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Design of Thermodynamic Vent/Screen Baffle Cryogenic Storage System

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Nomenclature

a	= screen surface area to unit volume ratio (ft)$^{-1}$
b	= screen thickness (ft)
D	= screen pore diameter (ft)
f	= friction factor
g	= gravitational constant (32.2 fps^2)
ΔP	= pressure drop (lb/ft^2)
Q	= screen tortuosity factor
Re	= Reynolds number
V	= fluid approach velocity (fps)
α,β	= experimentally determined constants
ϵ	= screen void fraction
ρ	= fluid density (lb/ft^3)
μ	= fluid viscosity (lb/fps)

Introduction

FUTURE space missions will require cryogenic fluid storage and expulsion subsystems capable of providing efficient long-term subcritical storage, reliable multiple low-*g* restarts, and predictable low-*g* liquid expulsion for auxiliary propulsion, life support systems, and in-orbit propellant transfer. Capillary systems using fine-mesh screens have been developed and shown to control fluid behavior for a wide variety of noncryogenic fluids in orbit.[1] However, to achieve similar expulsion success with cryogenic propellants during orbital storage and transfer, heat and mass transfer effects must also be controlled.

A number of techniques have been proposed to achieve the required thermal control. One concept uses a dual-screen liner and is designed to hold the cryogen off the tank wall to provide liquid-free venting.[2] This approach is relatively heavy and relies on passive, gravity-dependent thermal control, which has not been demonstrated in low gravity. Passive systems for thermal control, based on thermodynamic phase conversion, and using a wall-mounted heat exchanger, have been proposed to intercept and remove the heat entering the cryogen tank.[3] Active thermodynamic vent systems (TVS) using a pump and compact heat exchanger have been developed by NASA.[4,5] Use of a pump entails a potential decrease in system reliability, but results in fluid-dynamic and heat transfer processes that are not significantly gravity-dependent, and which have been satisfactorily demonstrated in ground tests.

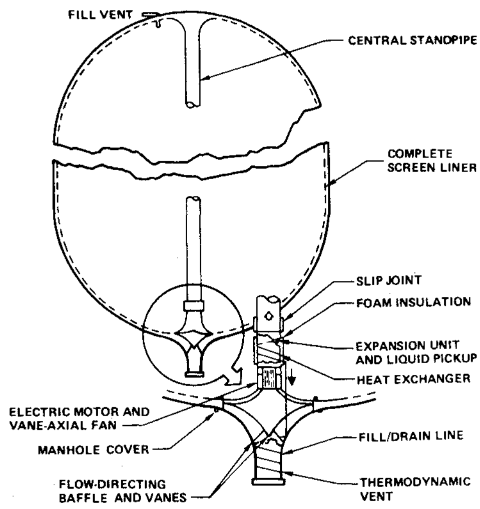

Fig. 1 Conceptual tank design.

The overall system concept studied is shown schematically in Fig. 1. The system consists of two major components: a single-screen complete wall liner and a pump-driven thermodynamic vent system. The annulus between the screen and the tank wall remains full of liquid at all times and serves two functions. First, it provides liquid communication from the outflow line to the bulk liquid in the tank, which, although its orientation in the tank is unknown, will be in contact with the tank wall because of the wetting characteristics of cryogens. This communication allows outflow and liquid transfer in low gravity. Second, the annulus provides a flow path for pumped liquid which will absorb tank incident heating, flow through the standpipe, and reject the absorbed heat to the thermodynamic vent system.

Experimental Program

To determine the important fluid dynamic characteristics of the system the flow and pressure characteristics of the pump/TVS must be known, together with screen liner properties, such as bubble point, flow loss, and annular pressure drop. To define these screen properties, a comprehensive screen survey was performed, and 10 screens ranging in pore size from 12-500 μ were selected. The important performance characteristics of these screens were experimentally determined using liquid hydrogen (LH_2) saturated at 50 psia. The screen bubble points were determined and were found to be correlated by extrapolated alcohol bubble point data. The LH_2 flowthrough pressure loss data were determined for the screens, were compared to other available flow-loss data, and were correlated with the Armour and Cannon[6] form of friction factor vs Reynolds number (see Nomenclature): $f=(\alpha/Re+\beta)$ where $f=(\Delta P\epsilon^2 Dg/Qb\rho V^2)$, $Re=(\rho V/\mu a^2 D)$, and α and β are experimentally determined constants.

The pressure loss for LH_2 flow along rectangular channels lined on one side with screen was experimentally determined for the first time. The data were correlated with the Moody[7] friction factor and Reynolds number, with a roughness parameter related to screen type and wire size. For square-weave screens, the equivalent roughness dimension is equal to the wire diameter, and for dutch-weave screens, the equivalent roughness dimension is equal to half the shute (fine) wire diameter. Details of the correlations for all screens

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Table 1 Screen performance parameters

Screen	Bubble Point Ft, LH_2	Flowthrough Parameters α	Flowthrough Parameters β	Roughness ϵ, in.	Weight lb/100 ft^2 (stainless steel)
325×2,300	1.580	3.2	0.19	0.0005	10.9
200×1,400	1.108	4.2	0.20	0.0008	18.6
720×140	0.580	11.0	0.47	0.00215	14.2
165×800	0.403	3.3	0.17	0.001	16.3
50×250	0.224	13.5	0.26	0.00225	23.2
24×110	0.1105	8.61	0.52	0.00525	63.5
500×500	0.540	5.7	0.65 (0.77)[a]	0.001	3.4
150×150	0.151	5.7	0.50(0.50)[a]	0.0026	7.0
60×60	0.0754	5.7	0.40 (0.61)[a]	0.0075	23.9
40×40	0.0559	5.7	0.60 (0.52)[a]	0.01	27.9

[a] Based on Euler number = $(S/1-S)^2$.

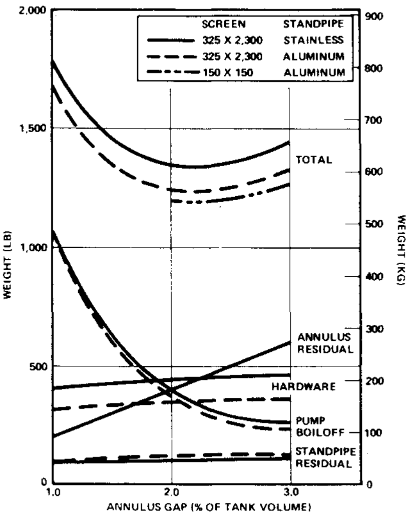

Fig. 2 Weight optimization for 5000 ft^3 LH_2 tank for 300 day mission.

are contained in Ref. 8. The important characteristics of the 10 screens tested are shown in Table 1.

Parametric Analysis

Because the screen annulus remains full of propellant at all times, it represents an undesirable residual and weight penalty which should be minimized. However, as the annulus gap is made smaller, the pressure loss for flow through the annulus increases, with two undesirable results. First, the pressure loss during outflow may exceed the screen bubble point resulting in screen breakdown and bubble ingestion into the outflowing liquid. Second, during coast, the pressure loss for the TVS flow is increased, resulting in higher pump power requirements, and thus higher heat input and equivalent boiloff of the cryogen. These effects were studied parametrically for a range of flow conditions and g-levels for LH_2 tanks from 50-5000 ft^3 and for liquid oxygen (LO_2) tanks from 5-500 ft^3, for 30- and 300-day orbital storage missions and for all 10 screens.

The screens and annulus gaps were selected so that half the screen bubble point would not be exceeded during outflow (a safety factor of 2). Then the annulus gap and central standpipe size were optimized for minimum residual and coast heating boiloff. The effects of annulus residual and pump boiloff counteracted each other as a function of annulus gap to give a minimum system weight value for annulus gap, as shown typically in Figure 2 for 5000 ft^3 LH_2 tank with a 300-day coast mission.

Conclusions

The parametric analysis, based on unique experimental data on screen properties, has shown that the integrated pump TVS/wall screen liner system is fluid-dynamically feasible for LH_2 and LO_2 tanks over a wide range of sizes and operating conditions. Further work will be necessary to determine thermodynamic feasibility, define fabrication concepts, and compare the pump TVS/wall screen liner system to other methods of orbital storage and transfer, such as supercritical or propulsion-accelerated systems.

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Optimum Orbital Control Using Solar Radiation Pressure

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Nomenclature

a,e	= orbit's semimajor axis and eccentricity
m	= mass of satellite
n	= mean angular speed in orbit
p	= solar pressure on a perfectly reflecting surface placed normal to the sun rays
C_q, S_q, T_q	= cos (q), sin(q), tan(q), respectively

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