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Propellant Management Device Conceptual Design and Analysis: Galleries

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PROPELLANT MANAGEMENT DEVICE CONCEPTUAL DESIGN AND ANALYSIS: GALLERIES

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ABSTRACT

While surface tension devices have been used in liquid propellant tanks for over thirty years, the conceptual design process and the analytical methods used to verify performance have been closely held by propellant management device (PMD) designers. This paper is the fourth in a series which will address the process and the techniques developed and used by PMD Technology to design and verify a PMD component - the gallery.[1, 2, 3]

All areas of concern inherent in gallery design and implementation will be addressed - starting from the dictating requirements, proceeding into the design configuration choice, and ending with required performance analysis. The result is a cohesive process by which one may design and verify the performance of the gallery PMD component.

I. INTRODUCTION

Surface tension forces are negligible in most engineering problems. However, in the low gravity environment of orbiting vehicles, surface tension forces are significant and often dictate the location and orientation of liquid within vessels, conduits, etc. By carefully designing structures within a propellant tank, one can utilize these forces to ensure gas free propellant delivery. These structures have come to be known as propellant management devices or PMDs.

Traditionally, PMDs are designed for each specific mission scenario and tank size. As a result, PMDs can be found in numerous sizes and configurations. PMD components can be classified into two broad categories: control devices and communication devices.[4] By definition, communication PMDs provide gas free propellant delivery by establishing a communication path between the bulk of the propellant and the outlet or another device component such as a trap. The gallery type PMD is a communication device.

A gallery PMD component is defined as a structure which creates an internal, or closed, flow path along which propellant can flow (the closed path definition excludes vanes which provide an open flow path external to the structure). This definition of galleries includes screen covered channels, porous element pick up assemblies connected by tubing, and liners. The typical gallery is a rectangular tube which follows the tank wall contour and is covered with screen on the side facing the tank wall.

Because wetted porous elements can prevent gas penetration, propellant flows into the gallery through the porous element and then along the gallery without gas ingestion through the exposed porous elements. Figure 1 illustrates the flow into and within a simple gallery. The dashed lines represent screen and the shading represents liquid. The arrows show the fluid flow direction.

The PMD design process starts with the evaluation of the mission requirements to determine whether a gallery is suitable. Once suitability is established, the design configuration and the design details are explored. Finally, with the design established, a thorough analytical investigation is conducted to verify performance. This last step is important since typical performance verification relies entirely on analysis.

This paper progresses along the same track as the design process. Section II addresses the physics of galleries and presents the basic equations. Section III describes the uses of galleries and establishes the requirements leading to them. Section IV presents the major design choices and discusses the utility of each option. Finally, Section V presents the analytical techniques used by PMD Technology to verify gallery design.

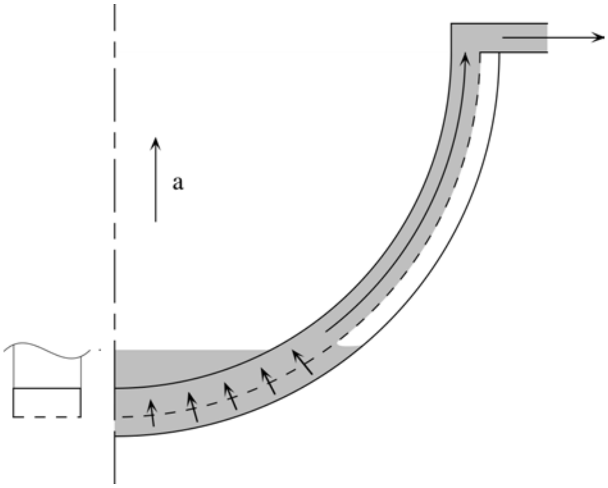

Figure 1. Gallery

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II. PHYSICS

The propellant illustrated in Figure 1 will flow up inside the gallery, against the hydrostatics, only if the porous element exposed to gas prevents the gas from entering the gallery. The wetted porous element will prevent gas ingestion until a specific head or pressure is applied. This head is known as the bubble point and depends upon the size of the pores in the porous element and the fluid properties.

In the most basic terms, gas will not enter the gallery if the bubble point is greater than the sum of the dynamic loads, the viscous losses, and the hydrostatics. If the bubble point is less than the loads, gas will enter the gallery and propellant flow against the hydrostatics will not occur. A simplified set of equations follows.

The pressure difference across the gas-liquid interface within the porous element resulting from the surface tension forces is defined by the Laplace-Pousielle equation:[5]

$$\Delta H \equiv \frac{P_{gas} - P_{liquid}}{\rho} = \frac{\sigma}{\rho}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (1)$$

Typically, the bubble point pressure is not analytically determined by equation (1) because the geometry and the statistics are complex whereas bubble point testing is straightforward. The bubble point is measured by increasing the pressure differential across a wetted porous element until gas penetrates.

In a gallery, the loads attempting to push gas through the porous element are:

$$\Delta H_{hydrostatic} = a\,\Delta z \qquad (2)$$

$$\Delta H_{pe\,flowlosses} = f\left(u_{pe}, \nu, pe\right) \qquad (3)$$

$$\Delta H_{arm\,flowlosses} = f\left(\mathrm{Re}\right)\frac{L}{D_{eq}}\frac{u_{arm}^{2}}{2} \qquad (4)$$

$$\Delta H_{dynamic\,head} = \frac{u_{arm}^{2}}{2} \qquad (5)$$

Very simply, one can equate the bubble point to the sum of the loads:

$$\frac{BP}{SF} \geq a\,\Delta z + f\left(u_{pe}, \nu, pe\right) + f\left(\mathrm{Re}\right)\frac{L}{D_{eq}}\frac{u_{arm}^{2}}{2} + \frac{u_{arm}^{2}}{2} \qquad (6)$$

Typically, this equation is solved for the safety factor on the porous element bubble point or the required submerged area given the desired safety factor and the specific screen and gallery.

The physics of gallery propellant delivery are shown schematically in Figure 2. While the physics of gallery flow can be explained by a relatively simply equation, the force balance does not address the loads applied to the PMD during transients which are often much worse. This basic force balance technique is a good tool for rough order of magnitude estimates and for feasibility studies, but because of its inherent errors and problems, it should not be used alone to validate or size a gallery.

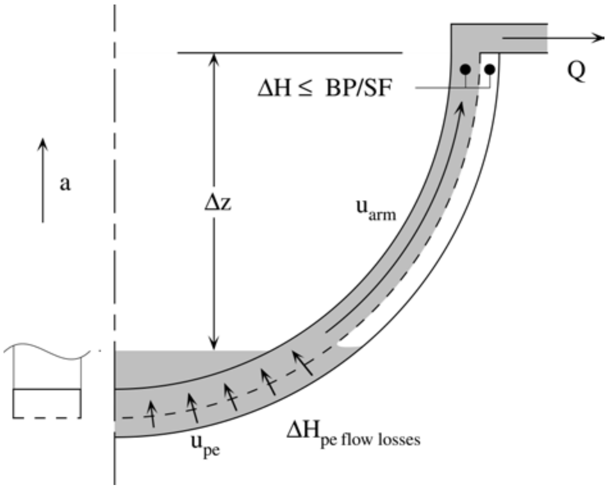


Figure 2. Physics of Galleries

The following aside presents an example of how this rough order of magnitude approach could be applied to a gallery arm located within a propellant tank.

Aside - Section II

Assume:

a) the propellant is nitrogen tetroxide (NTO) @ 68°F,
b) the acceleration is 0.005 g,
c) the gallery configuration is illustrated in Example Figure 1,
d) the screen is a 30x160 titanium plain Dutch weave,
e) the downstream submerged screen area is 2.0 in^2, and
f) the flow rate is 4.3 in^3/sec.

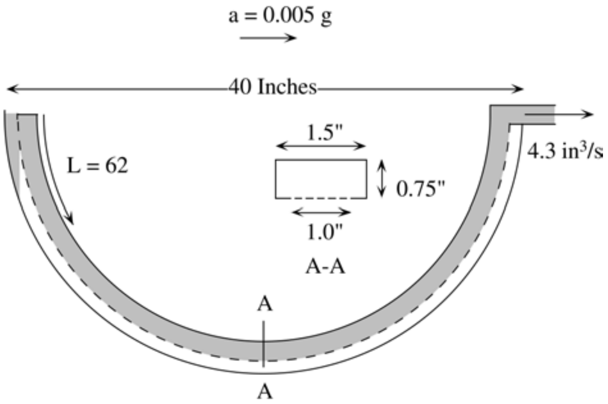
The bubble point of the screen in NTO is 1.9 g-in. Thus the gallery illustrated in Example Figure 1 will have a safety factor of 3.6 while supplying gas free propellant to the outlet.

Following are the specific calculations:

$$\Delta H_{hydrostatic} = (0.005\text{ g})\,(40\text{ in}) = 0.2\text{ g-in}$$

$$\Delta H_{pe\,flowlosses} = 0.27\text{ g-in (from test data)}$$

$$\Delta H_{arm\,flowlosses} = (0.032)\left(\frac{62\text{ in}}{1.0\text{ in}}\right)(0.019\text{ g-in}) = 0.038\text{ g-in}$$



Example Figure 1. Single Gallery Flow

$$\Delta H_{dynamic\,head} = \frac{(3.82\ \text{in/sec})^2}{2\ (386\ \text{in/s/g})} = 0.019\ \text{g-in}$$

$$\frac{1.9\ \text{g-in}}{3.6} \geq 0.2 + 0.27 + 0.038 + 0.019$$

$$0.53\ \text{g-in} \geq 0.53\ \text{g-in}$$

Alternatively, one could compute the submerged area of screen required to maintain a safety factor of three on the bubble point. In this example, a submerged screen area of 1.6 in^2 is required to maintain a safety factor of three.

Please note the small losses associated with the gallery arm as well as the small amount of submerged screen required for gas free flow with a safety factor of three. Of course, this analysis assumes steady flow.

III. USES OF GALLERIES

The principal advantages of surface tension PMDs over diaphragms or positive expulsion devices are low mass, high reliability (no moving parts), and good compatibility (100% titanium designs are possible). However, diaphragms can deliver gas free propellant in any attitude, in any quantity, and at almost any flow rate and acceleration. Because galleries can deliver propellant for any duration, they are one of the most mission flexible PMDs.

They are limited in acceleration and flow rate but these limitations typically do not preclude their use. However, galleries tend to be complex, heavy, expensive and not as reliable as alternative PMDs. Their use should be limited to those cases where mission flexibility is truly required.

Traditionally, the two principal uses of galleries are in flexible demand systems, and within traps and troughs where unrestricted access to the trap volume is required. Galleries are used in both monopropellant and bipropellant systems.

This section will address these uses and describe how viability is determined for each system. Before embarking upon the design of a gallery device, the requirements should be evaluated to determine if one is viable and if the subsequent design effort is justified. Since a gallery PMD can be the most complex, heavy, expensive, and risky PMD, viability is evaluated after the rejection of simpler PMD choices.

Flexible Demand Systems

Flexible demand systems require gas free delivery throughout thrusting in nonsettling directions for any duration. This required flexibility forces the PMD designer to look at total communication devices - ones that can bring propellant continuously from the propellant pool to the outlet. These include vanes and galleries. The vane PMD is by far the lightest, the simplest, the least costly, and the most reliable of PMDs. Unfortunately, vane PMDs are unable to provide propellant at moderately high flow rates or during moderately high accelerations. Galleries must be used. Figure 3 illustrates a gallery device fitted into a typical propellant tank.

Gallery PMDs can be designed to operate during accelerations as high as 0.1 g with fine porous elements. The acceleration capability of a gallery PMD is limited by the porous element pore size and the propellant properties.

The smaller the pore size, the higher the acceleration capability. Unfortunately, small pored porous elements generally have much higher flow losses as well as structural, cleanliness, and compatibility issues. A coarse plain Dutch weave titanium screen offers higher reliability and accelerations of 0.01 g are easily attainable in a typical satellite tank. Titanium perforated sheet and other titanium porous elements offer similar acceleration capability.

A PMD's flow rate capacity is a function of the flow losses through the porous element and thus the quantity of screen submerged. Pleating can be used to increase flow area and flow rate capacity. An all titanium PMD can be designed to accommodate a flow rate in excess of 10 in^3/sec with unpleated screen. Higher flow rates are possible with pleating and/or fine porous elements.

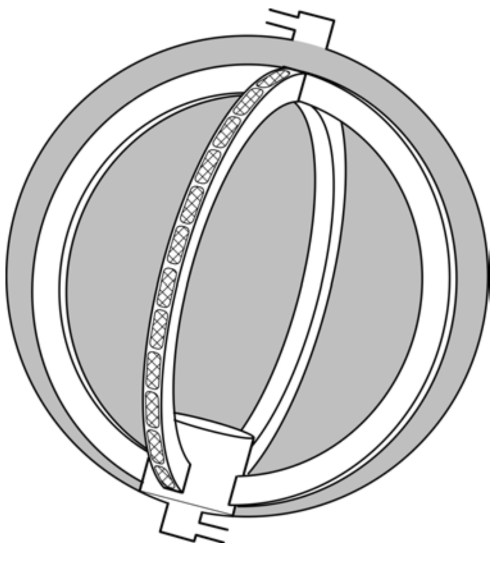


Figure 3. Gallery Concept for a Flexible Demand System

The flow rate and acceleration limits of galleries in flexible demand systems are related to one another and dependent upon four factors:

a) the tank size and geometry,
b) the gallery size,
c) the porous element type & the area per unit of gallery length, and
d) the allowable residual quantities.

Typically, the PMD designer is given these properties as well as acceleration and flow rate requirements and then must determine if a gallery PMD is viable.

Galleries can be rejected if the acceleration or the flow rate is so high that the surface tension forces within the porous element are unable to prevent gas penetration. The simplest method to determine the utility of a particular porous element for your application is to compute how much flow area is required to maintain a safety factor of three. The gallery arms losses are ignored since they must be kept very small to accommodate the ignition transient (see Section V Analysis). Thus the maximum tolerable porous element flow losses are

$$f\left(\frac{Q}{A_{pe}}, \nu, pe\right) = \frac{BP}{SF} - a\,\Delta z \tag{7}$$

The minimum flow area can then be calculated from the flow loss/flow velocity relationship.

If the flow area required of the candidate porous element is too large, a finer porous element with a higher bubble point should help. Unfortunately, very fine porous elements have many disadvantages including compatibility concerns, contamination potential, structural issues. 325x2300 twilled Dutch weave is the finest weave used in PMDs. It is available in stainless steel only, has a 2 micron nominal pore size (10 micron absolute), and has weft wires less than 0.001 inches in diameter. All of these present unique problems. In addition, because the weft wires are crushed against each other in twilled weaves, the flow losses are very high - often requiring that the screen be pleated to increase flow area. For increased reliability, fine screen should be avoided unless absolutely required.

On the other hand, a 50x250 plain Dutch weave screen is available in many materials, including titanium, has a 40 micron nominal pore size (60 micron absolute), and uses weft wires 0.004 inches in diameter. In addition, plain Dutch weaves have lower flow losses than twilled Dutch weaves. The wire diameter is not reduced in weaving which increases the screen's strength. Generally, plain Dutch weaves are a better choice if the required pore size is not too small.

The force balance analysis does not provide a complete model of the gallery as the transients must also be examined to ensure feasibility. Transient models are presented in the Analysis section.

While gallery PMDs are the most flexible and the easiest to explain to the uninitiated, they may not be suitable for all missions. For example, if a vehicle spins at 60 rpm, the hydrostatic loads produced by the spin rate could easily exceed the bubble point of the finest screen. For this application, a trough which holds sufficient propellant during 60 rpm spinning or, better, a trap which moves all of the screen into the propellant pool, thus eliminating all loads would be the better choice.

Even if a gallery device meets the mission requirements, it may not be the best choice. Typically galleries use large amounts of screen placed in proximity to the tank wall. This and the other factors decrease PMD reliability. Galleries should only be used where unlimited burn duration is required. They should be a last resort as all other PMD components are more reliable.

Within Traps and Troughs

Traps and troughs are PMD components designed to deliver fixed quantities of propellant. Often that propellant must be delivered in a long burn which requires that a gallery or pick up device be used within the trap or trough. Such a device is illustrated in Figure 4.

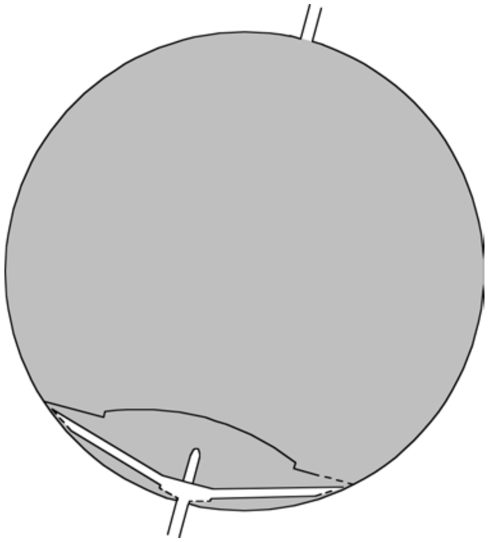


Figure 4. Gallery Concept for Within a Trap (or Trough)

Perforated sheet is often used on trap/trough galleries to eliminate the problems associated with screen. Perforated sheet does not wick and should not be used where gas might reside on both sides of the porous element.* Evaporation could compromise a nonwicking porous element. For this reason, most gallery PMDs in flexible demand systems use screen. However, the gallery device within a trap or trough is usually the last barrier to gas and thus gas should never be

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* Gas should never completely cover both sides of a porous element as wicking cannot resupply evaporated liquid regardless of wicking capability - the liquid must come from somewhere.

downstream of the porous element until depletion. Since evaporation cannot undermine the bubble point, perforated sheet is suitable for galleries within traps and troughs.

The viability of a gallery inside of a trap in terms of acceleration and flow rate is evaluated exactly as for a flexible demand system. A coarse porous element is more likely since the length scale is smaller.

IV. DESIGN

The simple gallery illustrated in Figure 1 is only one of numerous possible designs. This section will address qualitatively the various design issues including type, cross section, placement, and porous element choice.

Gallery Type

Gallery arms come in three design types: screen covered channels of a variety of cross sections, simple tubes linking pick up assemblies, and liners. These are illustrated in Figure 5.

A liner is a solid barrier which follows the wall contour. Porous elements are welded into the liner in positions where the propellant pool is expected to be. The flow path is established from the pool to the outlet within the gap between the liner and the wall.

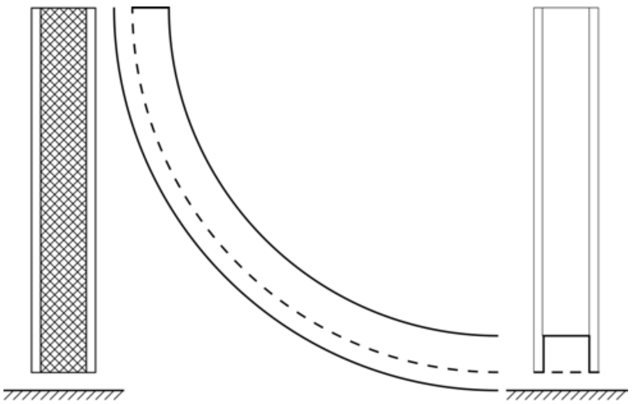
In general, the liner is the heaviest and least efficient gallery device. This is because a) a tank within a tank must be constructed and b) the gap is difficult to maintain, which results in a significantly larger gap than what is minimally required. Most, if not all, of the gap volume is residual.

Liners are used in very small tanks and within traps where the complexities of building very small channels or pick up assemblies is prohibitively costly. Liners should not be considered for large PMDs.

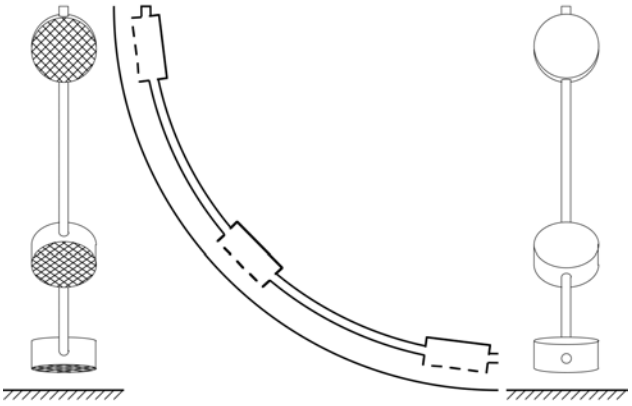
A pick up assembly type gallery reduces the porous element area by linking smaller pick up assemblies with tubing. Thus, porous elements are precisely placed only where they are required. Reducing screen area greatly increases reliability. In addition, the cost of manufacturing a PMD which consists of simple tubing and pick up assemblies is very attractive. Especially when those pick up assemblies are basically filter elements.

However, knowing precisely where propellant is at all times is not trivial. In a large tank, propellant may travel across the center of the tank. Is a pick up assembly required there? Generally not. But the answer requires a great deal of analysis to ensure that at least one pick up assembly retains liquid around it throughout all propellant reorientations.

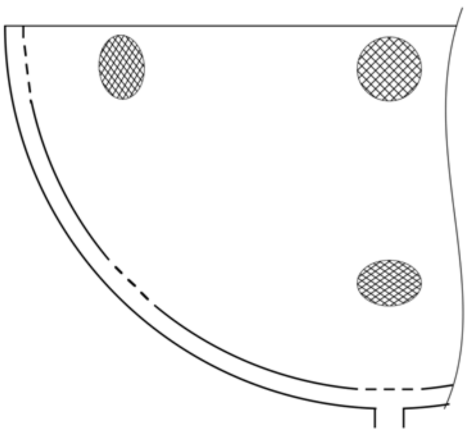
In addition, while each individual pick up assembly may wick, they do not necessarily communicate between each other. So it is important that each pick up assembly not be exposed to gas on both sides for long durations. Often gas will reside within the pick up assembly due to launch loads, horizontal handling, or end of life conditions. The pick up assembly PMD should be designed to push gas away from the porous element, preferably into the tubing.



Screen Covered Channel



Tubing Connecting Pick Up Assemblies



Liner

Figure 5. Gallery Types

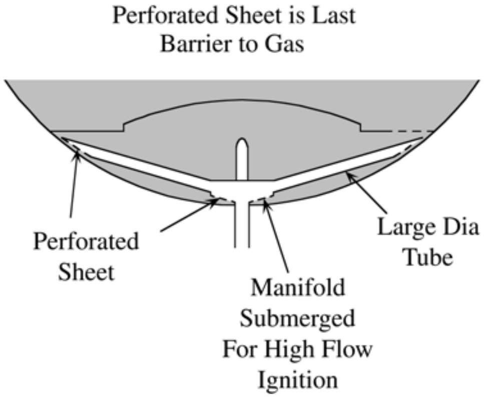


Figure 6. Successful Pick Up Assembly

Finally, the transients associated with accelerating the liquid in the tubes up to the demand rate are more difficult to accommodate with intermittent porous elements. Basically, when the thrusters are pulsed or propellant reorients from one region of the tank to another, the propellant within the gallery must be accelerated from zero velocity to the demand rate. This acceleration requires a finite duration. During this time, propellant is being acquired from the porous element closest to the outlet.

Intermittent pick up assemblies on the gallery results in higher velocities and a more difficult transient. The solution is to increase the porous element area or increase the tube diameter. The transients determine the size of the porous element and the tube diameter. A screen covered channel eases the transient effects. The screen along the channel's length contributes propellant during the transient and the channel cross sectional area is large. Both decrease the transient loads.

Figure 6 shows the pick up assembly in the trap of a successful communication satellite. The pick up assembly illustrated addresses successfully each of the above issues.

First, at least one of the perforated sheets on the ends of the arms is in contact with propellant throughout the mission. During reorientations, the propellant moves around the circumference of the trap - not across it - as a result of the corner formed between the tank and the horizontal section of trap housing.

Second, the pick up assembly is the final barrier to gas in the trap and, as such, will always be filled with propellant until depletion. Thus, the porous elements need not wick nor are they affected by evaporation. Perforated sheet is used.

Finally, the PMD delivers gas free propellant throughout the transients. During the highest flow conditions, the manifold perforated sheet is submerged which all but eliminates the worst transient. One will note that the tube size is relatively large at 0.8 inches in diameter.

The last design type, the screen covered channel, eliminates most of these issues and is by far the most popular gallery PMD.

With screen located along the entire length of the gallery and facing outboard toward the tank wall, the propellant reorientation issues are greatly reduced. Some propellant will tend to reorient in the gap between the tank wall and the gallery. Screen will always be in contact with this propellant allowing gas free access. The amount of propellant in the gap may be increased by increasing the width to the gallery.

At very high accelerations, the amount of propellant in the gap during a reorientation may be too small to accommodate the transient and alternative PMD devices may have to be implemented. This is rarely the case. In any event, precise screen placement is not required with screen along the entire channel length.

Evaporation is not a problem since the screen is continuous and can wick propellant to any screen experiencing evaporation. In addition, in zero g any gas within the arms will tend not fill the entire cross section of the arm and thus wetting the entire length of screen inside and out.

Finally, the transients are more easily accommodated with continuous screen. In addition, gallery arms tend to have relatively large cross sectional areas to support the screen. This also helps ease the transient loads.

Screen covered channels offer mission flexibility with reasonable performance. They are not necessarily the easiest to build but provide few operational problems.

Gallery Cross Section

Circular tubing is the first choice for a gallery cross section because of its low flow losses and ease of manufacturing. Unfortunately, if a porous element must be attached to it, a circular tube often becomes impossible to implement.

Simple tubes linking porous element pick up assemblies are always circular in cross section to a take advantage of low flow losses and ease of manufacture.

Unfortunately, most porous elements are not easily bent in two directions. Thus, a curved tube along a tank wall must have a flat region so that the porous element bends in only one direction. Cross section shapes which contain a flat region include ovals, rectangles, and triangles. All have been used with success. Several designs are shown in Figure 7.

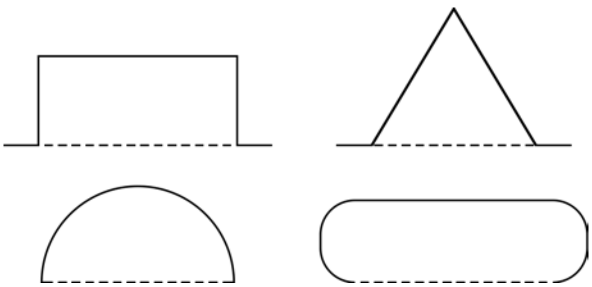


Figure 7. Sample Gallery Arm Cross Sections

The choice often is based on manufacturing concerns, though the cross sectional area and screen width is dictated by the PMD designer. Both the minimum screen area and cross sectional area are computed via the steady state or transient analysis. Most often the transient analysis is worst case and sizes all gallery components.

So many gallery cross sectional shapes have proven successful, it is difficult to choose the 'best'. Design and production engineers are best able to make this decision since its impact on PMD performance is relatively minor.

Gallery Number and Placement

Galleries need not be placed, as previously illustrated, along the tank wall extending radially and linearly from the propellant outlet (although this is the predominate position in existing designs). The three dictating factors for gallery placement are the path length, the separation between the gallery and the thrust vector, and the distance from the tank wall to the gallery.

The reason galleries typically extend from the outlet directly toward the opposite end of the tank is to minimize the path length from the propellant pool to the outlet. Longer paths result in larger flow losses and larger transient loads.

The placement of the galleries in the spacecraft coordinate system is also important. Many gallery PMDs contain just four arms. These arms are aligned with the thrust axes on the spacecraft and accelerations bisecting the arms are not a design requirement. Obviously, if an acceleration bisected the arms, a pool would form between the arms which the PMD could not access as shown in Figure 8. This could dramatically increase residuals.

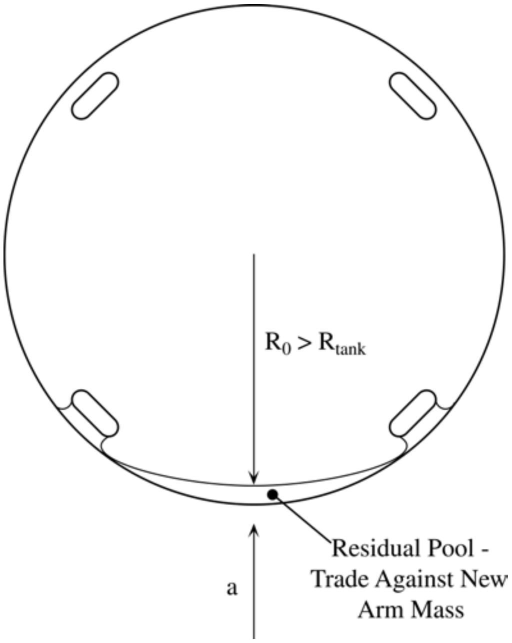


Figure 8. A Propellant Pool Between Arms

In omnidirectional systems, where a pool can form between arms, the number of gallery arms implemented is determined by trading the residual propellant mass in the pool against the mass of an additional arm. The pool volume can be estimated using the approach found in Reference 1. When the pool mass equals the arm mass (plus the additional residuals within the arm), adding another arm to the PMD will not reduce overall mass and the number of arms is optimal. Reference 6 describes a six arm gallery PMD which has omnidirectional capability.[6]

Galleries may or may not extend to the top of the tank. In a omnidirectional system, they must be able to reach propellant anywhere in the tank. In PMDs designed for fixed direction accelerations, such as lateral stationkeeping on a geosynchronous communication satellite, the galleries need only extend to the tank girth. However, ending the arms at the girth introduces a host of problems which must be addressed.

First, there are the structural and manufacturing issues associated with the attachment to the tank wall at the girth (cantilevering is generally not structurally possible).

Second, there are propellant reorientation problems. With the gallery arm ending at the girth, the propellant will reside principally in the outlet end of the tank in zero g. When a lateral acceleration occurs, the propellant will reorient to, and then past, the equilibrium position over the end of the arm. The arm could briefly lose contact with the propellant. Adequate propellant retention over the arm must be demonstrated. One solution is to run the arms to the top of the tank stopping the flow path at the girth.

The distance from the gallery to the tank wall should be large enough to prevent the arm from hitting or even coming close to the tank wall during vibration and should be small enough to pull the liquid up from the pool.

More than one screen has failed in qualification testing as a result of gallery contact with a tank wall during wet vibration. The fluid dynamic forces attempting to move the liquid in the small gap when the arm approaches the tank wall are immense. PMD Technology uses gaps as high as 0.75 inches to prevent gallery/tank wall impact.

However, moving the arm away from the wall can increase residuals if the arm loses contact with the pool. Fortunately, most galleries operate during accelerations which are small enough to allow significant propellant surface curvature.

This is illustrated in Figure 9. The arm remains in contact with the propellant until the pool is entirely consumed. Typical gallery/tank wall gaps are between 0.4 and 0.6 inches. Please note that liners have serious problems with vibration since they must maintain smaller gaps to reduce residuals.

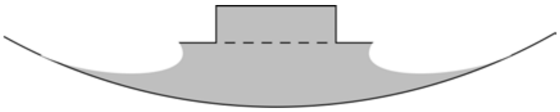


Figure 9. Propellant Rising in Gallery/Tank Wall Gap

Porous Elements

As previously illustrated, many types of porous elements have been used in gallery devices. Elements that wick are required if gas resides inside the gallery at anytime during the mission. Non-wicking porous elements can be implemented if gas never enters the gallery until depletion.

Section III Uses of Galleries roughly addressed the area of screen required and the pore size. Typically, the screen area and pore size are chosen as a result of the transient analysis which is explained in Section V Analysis.

Porous elements are typically placed on the outboard side of a gallery. This is to ensure a) that in zero g, the porous element is completely submerged in propellant and b) that during a reorientation, the porous element is in contact with some propellant.

Submerging all porous elements in propellant during zero g is not required but is good design practice. First, drying out of the screen is completely eliminated as a concern. Second, the ignition transient, which severely loads many galleries, is eliminated for most maneuvers, since the typical maneuver begins with no screens exposed to gas. Finally, since the screens are submerged, the PMD is less reliant on them for gas free propellant delivery. For example, screen is never found on the inboard side of gallery arms which would expose it to gas in zero g.

Traps and Manifolds

If the galleries run to the top of the tank, they may be manifolded together. Manifolding the arms is generally advantageous as multiple flow paths to the outlet are created.

With arms which reach to the top of the tank, gas ingestion during launch will occur. Three methods of dealing with this gas exist. First, eliminate the gas by ejecting it upon entry to zero g. Second, eliminate the gas by compressing it upon tank pressurization and dissolving it into the propellant. Third, retain the gas in the PMD throughout the mission by implementing a trap at the outlet junction of the gallery arms.

The first gallery PMD, designed by LMSC in 1969, eliminated the gas by ejecting it upon entry to zero g.[7] The gallery design was four arms extending from the outlet to the top of the tank. The arms led directly to the outlet with no other gas barriers except the screen on the gallery arms. After launch, when the vehicle entered zero g, the gas in the PMD was pushed through the dry screens at the top of the tank as the propellant within the arm rose. If the propellant inside of the arm rises more quickly than the propellant outside of the arm, the gas will be rejected before the screen is wetted. Drop tower testing was conducted to verify this phenomenon for this particular gallery geometry.

However, this approach is risky since it relies on dry screen at the top of the gallery through which the gas can be pushed. If the screen were wetted by slosh during launch or engine cutoff accelerations, the gas would remain in the PMD and would be ingested into the thrusters. Because of this risk, this is not the preferred approach.

Counting on all of the gas going into solution requires that a) the propellant loaded is initially unsaturated (or at least saturated at low pressure), b) the launch pressure is low relative to the operating pressure, and c) solubility/time dependence is well understood. Unfortunately, unsaturated propellant is difficult to attain, low launch pressures produce heavier propellant tanks, and time dependence of solubility depends on many factors and is not well understood. For all of these reasons, depending upon dissolution to get rid of gas is not feasible.

The most common solution is to implement a trap to retain the gas throughout the mission. Traps are typically cylindrical or clam shell shaped but may be any shape.[3] The simplest trap is a manifold with a pick up assembly within it. The gas is free to migrate from arm to arm and is prevented from entering the outlet by the trap's internal pick up assembly. A simple but not particularly efficient trap is illustrated in Figure 10. It is important to size the trap so that the internal pick up assembly is always in contact with liquid.

Traps have the added benefit of lowering gallery PMD residuals by allowing gas free access to some of the propellant within the arms.

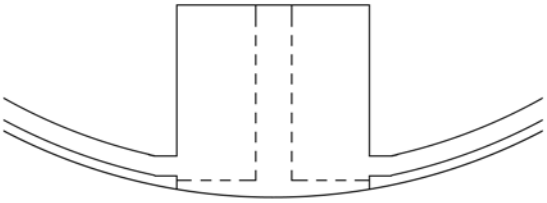


Figure 10. A Simple Trap

V. ANALYSIS

Besides simple bubble point tests verifying porous element integrity, no performance related quantitative testing in one g is typically conducted. As a result, extensive analysis using adequate safety factors to cover analytical uncertainty is required to verify performance.

PMD Technology has developed the techniques presented in this section to verify gallery compliance with the operating requirements. Two types of analyses are presented: one for steady flow along a gallery and one for unsteady flow.

Steady Flow Analysis

The main requirement of a communication device is to provide a flow path between the propellant and the outlet during adverse accelerations. To accomplish this during steady flow demand, a sufficient gallery porous element area must reside within the propellant pool, and the porous element area exposed to gas must prevent gas penetration.

Analysis predicting the propellant location during all phases of mission is vital to PMD verification. During steady accelerations, one can assume, as a first cut, that the propellant surface is planar as would be predicted with no surface tension. Since accelerations are typically on the order of milli-gs, surface tension is not negligible and a better approach is to predict the propellant surface location with surface tension effects included.

There are two basic methods used to compute static propellant surfaces. The first is to assume two dimensionality (either planar or axisymmetric), and to directly compute the surface curvature at the prescribed acceleration. The method to accomplish this is very straight forward and can be found in Reference 1. If the surface is not highly curved, this approximation may be sufficient for PMD verification.

However, if the propellant surface is highly curved or the tank/PMD geometry complex, a true three dimensional analysis should be completed. This is a tedious analysis requiring long set up times and iterative solutions. One tool used to predict the 3D surface is Evolver.[8] Evolver, is a minimum energy solver for surfaces in multidimensions. Designed as a tool for advanced theoretical mathematics, Evolver requires an understanding of vector calculus to set up and use - especially with complex boundary conditions. Several other tools are available but none is as general, and therefore, as capable as Evolver.

Once the propellant surface is defined for every maneuver, the quantity of porous element submerged can be accurately predicted. In addition, the volume of propellant in the tank, required to maintain sufficient porous element area submergence can be predicted. This is one component of the residual volume in the tank.

As previously explained, if the loads on the exposed porous element exceed the bubble point of the porous element, gas free flow will cease. The simple force balance presented in the physics section is sufficient to verify gas free propellant delivery during steady firing.

In most cases, more than one flow path exists from the pool in the tank to the tank outlet and the solution is iterative. First, assuming a flow rate along each path, the pressure drop along each path is computed. Second, if the pressure drops are not identical, then the flow division is adjusted and the process is repeated until the pressure drops are identical along each path.

One should note that to maintain the capillary integrity of the exposed porous element, the porous element must be wet. If the gallery contains gas and liquid within it, the gas must be shown to be sufficiently small so that no one screen can be exposed to gas completely on both sides. This can be accomplished by keeping the gas bubble away from the porous elements with internal fins or a trap.

During long thruster burns, the steady state analysis is accurate after the initial thrust ignition transient. During the ignition transient, a steady analysis is not adequate. An unsteady analysis is more appropriate and can help answer questions such as “Is sufficient porous element area submerged during the bulk space reorientation?” and “Can the propellant in the gallery be accelerated/decelerated without gas ingestion into the arms as the thrusters are pulsed or propellant moves within the tank?”

Unsteady Flow Analysis

To attain the steady flow modeled in the preceding section, the propellant must be accelerated from its static equilibrium position in zero g to the steady flow condition. This engine ignition transient is an unsteady phenomenon of particular interest because if the liquid in the galleries does not respond quickly to meet demand, the fluid in the porous element near the outlet will be consumed and gas ingested into the outlet. In addition to the ignition transient, thruster pulsing must be analyzed in terms of unsteady flow. The two areas of interest are the movement of the propellant both within and outside of the gallery.

Assume for the moment that the propellant is settled over a part of the gallery far from the outlet. As a thruster is pulsed off and on, the propellant within the arm will decelerate to no velocity and then upon thruster ignition accelerate up to the demand flow rate. Alternatively, one could assume that the propellant in the bulk space moves from one region of the tank to another switching submerged gallery arms. In both cases, the liquid in the gallery arm must be accelerated from zero velocity up to the demand flow rate. An unsteady model is used to demonstrate that gas ingestion does not occur due to the additional unsteady load.

First a very rough order of magnitude analysis is presented to provide a background for the more complete analytical model.

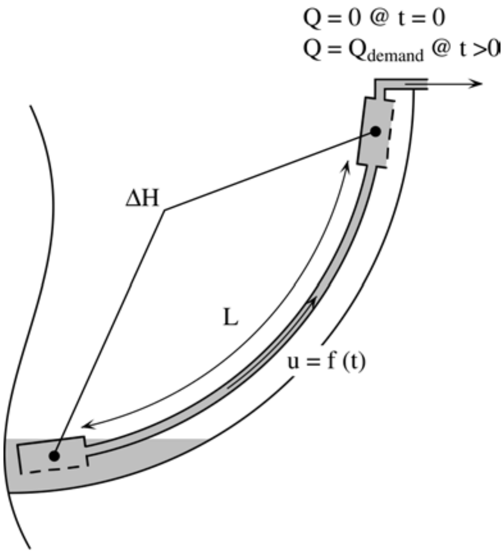


Figure 11. Transient Physics

Figure 11 shows an gallery with a tube connecting two porous element pick up assemblies. Initially the liquid in the gallery is at rest. At t = 0, propellant is demanded from the exposed end of the gallery. The inertia of the liquid in the porous element near the outlet is much less than the liquid in the long tube. As a result, to meet the demand, liquid is withdrawn from the exposed porous element. This causes gas to be pulled into the pores of the exposed porous element which, in turn, creates a pressure difference due to the surface tension. This capillary pressure will accelerate the liquid in the tube. The issue is whether the liquid in the tube can be accelerated up to the demand rate prior to gas being pulled through the exposed porous element.

Ignoring flow losses, a simple force balance can provide a ROM for the transient:

$$\Delta H = L \frac{du}{dt} \tag{9}$$

where ΔH is the driving head, L is the tube length and u is the velocity in the tube. Further assume that one half the bubble point is the driving head. (In reality the driving head is increasing but we are just developing a ROM estimate.) The time required to accelerate the arms up to the demand flow rate is:

$$\Delta t = \frac{2QL}{BP\, A_{arm}} \tag{10}$$

During this time, the exposed porous element is providing propellant. Since du/dt is constant in this ROM, the volume pulled from the exposed porous element is estimated as:

$$\mathrm{V} = 0.5\, Q\, \Delta t = \frac{Q^2 L}{BP\, A_{arm}} \tag{11}$$

Thus to ensure gas free propellant delivery during transients, the porous element area must be sufficient to deliver the above volume of propellant. One can conservatively estimate the volume available in a given screen as one half the open volume of the screen. This estimate is typically very conservative since the screen is not rigid and will provide some volume via physical movement of the screen. In perforated sheet, the volume available depends greatly on the geometry but also can be estimated.

A better way to predict the volume available is to measure it. The volume removed from a porous element vs. the head across the element can be measured and provides the function of head vs. volume removed required for a more accurate analysis.

The preceding ROM is not very satisfying for PMD verification as a result of the many assumptions. In addition, the ROM does not effectively deal with a porous element covered channel where propellant is available along the flow path. A model which tracks the arm velocity, the head across the exposed porous element, as well as the volume removed from the exposed porous element along the arm, is required for verification.

The unsteady model assumes one dimensionality along the given flow path. Flow losses through the screen and along the arm can be incorporated as well as the hydrostatics.

Figure 12 shows the differential control volume used to derive the differential equations. Please note that the volume available in the porous element is perceived as a thickness which addresses the area as a variable more effectively. The equations could be derived with volume as the dependent variable.

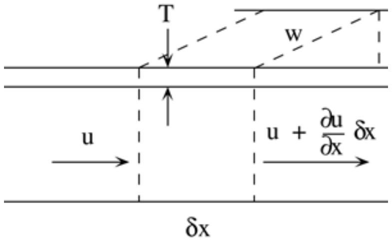


Figure 12. Differential Control Volume

The unsteady flow equations for the region exposed to gas can be derived from the continuity and momentum equations:

continuity:

$$\frac{\partial T}{\partial t} = \frac{A}{w}\frac{\partial u}{\partial x} \tag{12}$$

momentum:

$$\frac{\partial u}{\partial t} = -\left(u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial(\Delta H)}{\partial x} + a\frac{\partial z}{\partial x} + 2\nu\left(\frac{s}{A}\right)^2 u \right) \qquad (13)$$

equation of state (thickness vs. head):

$$\frac{\partial(\Delta H)}{\partial x} = \frac{\partial}{\partial x}\left(f\left(BP, T, T_0\right)\right) \qquad (14)$$

Because the flow is not as simple as the above friction term would seem to indicate (due to boundary layer development and turbulent flow), the losses must estimated for a few specific cases. The friction is often many times higher than the above approximation. When the computational simulations are conducted, two friction estimates should be used: the one above and one many times larger. The safety factor can be applied by ensuring that T does not fall below T_0/SF where T_0 is the initial thickness. In addition, one should examine the sensitivity of the analysis to the compliance of the porous element (ΔH vs. T) by varying the equation of state.

The equations can be solved using a two step Lax-Wendroff type scheme; one of the more popular methods for solving compressible flow problems with friction. For example, the method of Rubin and Burnstein is used successfully.[9] Velocity and thickness are calculated at half spaces and full time steps by averaging:

$$\begin{aligned} U_{i+\frac{1}{2}}^{\overline{n+1}} &= \frac{1}{2}\left(U_i^n + U_{i+1}^n\right) - \Delta t\left[\frac{F_{i+1}^n - F_i^n}{\Delta x}\right] \\ U_{i-\frac{1}{2}}^{\overline{n+1}} &= \frac{1}{2}\left(U_i^n + U_{i-1}^n\right) - \Delta t\left[\frac{F_i^n - F_{i-1}^n}{\Delta x}\right] \end{aligned} \qquad (15)$$

Note that U is u or T depending upon which equation is being evaluated, 12 or 13, and F is the right hand side of equation 12 or 13 multiplied by -dx. The second step in the solution process is:

$$U_i^{n+1} = U_i^n - \Delta t\left\{\frac{1}{2}\left[\frac{F_{i+1}^n - F_{i-1}^n}{2\Delta x} + \frac{F_{i+\frac{1}{2}}^{\overline{n+1}} - F_{i-\frac{1}{2}}^{\overline{n+1}}}{\Delta x}\right]\right\} \qquad (16)$$

The scheme is explicit and provides no artificial viscosity. Where shocks exist, artificial viscosity may be added to damp the overshoot created by the numerics but is generally not required. The stability condition is the classic Courant number restriction as both necessary and sufficient for stability.

Applying this method to a specific gallery requires that the boundary conditions be addressed. The end of the arm where the porous element is submerged may be dealt with by applying the boundary condition of ΔH_{N+1} equal to a function of the velocity at the N^{th} element (converted to porous element approach velocity to maintain continuity). Alternatively one can set up a separate set of differential equations which apply to the submerged cells which have porous element velocity a function of ΔH (the porous element flow loss relationship).

At the outlet end, many boundary conditions are possible and depend upon the actual gallery design. Multiple arms, a screen covered trap, a manifold all affect the correct boundary conditions for the model. In addition, if a manifold exists at the top of the tank it too must be modeled with the appropriate boundary conditions.

Multiple arms are modeled with separate models joined at the boundaries and the equations solved simultaneously.

Using these analytical techniques, a gallery PMD can be shown to provide gas free flow during engine ignition, pulsing and propellant reorientation. Analyzing worst case transients such as igniting all the thrusters simultaneously with the propellant as far as possible from the outlet and with a safety factor of two or three will ensure gas free delivery so long as sufficient porous element area is submerged.

To verify that propellant is always in contact with a porous element requires a time dependent model of the liquid outside of the gallery. Three methods of varying accuracy currently exist to make these predictions.

First, one can estimate the bulk propellant reorientation time from the free fall time. To obtain an estimate, one must determine if surface tension has a role in the reorientation. The Bond number is the ratio of inertial forces to surface tension forces. If the Bond number is greater than 10, surface tension is negligible when computing the reorientation time:

$$Bo = \frac{\rho a r^2}{\sigma} > 10 \qquad (17)$$

With surface tension negligible for the bulk propellant, the propellant will reach the submerged porous element in the free fall time (approximately). The time required to completely settle all the propellant can be estimated as three times free fall. This is conservative as propellant will begin to be accessible at close to the free fall time.

$$t_{estimate} \cong 3\, t_{free\,fall} = 3\sqrt{\frac{2\Delta h}{a}} \qquad (18)$$

This does not predict how the propellant reorients. To verify that sufficient porous element area is submerged during the reorientations requires another step. The gap between the gallery and the tank wall can act as small sponge; retaining propellant during the reorientation. If the demand flow rate times the free fall time is significantly less than the volume retained in the gap, the propellant in the gap can be used to supply the demand during the reorientation.

Since the above method is rough order of magnitude, large safety factors should be used.

To attain a more accurate description of the propellant reorientation, a three dimensional model should be constructed. Flow-3D, a three dimensional free surface computational fluid dynamics (CFD) model may be used.[10]

Care must be used in setting up the models due to the large scale differences between the gallery/tank wall gap and the tank itself. In addition, Flow-3D's ability to accurately model surface tension is limited since estimating the surface curvature is a second derivative. Accurately predicting second derivatives is notoriously difficult without extremely fine grids.

The last method is to use the vane models presented in Reference 1 to model the propellant in the gap between the tank wall and the gallery. The model is of a ribbon vane. This is perhaps the best method since a) the model is valid during the worst case conditions near EOL, and b) in screen covered channels, the screen is located in the gap so predicting the screen area submerged is straightforward.

The difficulty with vane models is that surface tension must be significant in the gap for the model to be valid. As a result, vane models are only useful at lower accelerations.

Alternatives to the above recommended methods include finite element CFD codes which can accommodate the scale differences via gridding. However, to the author's knowledge there are no verified codes available which can address this problem which must deal with free surfaces and surface tension.

The best method of verification is to use all available tools and to design the PMD with a great deal of conservatism. Because of the paucity of good tools, screen covered channels should be preferred over connected pick up assemblies. A screen covered channel has screen along the entire gap which tends to retain propellant. Thus the risk of insufficient flow area and subsequent gas ingestion is minimized.

Analysis Summary

A number of assumptions were incorporated into the analysis to keep it simple and straightforward. These assumptions are conservative.

One might argue that, with a safety factor of two and a conservative analysis, the resulting device is over designed. Depending upon the circumstances, this may or may not be true. However, the approach taken guarantees a robust design which easily meets requirements and provides some additional capability. Typically, the impact of any over-design is minimal.

An alternative approach might be to incorporate in the analysis more accurate, but not necessarily conservative, assumptions. Since fluid mechanics is not an exact science, this approach will a) make the analysis much more difficult and b) not guarantee a PMD component which will meet requirements.

Also, reducing the safety factor is not recommended. The safety factor is not only incorporated to accommodate uncertainty in the analysis, but also to accommodate uncertainty in manufacturing. It is very difficult to analyze every manufacturing tolerance. The safety factor allows for these uncertainties as well as analytical uncertainties.

The verification approach using simple, conservative analysis coupled with a safety factor of two a) alleviates concerns of analytical accuracy b) virtually guarantees requirement compliance without ground testing (which in most often not possible), and c) allows for manufacturing uncertainty. This approach is widely used on all PMD components and has proven itself with no known PMD performance failures to date.

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NOMENCLATURE

Greek

ρ ≡ liquid density
σ ≡ liquid-gas surface tension
ν ≡ liquid kinematic viscosity

Δ ≡ change

English

a ≡ acceleration
h ≡ height
pe ≡ porous element
r ≡ radius
s ≡ wetted circumference
t ≡ time
u ≡ velocity
w ≡ width
z ≡ height relative to acceleration vector

A ≡ area
BP ≡ bubble point
Bo ≡ Bond number
D_{eq} ≡ equivalent diameter
ΔH ≡ head difference
L ≡ length
P ≡ pressure
Q ≡ volumetric flow rate
R ≡ principal radius of curvature
Re ≡ Reynolds number
SF ≡ safety factor
T ≡ thickness
T_0 ≡ thickness at zero ΔH
V ≡ volume

Subscripts

pe ≡ porous element
arm ≡ gallery arm

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NOTES