Application of Etched Disk Stacks in Surface Tension Propellant Management Devices

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A novel propellant management device (PMD) employing chemically etched disk stacks is presented for a spacecraft application in both spinning and zero-gravity environments. The surface thermodynamic, hydrostatic, and hydrodynamic principles underlying the stack design are discussed in conjunction with parametric examination of the flow passages in etched disk stacks as applied to a bipropellant propulsion subsystem. The performance of stacks during operational phases of the mission is analyzed. Results of the analyses provide confidence that liquid will be retained (no gas ingestion) in the etched flow passages over the entire mission. The stacks are designed to provide high safety margins against gas ingestion in the etched flow passages during worst-case on-orbit operations in low-gravity environments. The design provides an expulsion efficiency greater than 99.9%. The PMD concept has demonstrated design ruggedness without gas ingestion in the tested launch vibration environments in addition to demonstrating ability to perform expulsion in an inverted tank ($-1g$ environment) up to tank diameters of 23 in. The etched disk technology is well proven and is widely used in spacecraft industry for making propellant filters. The PMD is lightweight (~ 1.7 lbm) and, due to the simplicity of design, the fabrication, installation, and testing procedures are facilitated.

Nomenclature

b = depth of etched disk slot
D_i = inside diameter of etched disk
D_o = outside diameter of etched disk
D_T = inside diameter of propellant tank
d_i = inside diameter of manifold (gallery)
d_o = outside diameter of manifold (gallery)
F = flow margin (dimensionless)
g = acceleration in general
g_E = acceleration due to Earth gravity
g_S = acceleration due to spacecraft spin
g_T = acceleration due to thrust
H = height of etched disk stack
h = height of stack exposed in ullage
h_u = ullage height in tank
L = slot length (length of flow passage)
$\dot{m}_s$ = mass flow rate through slot
$\dot{m}$ = mass flow rate through stack
N_d = number of disks per stack
N_s = number of slots per disk
P_g = gas pressure
P_ℓ = liquid pressure
ΔP_b = bubble-point pressure drop in slot
ΔP_f = frictional pressure drop in slot
ΔP_h = hydrostatic pressure drop in ullage exposed stack
ΔP_s = spin-induced hydrostatic pressure drop in ullage exposed stack
r_i = distance from spin axis to topmost stack
r_ℓ = distance from spin axis to liquid level in tank
w = slot width
θ = contact angle
μ = absolute viscosity
ρ = mass density
σ = surface tension
ω = angular spin speed of spacecraft

Subscripts

c = combined (hydrostatic and hydrodynamic)
fu = fuel
ox = oxidizer

Introduction

SURFACE tension propellant management devices (PMDs) are required in propellant tanks that operate in low-acceleration environments, often called zero-gravity or microgravity environments. The primary function of PMDs is to provide propellant orientation for center of gravity (c.g.) control and to separate the liquid and pressurant gas so that gas-free liquid flow is available to thrusters upon demand. These devices ensure that none of the pressurization gas is expelled from the tank into the propellant feed system until the liquid in the tank is nearly depleted. For many mission applications, PMDs are superior to positive expulsion devices such as bladders, bellows, and diaphragms because surface tension devices are significantly lighter, passive in operation, and more reliable. Conventionally, these assemblies are made of various combinations of formed sheet metals, machined parts, woven screens, and/or perforated sheets. As opposed to these conventional elements, the PMD described in this paper employs chemically etched disk stacks as porous surface tension elements that work as liquid-gas separators, allowing liquid to enter, but preventing gas from entering the stacks. The etched disk PMD concept was developed, built, tested, and patented in 1981.[1,2] The etched disk stacks offer several notable advantages over conventional PMD designs:

1) The chemical etching process gives uniformity and close dimensional control of flow passages allowing more accurate control of the liquid bubble-point pressure than conventional screens, vanes, and gallery/reservoir designs.

2) The PMD concept has demonstrated design ruggedness by withstanding launch vibration environments without gas ingestion in addition to demonstrating its ability to expel gas-free fluids in an inverted position up to tank diameters of 23 in. ($-1g$ environment).

3) The PMD weighs less than 2 lb and offers an expulsion efficiency of greater than 99.9% of the total liquid volume.

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4) Because of simple fabrication and assembly processes, it is easier to achieve and maintain required cleanliness levels with etched disk stacks than it is with conventional screens.

This paper describes the principles used in designing PMDs for application to a geosynchronous communication satellite operating in both spinning and zero-gravity environments. The surface tension, hydrostatic, and hydrodynamic principles underlying the design and optimization of etched flow passages and subsequent integration into complete PMDs are discussed in depth, and the stack performance during the various mission phases is analyzed.

Etched Disk Concept

General Background

Fluid behavior in liquid containers subjected to low-gravity environment is significantly different from that in normal Earth gravity due to the dominance of such intermolecular forces as adhesion, cohesion, and surface tension. These forces are extremely small and are usually neglected in the design of fluid systems operating under much larger forces such as Earth gravity. In zero gravity, liquid surface tension forces govern, and the liquid in the tank tends to adhere to the tank wall as illustrated in Fig. 1. To reorient the liquid to the tank outlet and ensure gas-free propellant outflow upon demand, a metallic structure called a PMD is installed in the tank. The PMD effectively utilizes the surface tension property of liquid propellants to dominate the acceleration and flow inertia forces and to preferentially position the liquid in the tank.

The basic PMD element is a circular, titanium disk with etched slots on one face, as shown in Fig. 2. When stacked one upon another, these slots form flow paths that permit liquid to enter, but prevent gas from entering the wetted slots. The liquid surface tension is thus utilized to seal the slots against pressurant gas flow. From stack slots the liquid flows into the manifold through small holes drilled into the manifold surface as shown in Fig. 2. From the manifold the liquid, in turn, flows to the tank outlet. A tubular structure of etched disk stacks called the "gallery" is illustrated in Fig. 3. The gallery is entirely primed with liquid during the fill operation. The etched disk elements allow liquid to enter the gallery and keeps the gas out due to the small liquid-filled pores.

PMD Design

The PMD discussed in this paper is designed for a conventional bipropellant propulsion subsystem that incorporates two monomethyl hydrazine (MMH) fuel tanks and two nitrogen tetroxide (NTO) oxidizer tanks. Basic parameters and mission environments are cited in Table 1. The PMD is an all-welded, all-titanium design consisting of tubular galleries joining several stacks of etched disks as shown in Fig. 4. The two on-orbit stationkeeping galleries are formed by connecting the two nearly semicircular gallery quadrants, each containing three "small" etched disk stacks as shown in Fig. 3. There are altogether 12 small stacks for zero-gravity operation on-orbit and one large stack for spinning operation during apogee maneuver. The stack-design parameters cited in Table 2 are optimized based on operational requirements of the spacecraft in spinning and zero-gravity environments.

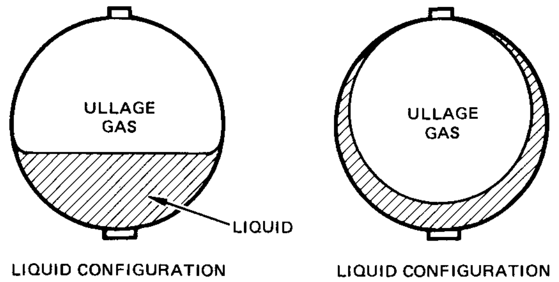

Fig. 1 Equilibrium configuration of liquid/gas interface in a propellant tank (same fill fraction).

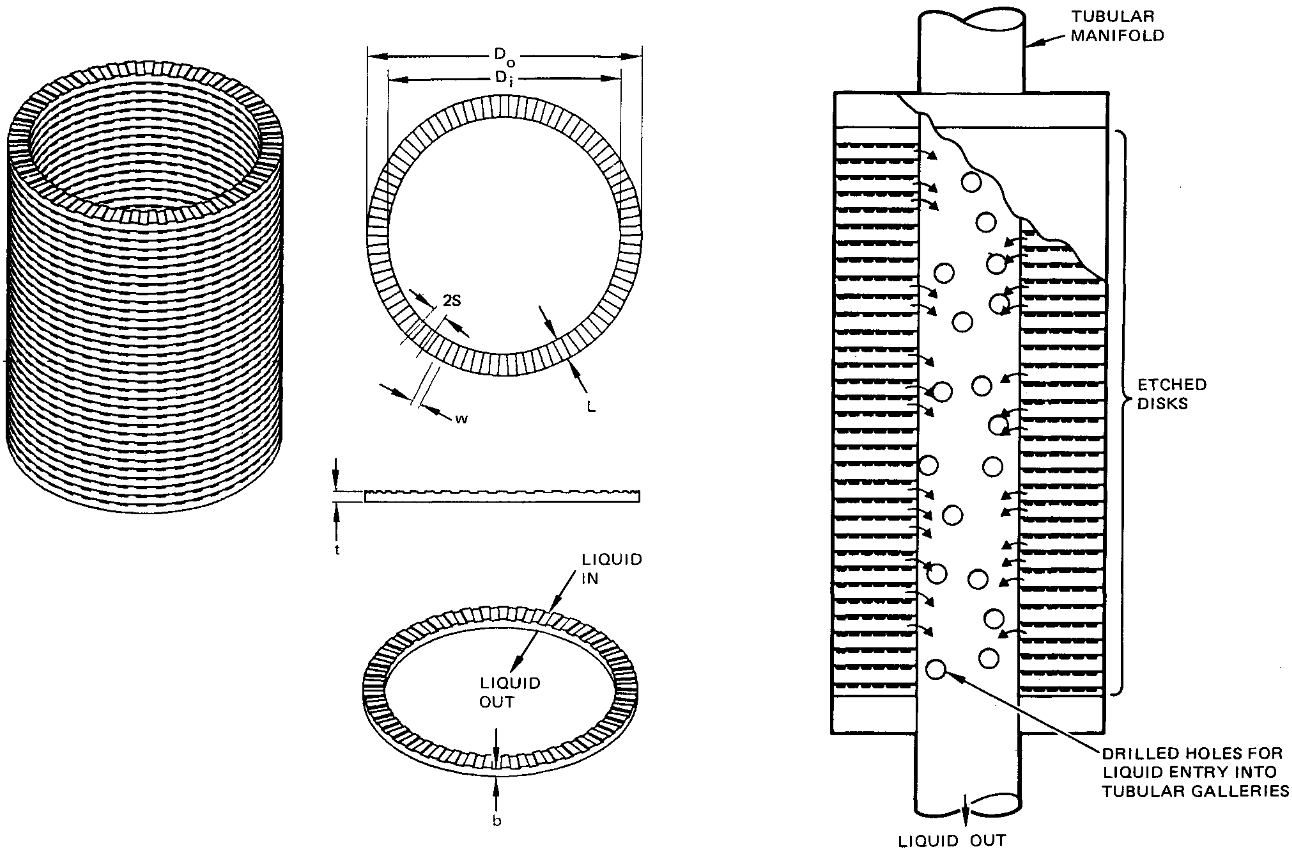

Fig. 2 Etched disk stack.

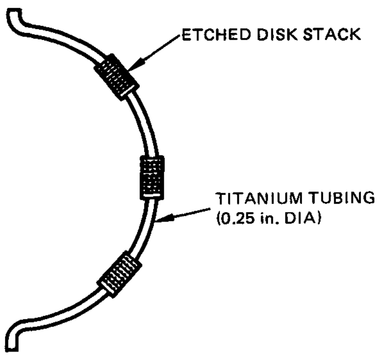

Fig. 3 Gallery quadrant assembly.

The two stationkeeping galleries, located 90 deg apart, and a spin-feed gallery are all manifolded together. The stationkeeping galleries supply propellant to the tank outlet for supplying the 5-lbf thrusters during on-orbit operations in low gravity. These galleries are positioned in the tank to always be in the plane of the primary maneuvers of the spacecraft. For a geosynchronous communications satellite, one gallery is located in the east/west plane and the other in the north/south plane of the vehicle, as shown in Fig. 4. These locations serve two purposes: it ensures that the propellant will feed a gallery during a maneuver, and it minimizes the delay times (required to rewet surfaces) between major maneuvers.

During spin phase, propellant is fed to the tank outlet through a separate spin-feed gallery. Providing a separate spin-feed gallery eliminates the need for a spin port and allows a common tank outlet for both spinning and zero-gravity operations in addition to simplifying ground-servicing opera-

Table 1 PMD design and mission environments

Propulsion subsystem type	Bipropellant (MMH/NTO)
Number of oxidizer tanks	2 (spherical, 35 in. diam)
Number of fuel tanks	2 (spherical, 35 in. diam)
Number of zero-gravity manifolds	2 (6 small stacks/manifold)
Number of spin-feed manifolds	1 (1 large stack/manifold)
Expulsion efficiency	>99.9%
Tank and PMD material	Titanium
PMD weight/tank	1.7 lb
Maximum friction losses in tank (PMD and ground drain)	0.2–0.5 psid
Spacecraft spin rate during apogee maneuver	10 rpm
Number of 110-lbf thrusters firing during apogee manuever	1
Number of 5-lbf thrusters firing simultaneously in steady state in zero gravity	2
Number of 5-lbf thrusters firing simultaneously in pulsing operation in zero gravity	6
Spacecraft accelerations	
Ground servicing	$1g_E$
Launch	5–$8g_E$
PKM solid motor firing	3–$4g_E$
Spinning environments	$0.1g_E$
On-orbit (zero-gravity) environments	$0.003g_E$

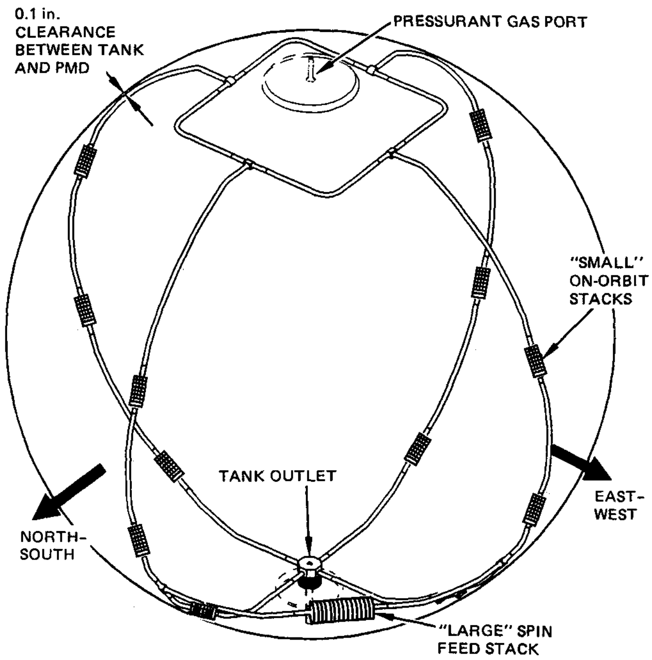

Fig. 4 PMD tank schematic.

Table 2 Design of etched disk stacks[a]

Parameter	PMD		
	Small stack (zero-gravity manifold)	Large stack (spin-feed manifold)	Ground drain
Disk outside diameter D_o, in.	0.65	1.30	1.30
Disk inside diameter D_i, in.	0.55	1.10	1.10
Disk thickness t, in. (μm)	0.002 (50)	0.002 (50)	0.002 (50)
Slot depth b, in. (μm)	0.0007874 (20)	0.0007874 (20)	0.0007874 (20)
Slot width w, in.	0.021	0.021	0.021
No. of slots/disk N_s	45	90	90
No. of disks/stack N_d	576	1902	538
Stack height H, in.	1.152	3.804	1.076
No. of stacks required/tank	12	1	2
Volumetric flow rate of propellant/tank, ft^3/s at 70°F	0.00037[b]	0.001234[c]	0.001234
Stack-design flow rate, ft^3/s at 70°F	0.00037	0.001234	0.000617
Oxidizer bubble-point pressure $(\Delta P_b)_{ox}$, psid	0.392	0.392	0.392
Fuel bubble-point pressure $(\Delta P_b)_{fu}$, psid	0.52	0.52	0.52
Oxidizer stack frictional pressure drop $(\Delta P_f)_{ox}$, psid	0.087	0.087	0.15
Fuel stack frictional pressure drop $(\Delta P_f)_{fu}$, psid	0.174	0.174	0.306
Oxidizer stack flow margin $(\Delta P_b/\Delta P_f)_{ox}$	4.53	4.53	2.61
Fuel stack flow margin $(\Delta P_b/\Delta P_f)_{fu}$	3.0	3.0	1.7
Stack weight (without end supports), lbm	0.014	0.19	0.054
Stack material	Titanium	Titanium	Titanium

[a]Same stack design for both oxidizer and fuel tanks. Tubular manifold outside diameter $d_o = 0.25$ in. Tubular manifold inside diameter $d_i = 0.21$ in. Length of tubular manifold $= \pi D_T$. No. of zero-gravity manifolds = 2. No. of spin-feed manifolds = 1. Clearance between tank wall and zero-gravity manifold (fillet thickness) $t_f = 0.1$ in. Manifold material = titanium.

[b]Based on six 5-lbf thrusters firing simultaneously in steady state.

[c]Based on one 110-lbf thruster firing.

tions. Providing a common tank outlet also simplifies manufacturing of tank shell and propellant manifold routing. The single large stack in the spin-feed gallery is designed to accommodate the larger flow rate demand of the 110-lbf thruster firing during the apogee maneuver.

As is evident in Fig. 4, the galleries are located close to the tank wall (with about 0.1-in. clearance) to position propellant close to the galleries for expulsion on demand. The gallery acts as a vane to maintain propellant control until the propellant in the tank is nearly depleted. This gives expulsion efficiency of greater than 99.9% of the total liquid volume in the tank.

The design illustrated in Fig. 4 can be easily adapted to incorporate a liquid trap at the bottom of the tank. Such a feature would be needed when the center of mass of the satellite needs to be known very accurately for precise pointing requirements and for other orbital operations. The trap can be designed to contain the liquid required for orbital control of the satellite.

It should be noted that the orientation of the galleries and the sizing of the etched disk stacks are driven by the particular application and specific mission requirements and will be different for each application.

Operation

The operation of the tank and the associated liquid orientations during the three distinct phases of a spacecraft mission—ground-servicing operations, spinning operations, and non-spinning (low gravity) operations—are illustrated in Fig. 5 and described in this section.

Ground-Servicing Operations

Major ground-servicing operation-propellant loading ensures that during this process the internal volume of the entire PMD is primed with the propellant and that no gases are trapped in the PMD as explained subsequently.

During the propellant loading process, the propellant enters the gallery through the bottom port and fills the galleries until the liquid head is sufficiently high to cause the head pressure to overcome the bubble-point pressure of the bottom stacks, which is 0.52 psid (psi difference) for MMH stack and 0.39 psid for NTO stack. Once these bubble-point pressures have been exceeded, the fluid starts flowing through the bottom stack into the tank, and the excess head in the galleries decreases and becomes equal to the fluid height within the tank itself. The filling process continues with the liquid heights in the gallery and the tank always at the same level and the gas in the gallery continually being expelled from the unwetted stacks. As the fluid nears the topmost stacks, gas is continually expelled until the highest elements in the topmost stacks are wetted by the fluid inside the tank. Filling continues until the entire tank volume is filled and an overflow condition is achieved. The propellant is then off-loaded until the desired launch load is attained. The process of overfilling and then off-loading precludes the possibility of gas ingestion into the gallery. To facilitate ground draining and to minimize liquid residuals, two stacks of etched disks are provided at the tank outlet and integral to the outlet fitting (not shown in Fig. 4). Details of the ground-drain stacks are listed in Table 2.

Spinning-Phase Operations

During the apogee maneuver, the spacecraft is spinning with fill fractions in the range of 70–95% of the total tank volume and continues to spin until the tank reaches a fill fraction of about 20%, supplying propellant to the 110-lbf thruster. The spinning acceleration field is about $0.1g_E$. After completion of apogee maneuver, the spacecraft is spun down, and the liquid reorients to the zero-gravity configuration.

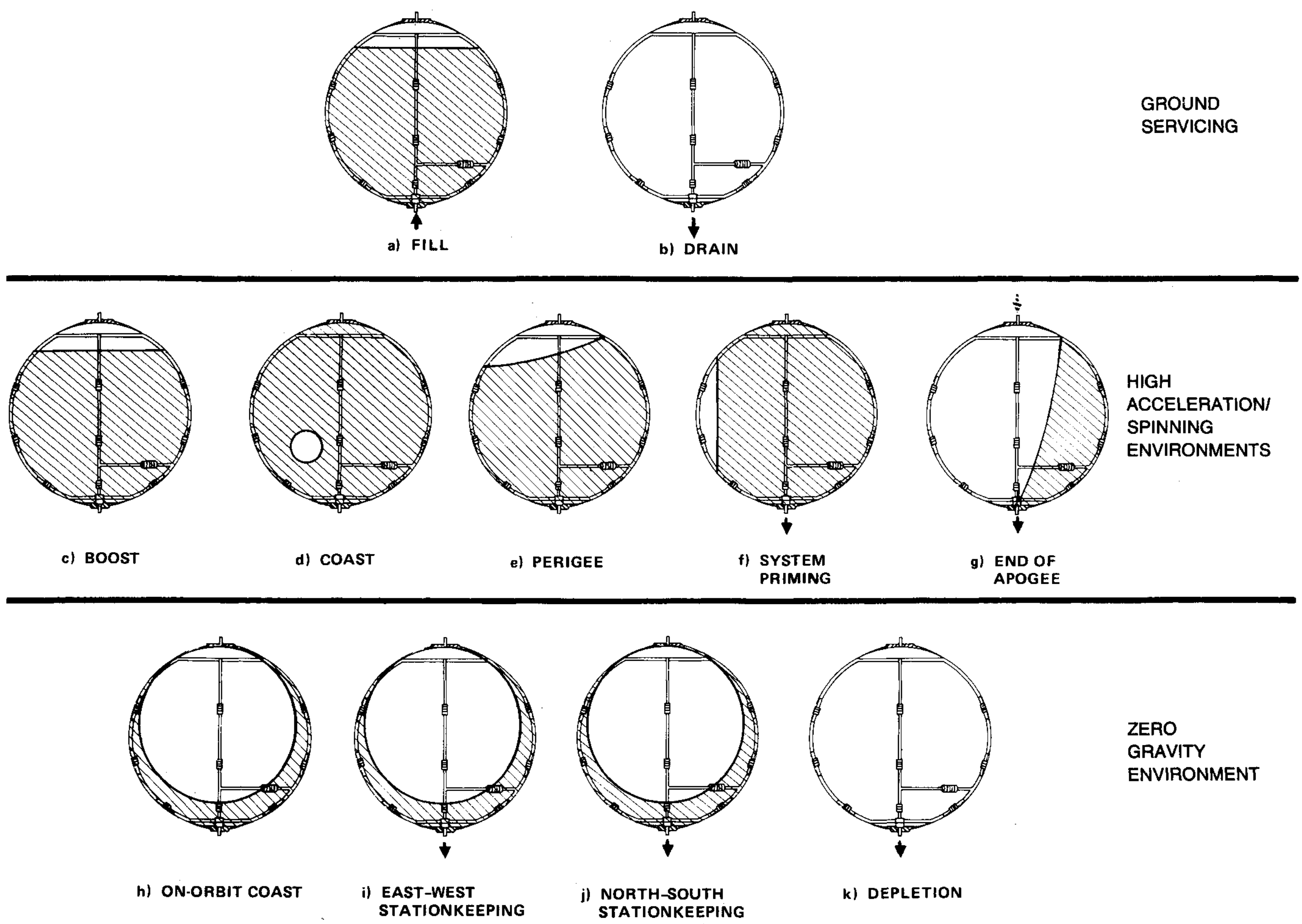

Fig. 5 Spacecraft operational sequence.

Nonspinning Operations

Orbital operations are performed in the zero-gravity environment by 5-lbf thrusters firing in various combinations for desired stationkeeping, with the liquid in the positions shown in Fig. 5. In geosynchronous satellites, the liquid coalesces near the gallery elements. As the tank is depleted, the liquid remains at the galleries and, since these feed elements (stacks) are located in the plane of the major maneuvers, expulsion of the liquid continues until the tank is nearly depleted.

Surface Tension and Hydraulic Design of Etched Disk Stacks

The etched disk stack is the basic PMD element. The surface tension, hydrostatic, and hydrodynamic principles governing the stack design under the various mission phases are discussed and analyzed in this section.

Bubble Point and Contact Angle

The principal liquid properties governing the stack design are the surface tension and its tendency to wet or adhere to the solid surface as evidenced by the contact angle. The surface tension forces within the etched disk slots are characterized by the minimum bubble-point pressure, which is the minimum ΔP required to force a gas bubble through an etched disk stack primed (wetted or filled) with a liquid. The bubble point is measured by a test commonly employed by filter manufacturers for determining the slot depth (pore opening) of the filter. In this test, the test specimen (filter) is immersed under standard conditions in a bath of liquid isopropyl alcohol (IPA), and the gas pressure in the specimen is gradually increased until the first bubble breaks through a pore to the IPA. The pressure at which the first bubble breaks through is called the bubble-point pressure and is an indication of the pore size. The theoretical bubble point ΔP_b in a rectangular slot of depth b, as derived from the principle of capillary height between parallel plates, is expressed as

$$\Delta P_b = P_g - P_\ell = \frac{2\sigma \cos\theta}{b} \tag{1}$$

For most liquid-metal contacts, the contact angle θ varies from 0 deg to at the most 5 deg and does not have significant effect on the bubble point. The fuel and oxidizer bubble points are plotted in Fig. 6 as a function of slot depth. The higher bubble point of the fuel is due to its higher surface tension. Relevant

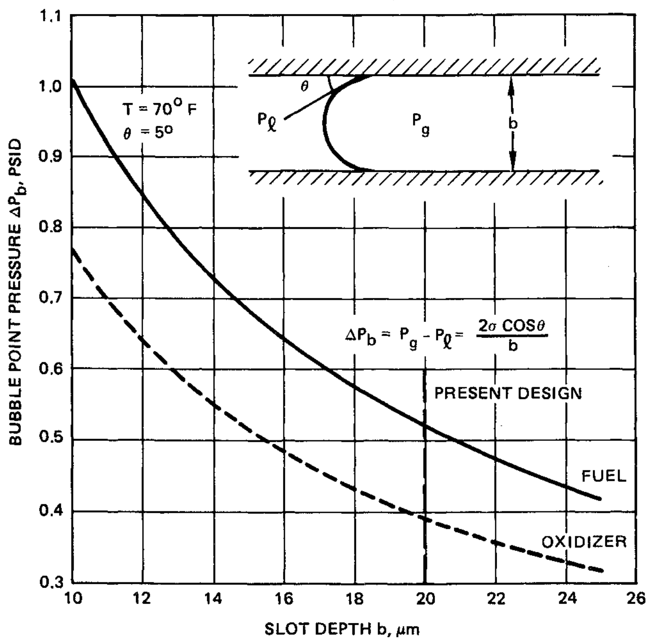

Fig. 6 Bubble-point pressure in etched disk slot.

Table 3 Fluid properties at 70°F

Fluid	Density, g/cm³ (lbm/ft³)	Viscosity, μ, centipoise (lbm/ft-s)	Surface tension, σ, dynes/cm (lbf/ft)
MMH	0.874 (54.54)	0.803 (0.000539)	34.2 (0.00234)
NTO	1.44 (90.04)	0.408 (0.000274)	25.8 (0.00177)
IPA	0.78 (48.4)	2.5 (0.00168)	21.7 (0.00149)
Freon	1.56 (55.3)	0.694 (0.000466)	17.8 (0.00122)
Water	1.0 (62.4)	0.98 (0.000658)	72.75 (0.00499)

propellant properties are cited in Table 3, along with the properties of referee fluids and water, for comparison purposes. In the present design, all stacks within the tank are sized to provide the same bubble point using a slot depth of 20 μm. In an experimental gallery containing 400 disks with etched slot depths of 10 μm, the stack-to-stack bubble point was found to vary by ±3% of the predicted value.[1] With the larger 20-μm slot depth of the present design, the percentage variation in bubble point is expected to be even smaller.

Once the stacks are assembled and cleaned, clean referee fluids (Freon for the oxidizer and IPA for the fuel) are used to determine the bubble point to verify that the allowable passage size has been maintained within the tolerance limits. Subsequently, the "boil point" is determined to verify uniformity of the passage dimensions and ensure that the stack pressure drop is uniform. (The boil point of a stack is defined as the pressure at which a significant number of flow passages exceed their respective bubble points.) Following these static tests, the stack is flow tested to determine the frictional pressure drop to verify design values and finally the stack is subjected to a cleanliness verification test.

To provide gas-free propellant throughout the mission, the bubble-point pressure ΔP_b within the etched slots must be greater than 1) the hydrostatic head ΔP_h, exerted on the stacks exposed to the tank ullage during nonflow and spin conditions (i.e., $\Delta P_b/\Delta P_h > 1$) and 2) the hydrodynamic (frictional) losses ΔP_f, during liquid flow through the slots, in spinning and zero-gravity operations (i.e., $\Delta P_b/\Delta P_f > 1$).

Ullage Hydrostatic Head

The etched disk slot design must be adequate to prevent "breakdown" of the surface tension forces against hydrostatic head of tank ullage under 1) normal Earth gravity g_E, while on ground; 2) high thrust acceleration g_T, during boost and perigee phases; and 3) spin-induced accelerations g_S, during apogee maneuvers.

The maximum height to which a stack can be exposed in the ullage without gas ingestion depends upon the balance between the hydrostatic head and the bubble-point pressure. Insofar as $\Delta P_h \leq \Delta P_b$, the gas will not break through the etched disk slots and vice versa.

The hydrostatic pressure is given by

$$\Delta P_h = \rho g h \tag{2}$$

Equating the slot bubble point ΔP_b [Eq. (1)] and hydrostatic pressure ΔP_h [Eq. (2)] and solving for h gives

$$h = \frac{2\sigma \cos\theta}{\rho g b} \tag{3}$$

where h is the maximum height in the ullage to which a primed stack can be exposed without gas ingestion. In Eq. (3), the acceleration g depends upon whether the spacecraft is subjected to earth gravity g_E or to the high thrust levels that occur during launch and solid perigee kick motor (PKM) firing g_T or to spin-induced acceleration environments g_S.

Maximum ullage exposed heights for fuel and oxidizer stacks are plotted as a function of spacecraft acceleration environments in Fig. 7. As seen from Fig. 7, the oxidizer supports only one-half the hydrostatic head due to its lower surface tension and greater density compared to the fuel. Thus, the hydrostatic design of a PMD for a conventional bipropellant system is governed by the oxidizer properties.

Hydrostatic Head on Ground

Since the tanks are loaded to initial fill fraction of about 95% of the total tank volume and no stack is usually exposed to the ullage at such high fill fractions (i.e., all stacks are submerged as shown in Fig. 5a), gas breakthrough will not occur on ground.

Hydrostatic Head During Boost/PKM Phase

During launch, the spacecraft experiences acceleration levels of about 5-8 times the normal Earth gravity. During PKM firing, the acceleration levels are 3-4 times that of normal Earth gravity. The maximum height of the stack that can be exposed to the ullage without gas ingestion is about 1.5 in. for the fuel tank stack and 0.7 in. for the oxidizer tank stack based on worst-case acceleration levels of $8g_E$, as plotted in Fig. 7. The lower number of 0.7 in. sets the design limit. Thus, gas breakthrough is possible during launch if the topmost stacks are uncovered by more than 0.7 in. Two design alternatives are available to preclude the gas-breakthrough possibility:

1) The PMD is usually designed so that the highest stack element is always submerged during high-acceleration periods (i.e., launch, ascent, and PKM burn), as shown in Figs. 5c and 5e.

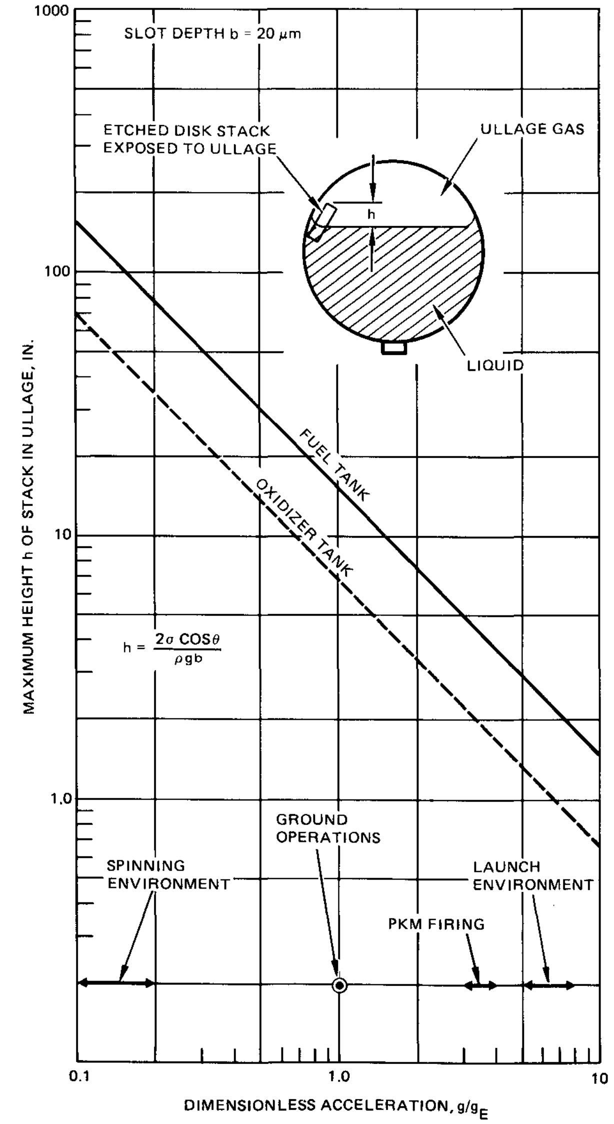

Fig. 7 Maximum stack height in ullage for liquid retention.

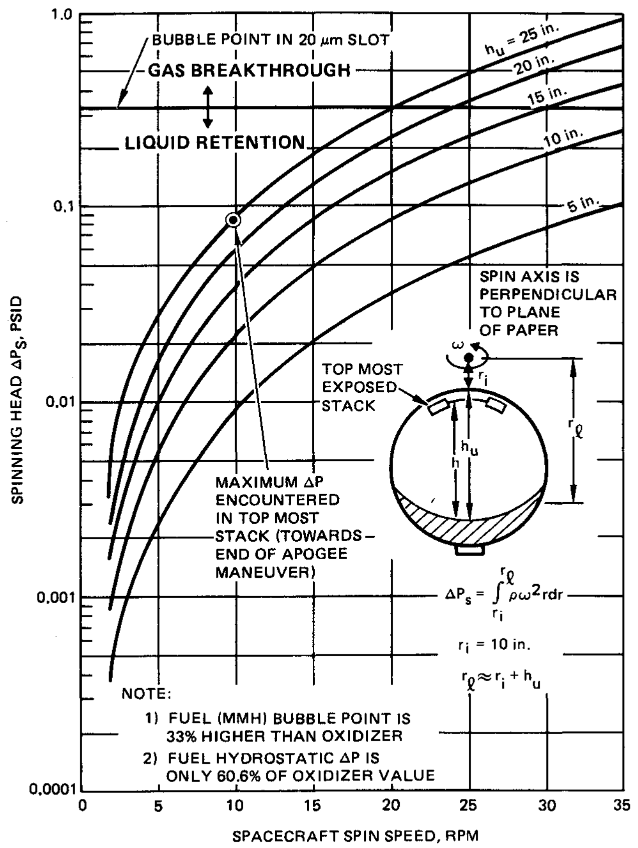

Fig. 8 Bubble-point and hydrostatic ΔP in spinning oxidizer tank.

2) The bubble point of the exposed stacks can be increased by reducing the slot depth b if necessary. However, this alternative (having stacks with two different bubble points within the same PMD) is not desirable, since two bubble-point tests and two flow tests are required instead of a single one. Furthermore, during flow conditions, the stacks with smaller slot depths will cause higher pressure drop because the frictional losses increase significantly with a decrease in slot depth, as will be shown later.

Even if the tank fill fractions are lower and the topmost stacks are uncovered by more than 0.7 in., leading to subsequent gas ingestion during this phase of the mission, it is not considered catastrophic to subsequent operation of the PMD. This is because the stacks, if exposed, could be rewetted either by the fluid in the tank "washing" over the exposed elements upon removal of the induced boost or PKM acceleration vector or by capillary motion of the liquid within the tubing of the galleries.

Spin-Induced Accelerations

During boost and PKM firing, the thrust acceleration levels are high, but all of the stacks are completely submerged in the liquid, since the tanks are about 95% full. Conversely, during the apogee maneuvers, the thrust acceleration levels are low but the ullage height increases as the propellant is expelled from the tank. As a result several stacks are exposed to the ullage as shown in Fig. 5g. It is important to ensure that the surface tension forces are sufficiently high to prevent gas breakthrough against hydrostatic head in spin-induced environments. The hydrostatic ΔP experienced by a ullage exposed stack in a spinning tank varies with ullage height and is

$$\Delta P_s = \frac{\rho\omega^2}{2}\left[r_\ell^2 - (r_\ell - h_u)^2\right] = \rho\omega^2 h_u \left(r_\ell - \frac{h_u}{2}\right) \tag{4}$$

Toward the end of apogee maneuver, the tanks are only about 20% full and the ullage height is maximum (about 25 in.), representing the maximum spin head. The spacecraft spin rate during apogee maneuver is 10 rpm, thus $g_S = \omega^2 r_\ell$ is about 3.7 ft/s^2. The slot bubble point and spin field ΔP for various ullage heights of the oxidizer tank are plotted against the spin speed in Fig. 8. As seen from Fig. 8, a maximum hydrostatic ΔP of 0.083 psid is experienced by the ullage exposed stacks in the oxidizer tank at maximum ullage height of 25 in. Since the oxidizer bubble point in the 20-μm slots is 0.39 psid, the PMD provides a hydrostatic margin of 4.7 against gas breakthrough in spinning environment. The corresponding hydrostatic margin offered by the fuel tank stacks is 10.3 due to the higher surface tension and lower density of the fuel as compared with the oxidizer.

Hydrodynamic Head

In the design of etched flow passages, the ratio of design bubble point to frictional losses (called flow margin) is of prime importance to ensure that the galleries as tested on the ground will guarantee proper on-orbit operations upon thruster flow demands. The present design provides identical flow margins for all stacks under flow conditions. This feature ensures that precise control under flow is maintained whether the flow demand is high (as it is in the large stack during 110-lbf thruster firing in spinning environment), or small (as it is during 5-lbf thruster firing in low-gravity environment). In addition, identical flow margins of the large and small stacks ensure uniformity of the flow passages, regardless of the stack diameter or height, and simplifies testing, since only one parameter (i.e., one bubble point and one flow ΔP) is required to be tested for all etched disk sizes.

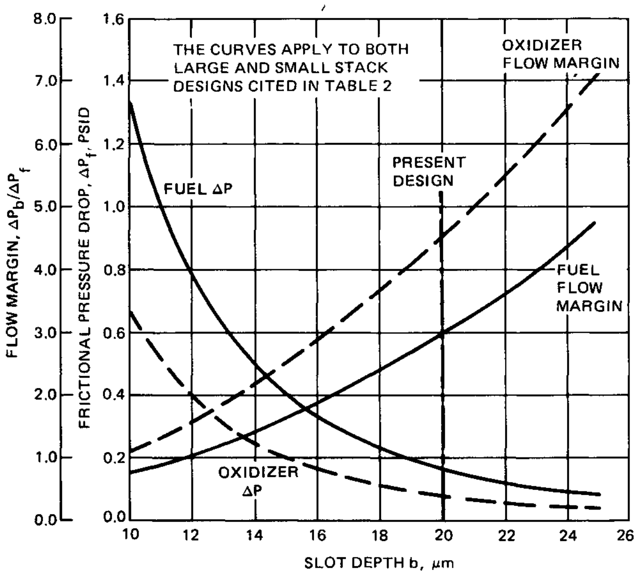

Fig. 9 Frictional losses and flow margins in etched disk stack.

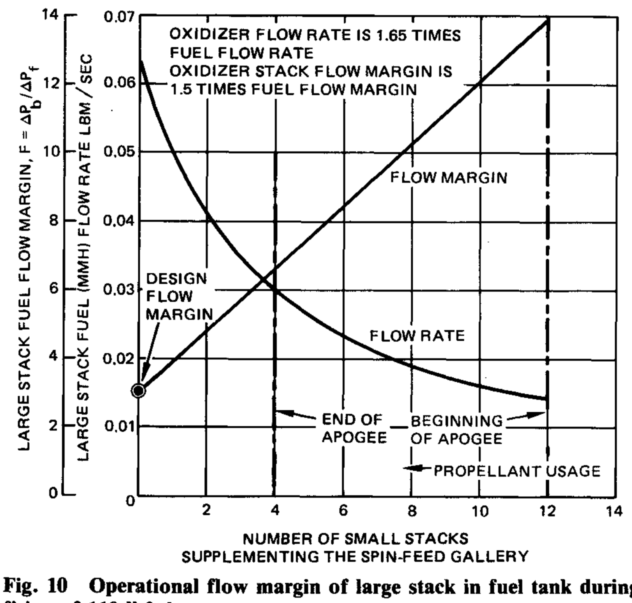

Fig. 10 Operational flow margin of large stack in fuel tank during firing of 110-lbf thruster.

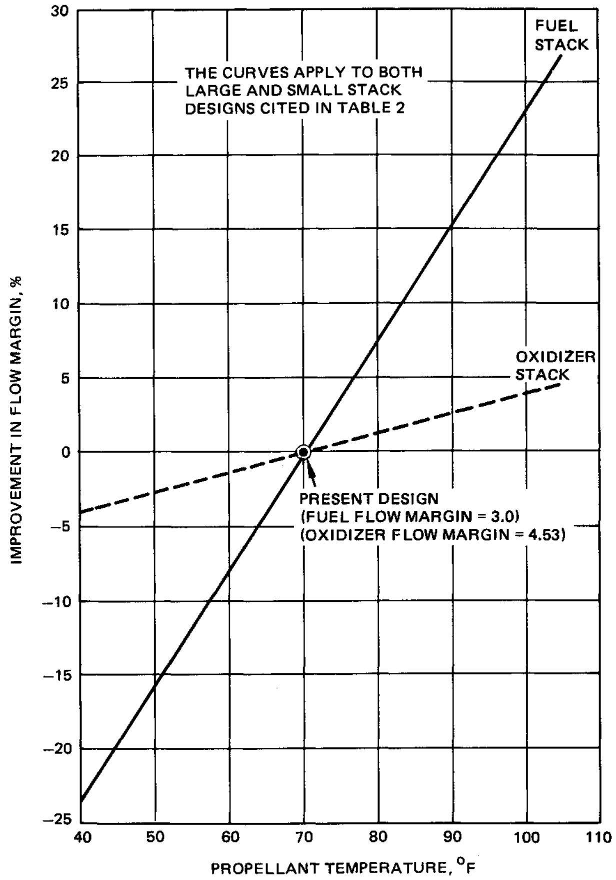

Fig. 11 Effect of propellant temperature on stack flow margin.

Stack-Design Flow Rates

Flow through etched disk slots is laminar and, as such, frictional pressure drop is directly proportional to flow rate through the stack. The stack design must provide a preselected ratio of bubble point to frictional ΔP based on worst-case design flow rates, which depends on the number of thrusters firing at the same time. In the worst case of six 5-lbf bipropellant thrusters fired simultaneously in steady-state conditions, the respective oxidizer and fuel flow rates are 0.0667 lbm/s and 0.0404 lbm/s. Furthermore, since the propulsion subsystem incorporates two oxidizer and two fuel tanks, the worst-case on-orbit flow rates per tank are 0.0333 lbm/s for the oxidizer tank and 0.0202 1bm/s for the fuel tank. This flow demand is shared equally by all of the stationkeeping stacks (small stacks) within the PMD. The stack design discussed in this paper is, however, based on highly conservative assumption that only one stack supplies the entire tank flow demand. Thus, the small stack for the oxidizer tank is designed for an oxidizer flow rate of 0.0333 lbm/s, and the fuel tank stack is designed for a fuel flow rate of 0.0202 1bm/s. The fuel tank stack is designed to provide flow margin of 3.0 against the slot bubble point. This design gives a higher flow margin of 4.53 for the oxidizer tank stack because of the lower viscosity of oxidizer. In reality, a design flow margin of 3.0 for the fuel tank stack corresponds to operational flow margin of 36.0 for the fuel tank PMD and 54.0 for the oxidizer tank PMD, since all 12 stacks share the flow demand.

The single large stack in the spin-feed gallery supplies the larger flow rate demand of the 110-lbf thruster, which is 0.11 lbm/s of oxidizer per tank and 0.0667 lbm/s of fuel per tank

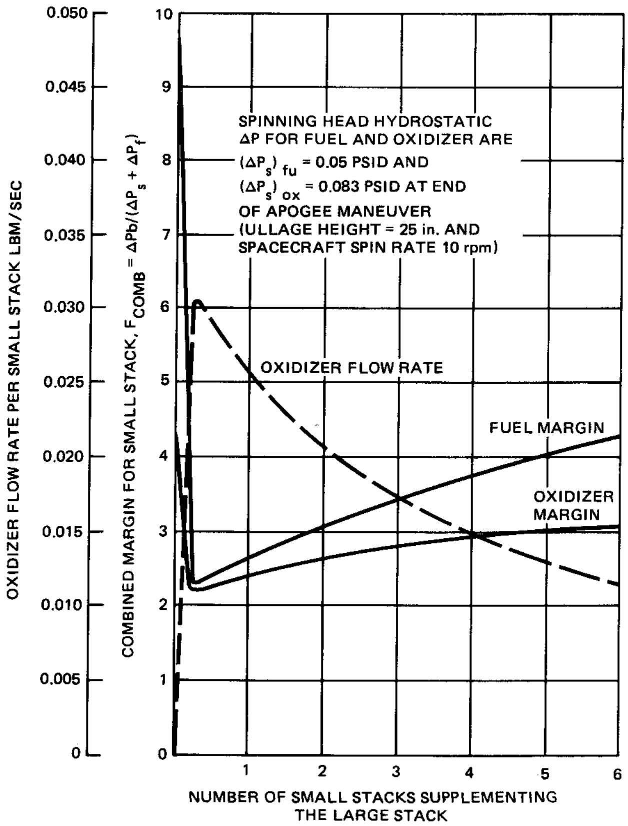

Fig. 12 Combined margin against gas ingestion at end of apogee maneuver.

in a four-tank system. The large stack design is based on these flow rates. As with the small stack, the large stack in the fuel tank is designed to provide a design flow margin of 3.0 against the slot bubble point. In reality, a flow margin of greater than 3.0 is achieved by this stack, since a number of small stacks submerged in the liquid also supplement the flow demand, as Fig. 5g shows.

Frictional ΔP in Etched Disk Slots

The frictional losses depend upon the mass flow rate, flow velocity, and Reynolds number in the slot. Since the flow rate corresponding to nominal thruster operation is distributed into the numerous slots within the stack, the slot flow is highly laminar (porous) with $Re = \rho u b/\mu$ of the order of unity and the slot flow velocity u of about 0.1 ft/s at design flow rates listed in Table 2. The frictional pressure drop in laminar flow through a rectangular slot is given as[3]

$$\Delta P_f = 12\dot{m}_s\left(\frac{\mu}{\rho}\right)\left(\frac{L}{b^3 w}\right) \tag{5}$$

Predictions of Eq. (5) are found to be in excellent agreement with test data in water.

Noting that $\dot{m}_s = \dot{m}/N_s N_d$, and $L = (D_o - D_i)/2$, Eq. (5) can be rewritten as

$$\Delta P_f = 6\dot{m}\left(\frac{\mu}{\rho}\right)\left(\frac{D_o - D_i}{b^3 w N_s N_d}\right) \tag{6}$$

The stack should be designed to minimize frictional losses. For this, the slot depth b should be as deep as possible. The maximum slot depth is, however, limited by the disk thickness. To ensure adequate mechanical strength of the disk, the maximum slot depth is usually limited to one-half of the disk thickness. In addition to reducing frictional losses, deepening the slot lightens the disk, since more disk material is removed in etching deeper slots. Frictional losses for oxidizer and fuel stacks are plotted in Fig. 9 as a function of slot depth and apply to both the small and large stack designs with the parameters cited in Table 2.

It is noted from Eq. (6) that the frictional losses in laminar flow are proportional to $\dot{m}\mu/\rho$, where $\dot{m}/\rho$ is the stack volumetric flow rate. For conventional bipropellant thrusters operating at nominal oxidizer-to-fuel mass mixture ratio of 1.65, the volumetric flow rate is the same for both the oxidizer and the fuel. Therefore,

$$\frac{(\Delta P_f)_{\rm fu}}{(\Delta P_f)_{\rm ox}} = \frac{\mu_{\rm fu}}{\mu_{\rm ox}} \tag{7}$$

Since the ratio of fuel to oxidizer absolute viscosity is about 2.0, frictional losses in the slot due to fuel flow are twice as high as those due to oxidizer flow, as can be seen from Fig. 9. This is an important factor in the stack design, as it results in the hydrodynamic design of the stack being governed by the fuel. Conversely, the hydrostatic design of the stack is governed by the oxidizer, as noted earlier.

Flow Margin

For the etched disk stack to supply gas-free liquid to the tank outlet, the flow margin $F = \Delta P_b/\Delta P_f$ must be greater than unity. Dividing Eq. (1) by Eq. (6) for slot flow gives the flow margin

$$F = \frac{1}{3\dot{m}}\left(\frac{\rho\sigma\cos\theta}{\mu}\right)\left(\frac{b^2 w N_s N_d}{D_o - D_i}\right) \tag{8}$$

Based on the fluid properties and nominal flow rates of oxidizer and fuel for oxidizer-to-fuel mass mixture ratio of 1.65, the oxidizer stack offers a flow margin 1.5 times greater than the fuel stack. Thus, a specified design margin on fuel stack offers 1.5 times more conservative flow margin for the oxidizer stack. Flow margins for oxidizer and fuel are plotted against slot depth in Fig. 9 and apply to both the "large" and "small" stack designs with the parameters cited in Table 2. As mentioned earlier, the worst-case operational flow margins for the small stack will be 12 times greater than the design flow margins, since all of the 12 stacks will be feeding the station-keeping galleries during low-gravity operations.

The operational flow margins for the spin-feed stack will also be greater than the design flow margin of 3.0, depending upon the fill fraction, enabling a number of small thrusters to supplement the large stack, which decreases the frictional losses through the large stack and increases its flow margin. The flow is shared between the large stack and a number of small stacks in order to maintain equal ΔP in all of the stacks. Operational flow margins and flow rates for the large stack are plotted in Fig. 10.

As seen from Eq. (8), the flow margin is proportional to the fluid properties group $\sigma\rho/\mu$, which, in turn, varies with temperature. The values of these parameters decrease with an increase in temperature. However, the decrease is most predominant for viscosity. The effect of propellant temperature on flow margin is illustrated in Fig. 11. The present stack design is based on propellant temperatures of 70°F. Designing at lower temperatures (say, 40°F) would require about a 25% increase in the stack height (and weight) to maintain the design-fuel flow margin.

Combined Hydrostatic and Hydrodynamic Margin

The flow requirements during PKM burn are met by one or two 5-lbf thrusters firing to correct for nutation effects. Since the acceleration level is high and the liquid/gas interface is well defined, and since all stacks are completely submerged, the combined effects are not significant. During the apogee firing, after the PMD stacks become exposed under low-gravity environments, the worst case occurs very near the end of the final apogee burn as the spin head is maximum at this point. Under this condition, the margin (combining the frictional and gravitational forces) must be greater than unity to prevent gas ingestion. The combined margin is given as

$$F_c = \frac{\Delta P_b}{\Delta P_s + \Delta P_f} \tag{9}$$

Toward the end of apogee maneuver, as seen earlier, the maximum hydrostatic ΔP in the oxidizer tank stack is 0.083 psid under a spinning field of 10 rpm. The corresponding hydrostatic ΔP in the fuel tank is 0.05 psid. At this point, about 4–6 small stacks and a single large stack are sharing the flow demand of the 110-lbf thruster (which is 0.1101 lbm/s per oxidizer tank and 0.0667 lbm/s per fuel tank). The flow is shared between the submerged large and small stacks in order to maintain equal ΔP in all of the stacks. Combined hydrostatic and flow losses decrease resistance to gas ingestion in exposed stack slots and thus the combined margin decreases. Combined margin and small stack flow rates are plotted in Fig. 12 as a function of the number of small stacks supplementing the spin-feed gallery during the firing of the 110-lbf thruster. As seen from Fig. 12, the combined margin is governed by the oxidizer and is 2.9 with four small stacks feeding the gallery. The corresponding margin achieved in the fuel tank is 3.8. Since the margin is comfortably greater than unity, gas ingestion will not occur.

Frictional Losses in Tank

The frictional losses within the propellant tank include losses in the PMD stacks, manifolds, and ground-drain stacks at the tank outlet. These losses are maximum during the operation of the 110-lbf thruster and are estimated to be less than 0.5 psid. During on-orbit operations of the small thrusters, these losses are negligible. Thus, the tank ΔP is too small to have a measurable adverse effect on the thruster specific impulse.

Propellant Residuals and Expulsion Efficiency

As the spacecraft is nearing the end of life, small residual amounts of propellant will stick to the PMD and become unusable. These residuals are both external and internal to the PMD. The external residuals represent the clearance (fillet) volume between the tank internal surface and the PMD. The internal residuals represent the internal volumes of the tubular manifolds and the total number of stacks. The expulsion efficiency is the measure of usable propellants and is calculated to be greater than 99.9%.[4]

When the spacecraft is nearing the end of life, gas ingestion may occur if the stacks become uncovered. These possibilities have been examined in depth,[4] and the results of the analysis indicate no gas ingestion at end of life.

Conclusions

1) A PMD concept employing chemically etched disk stacks as a controlling surface tension element is described.

2) The surface thermodynamic, hydrostatic, and hydronamic principles underlying the design of etched flow passages are discussed in depth.

3) A preliminary PMD design is presented for a geosynchronous spacecraft operating in both spinning and zero-gravity environments.

4) The etched flow passages provide high safety margins against gas break through during all of the operational phases of the mission.

5) The PMD provides expulsion efficiency of greater than 99.9% and weighs less than 2 lb.

6) The design is rugged and is based on well-proven technology and offers simplicity of fabrication, installation, and testing.

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