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Influential factors for liquid acquisition device screen selection for cryogenic propulsion systems

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HIGHLIGHTS

- The set of factors which dictate LAD design for all cryogenic propulsion systems are presented.
- Bubble point pressure, flow through screen pressure are primary factors.
- Wicking rate, screen compliance, and material compatibility are secondary factors.
- Governing equations are derived to create models for each influential factor.
- Each analytical model is validated by nearly 4 decades of experimental data.

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ABSTRACT

This paper presents the influential factors which govern screen selection for liquid acquisition devices (LADs) operating in microgravity conditions for future in-space cryogenic propulsion engines and cryogenic propellant depots. Space flight requirements, which include mass flow rate, acceleration level and direction, and thermal environment, dictate screen selection for a particular mission. The five influential factors include bubble point pressure, flow-through-screen pressure drop, wicking rate, screen compliance, and material compatibility. Governing equations and analytical models for these parameters are developed from first principles. A comprehensive survey of the historical data on coarser LAD meshes over four decades of work is conducted, and liquid hydrogen data for finer Dutch Twill meshes (325 × 2300, 450 × 2750, 510 × 3600) from recently concluded experiments is also presented to validate analytical models. Each of these parameters is measurable from ground based tests, making it facile to predict flight system performance. Therefore analytical models in this paper will be valuable for future LAD designs for both cryogenic and storable propulsion systems. Additionally, analysis will be given on the impact of the factors on liquid hydrogen systems.

1. Introduction

The purpose of this paper is to develop analytical models for the influential factors which govern screen selection for liquid acquisition devices (LADs) operating in microgravity conditions. These models can then be used to predict flight performance of LADs for future in-space cryogenic propulsion engines and cryogenic propellant depots. Space flight requirements, which include mass flow rate, acceleration level and direction, and thermal environment, dictate the selection of the screen for a particular mission. The five influential factors are bubble point pressure, flow-through-screen pressure (FTS) drop, wicking rate, screen compliance, and material compatibility. In order to validate the analytical models, historical data on LAD meshes from over four decades of work is assembled and reported in this work. In all, twenty-seven different screen meshes and five screen mesh types are included in this study.

The outline of the paper is as follows: First a general background into microgravity fluid transfer, liquid acquisition devices, and screen types is given to familiarize the reader with the challenges of low Bond number liquid control and transfer. Then, for each influential factor, background and justification to its relevance and importance are presented. Next, analytical models for each factor are derived from first principles and the methodology for how to conduct an experiment to measure the factor is presented. Finally, historical data and recent liquid hydrogen (LH_2) data is gathered presented to anchor and validate the models.

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2. Background

The transfer of liquid-only cryogenic propellant is a challenging problem due to the uncertainty of the location of the liquid/vapor (L/V) interface within the propellant tank. Without the presence of a strong gravitational force, the ability to predict where the liquid phase is positioned inside a tank is difficult and requires a method of L/V interface control. Conceivably, there are two active ways and one passive way to control the L/V interface inside a propellant tank to ensure that the tank outlet is sufficiently covered with liquid at all times during a mission. First, a thrusting maneuver that causes a linear translation of the vehicle can be performed to settle the propellant near the tank outlet. Second, a thrust maneuver that causes a rotation can be imposed on the propellant tank in order to settle the liquid to the tank walls near the outlet. Both methods consume propellant and are considered inefficient. The third approach is the use of passive control with LADs. LADs are considered the most beneficial method of L/V interface control because they do not waste propellant and they do not require complex devices like rotating components.

The purpose of a LAD is to separate the liquid and vapor phases within a propellant tank, and to transfer vapor-free liquid from the tank to a transfer line despite the variable gravitational and thermal environment of Low Earth Orbit (LEO). LADs rely on surface tension forces to control the phase separation, and thus are best suited in low Bond number environments, where Bond number is defined as:

$$Bo = \frac{\rho g L^2}{\gamma} \tag{1}$$

where ρ is the density of the fluid, g is the acceleration due to gravity, L is the length scale of the system, and γ is the surface tension of the fluid. In high Bond number environments, gravity can be used to separate phases and drive liquid flow out of the tank. However in the low Bond number environment of LEO, surface tension force is on the order of, or much greater than, the hydrostatic force of the liquid. For example, for the proposed liquid hydrogen fueled depots, the acceleration of gravity in LEO is on the order of 10^{-6} m/s^2. With a propellant tank hydrostatic length scale of 1 m, an LH_2 density and surface tension of 71 kg/m^3 and 2 mN/m, respectively, the Bond number in LEO is 0.355, indicating that the surface tension force is not just comparable but also greater than the hydrostatic force.

LADs come in many different styles, of which there are three main types of LADs: vanes [34], sponges [35], and screen channel LADs [36]. These types of LADs are shaped differently but all use the same surface tension mechanism to move liquid. The screen channel LADs were chosen for this study because they are the most robust type of the three. They are able to supply a larger span of flow rates and withstand larger accelerations before vapor ingestion relative to other types of LADs [25].

Screen channel LADs have proven flight heritage over the past five decades. Most notably, LAD screens have been used in the Mars Viking mission [52] and the Shuttle Orbital Maneuvering System [50] and Reaction Control System [18]. The screen channel LADs, which are multiple hollow ducts each with one wall made of porous screen, are spread out within the tank and joined together at the tank outlet. They are entirely filled with liquid when the storage tank is full. When liquid flow is driven out of the tank, the liquid is drained through the channels toward the outlet. Meanwhile the remaining liquid in the tank is drawn through the screens to the inside of the channel. If vapor contacts part of a screen, the liquid within the microscopic screen pores naturally generates a capillary force that resists vapor passage into the channel. In this way the LAD channels ensure that single phase liquid is being supplied to the exit until the tank is emptied.

LADs are used in two distinct applications. The first of these is an in-space propulsion engine. By design, all in-space propulsion engines require vapor-free liquid for safe and stable operation. The second application is a fuel depot, which is basically an orbiting propellant-storage tank. Its main purpose is to provide propellant to space vehicles in a low Bond number environment so that deep space travel is more accessible. Due to the projected cost of launching and storing propellant in LEO, single phase liquid propellant transfer is desired so that a high liquid-volume fraction in the customer vehicle receiver tank can be achieved.

These two applications differ in required transfer flow rate and the gravity environment. In-space engines typically require high flow rates in order to generate the thrust they need, whereas fuel depots can settle for much lower flow rates depending on the fill-time requirements. In-space engines also “create” their own gravity by thrust acceleration. This acceleration can be used to settle the remaining liquid to the outlet, making single-phase liquid transfer much easier. Fuel depots are generally maintaining an orbit and do not experience large accelerations. Since gravity is negligible in LEO, the liquid in fuel depots will move to unpredictable locations. Therefore, depending on the specific mission requirements, clearly a robust LAD system is desired to extract vapor free liquid, despite varying thermal and gravitational levels of space.

The highest performance propulsion engines, besides engines powered by nuclear fission, use a liquid oxygen–liquid hydrogen (LOX/LH_2) combination as propellant. Therefore it is desirable to develop LOX and LH_2 storage and transfer systems that can be incorporated into in-space engines and fuel depots. But supplying vapor-free LOX or LH_2 to a transfer line en route to an engine or receiver depot tank is challenging due to the propellant’s low normal boiling point (NBP), low liquid density, low surface tension, and low viscosity. In addition, cryogenic propellants are susceptible to parasitic heat leak, and there is a limited range of thermodynamic conditions under which they exist as liquids. Therefore, in order to take advantage of the high performance of LOX/LH_2 propulsion and enable future planetary manned missions, refinement of existing cryogenic propellant technology will be necessary.

The types of weaves typically used in screen channel LADs are Dutch Twill, Plain Dutch, Reverse Dutch, Twilled Square, and Plain Square. 3D models of the Dutch Twill, Plain Dutch, and Twilled Square weave are shown in Fig. 1. Each weave type has a different weave pattern of its warp and shute wires, which run perpendicular to each other. The Plain Square weave is the simplest; the warp and shute wires are the same diameter and pass each other in an over-and-under pattern. For the Twilled Square weave the warp and shute wires are also the same diameter but each shute wire passes over two warp wires and then under two warp wires, repeating that pattern. The Plain Dutch weave has the same pattern as the Plain Square weave but the warp wires are larger in diameter than the shute wires which creates smaller pore diameters than the Plain Square and Twilled Square. The Reverse Dutch weave is the inverse of the Plain Dutch – the shute wires are larger than the warp wires. The Dutch Twill weave combines the Plain Dutch and Twilled Square weaves – it has the same weave pattern as the Twilled Square but has larger warp wires than shute wires like the Plain Dutch. The Dutch Twill weave creates the smallest pore diameters and the most tortuous flow path for gas ingestion across the wetted screen. A screen is also classified by the number of warp and shute wires per inch in each direction. For example, the 450x2750 Dutch Twill weave has 450 warp wires per square inch in one direction and 2750 shute wires per square inch in the direction perpendicular to the first.