude of the first order hydrostatic pressure loss and validity of the full 1D model. When compared to room temperature predictions, the FTS pressure drop is shown to be temperature dependent, with a significant increase in flow resistance at LH_2 temperatures. Model predictions of frictional and dynamic losses down the channel compare qualitatively with LOX LADs data. Meanwhile, the 1D model predicted breakdown points track the trends in the LH_2 inverted outflow experimental results, with discrepancies being due to a non-uniform injection velocity across the LAD screen not accounted for in the model.

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1. Introduction

Future long duration human and robotic exploration missions will require efficient methods to transfer high performance cryogenic propellants from a storage tank. Cryogenic propellants are much more difficult to store and transfer than the traditional storable propellants (i.e. propellants that exist as liquids at room temperature) due to their low normal boiling point (NBP), low surface tension, and high susceptibility to parasitic heat leak. Since all in-space cryogenic engines and future cryogenic fuel depots will require vapor free liquid delivery, propellant management devices (PMD) are required to sufficiently cover the storage tank outlet with liquid, despite the variable thermal and gravitational conditions of microgravity. One such PMD, a screen channel liquid acquisition device (LAD) uses surface tension forces to maintain liquid flow to the outlet and transfer line. As shown in Fig. 1, screen channel LADs, or gallery arms closely follow the contours of the tank wall. The channel side that faces the wall is covered with a fine mesh screen with 10–100 μm sized pores while the other three sides are solid metal. The channels all converge at the tank outlet. During either quiescent or transient flow environments, the screen serves three purposes:

1. To allow liquid to flow into the channel and down to the tank outlet.
2. To block vapor admittance into the channel.
3. To wick liquid along the screen in the event of screen dry-out due to evaporation.

The screen will separate phases as long as the pressure difference across the screen does not exceed the bubble point pressure, which is defined as:

$$\Delta P_{BP} = \frac{4\gamma_{LV}}{D_P(T)} \tag{1}$$

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http://dx.doi.org/10.1016/j.cryogenics.2014.03.005
0011-2275/Published by Elsevier Ltd.

Nomenclature

a	surface area to volume ratio (m^{-1})
A_C	flow through screen cross sectional area (m^2)
B	screen thickness (μm)
C	constant associated with viscous pressure drop
D_H	hydraulic diameter (m)
D_p	screen pore diameter (μm)
e	pipe roughness (m)
f	friction factor
F_D	drag force per unit area for flow past a spherical particle (N/m^2)
F_T	total drag force per unit area for flow past a bed of spherical particles (N/m^2)
H	depth of the LAD channel (m)
HEX	heat exchanger
L	length of the LAD channel (m)
L_b	length of the LAD channel below the tank liquid/vapor interface (m)
$\dot{m}_{LAD}$	outflow rate through the LAD channel (kg/s)
N	number of spheres per unit area ($1/m^2$)
N_{Re}	modified Reynolds number
P	tank pressure (kPa)
P_{SAT}	saturation pressure based on the temperature of the liquid at the screen (kPa)
Q	tortuosity factor
r	radius of spherical particle (m)
U	fluid velocity through screen (m/s)
V_{solid}	solid volume fraction of the screen (m)
V_{sphere}	volume of a sphere in the packed bed (m^3)
$\dot{V}$	volumetric flow rate (m^3/s)
W	width of the LAD channel (m)
ΔP_{BP}	bubble point pressure (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)
$\Delta P_{inertial}$	inertial pressure loss (Pa)
ΔP_{other}	transient pressure drop terms (Pa)
ΔP_{total}	total pressure loss for LAD system (Pa)
ΔP_{visc}	viscous pressure loss (Pa)
α	coefficient associated with viscous pressure drop
β	coefficient associated with inertial pressure drop
ε	screen porosity, or void fraction
γ	surface tension (mN/m)
λ_n	eigenvalues for frictional pressure drop
μ	viscosity of the liquid (Pa*s)
ρ	density of the liquid (kg/m^3)
θ_C	contact angle

where γ_{LV} is the surface tension of the liquid and $D_P(T)$ is the effective pore diameter, where contact angle is assumed zero [1,2]. Therefore, for a given liquid, higher bubble points are achievable using finer mesh screens. The total pressure loss in the LAD system must be less than the bubble point pressure to prevent vapor ingestion into the channel:

$$\Delta P_{total} < \Delta P_{BP} \tag{2}$$

where the total pressure loss is expressed as:

$$\Delta P_{total} = \Delta P_{hydrostatic} + \Delta P_{FTS} + \Delta P_{friction} + \Delta P_{dynamic} + \Delta P_{other} \tag{3}$$

where $\Delta P_{hydrostatic}$ is the hydrostatic pressure within the channel, ΔP_{FTS} is the flow-through-screen (FTS) pressure drop across the screen due to liquid flow, $\Delta P_{friction}$ is the frictional loss down the LAD channel, $\Delta P_{dynamic}$ is the dynamic pressure drop due to inflow into the channel, and $\Delta\ P_{other}$ is the pressure loss contribution due to vibrations, propellant sloshing, and/or transients at the start of flow demand.

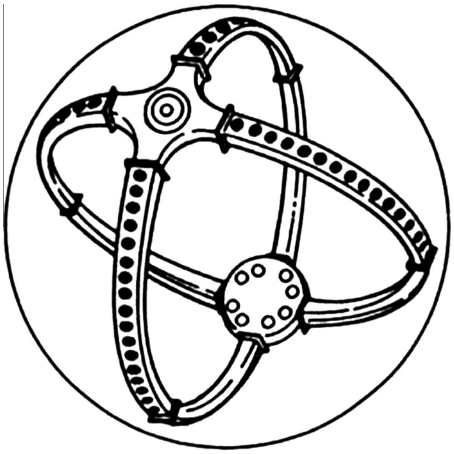

Fig. 1. Full communication screen channel gallery arm.

Previous work has shown that the pore diameter is actually temperature dependent, and that the screen shrinks as the temperature of the system decreases towards cryogenic temperatures [3]. Previous experimental and analytical work has also shown that this simplified bubble point model holds well for room temperature liquids and for normally saturated liquid states in liquid hydrogen (LH_2) [4,5], liquid nitrogen (LN_2) [3], liquid oxygen (LOX) [6–8], and liquid methane (LCH_4) [9,10], but breaks down when the liquid is subcooled (i.e. the temperature of the liquid at the LAD screen is less than the saturation temperature based on the pressure at the screen) as shown in many of these experiments. There is an additional degradation term that must be added to the simplified model in the case where the pressurant gas in contact with the screen is warmer than the liquid propellant at the screen [11]. Therefore, for normally or near-normally saturated states, where the temperature of the gas and liquid are constant, Eqs. (1) and (2) can be used to determine the point at which the LAD breaks down, or ingests vapor into the channel.

In a 1-g environment, the hydrostatic pressure drop is the leading order term, FTS pressure drop is second order. While frictional and dynamic losses down the channel scale with the size of the LAD, they are third order effects in 1-g. In the microgravity environment of Low Earth Orbit (LEO) however, during steady flow, the hydrostatic term is minimized and the FTS pressure becomes the leading order term, while frictional and dynamic channel losses are a second order effect. During transient events such as vehicle reorientation and station keeping maneuvers, accelerations are generated which can be large enough to break the channel down.

The purpose of the current work is twofold:

1. To derive a steady state pressure drop model for screen channel liquid acquisition devices operating in cryogenic propellant tanks.
2. To present new cryogenic LAD performance data to compare against the model and to validate it at cryogenic temperatures. Of specific interest are the recently conducted LH_2 LAD outflow tests from [12].