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Propellant Management Devices – Functional Design Methodologies and Verifications

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Propellant management device, PMD, PMD tank

Acronyms
CFD = Computational Fluid Dynamics
CoM = Center of Mass
GEO = Geosynchronous
GNC = Guidance, Navigation, and Control
LEO = Low Earth Orbit
MEO = Medium Earth Orbit
OCM = Orbit Correction Maneuvers
PMD = Propellant Management Device
VoF = Volume of Fluid

Abstract
Surface tension Propellant Management Devices (PMDs) have been a common feature in space propulsion systems from as early as 1960s. Space missions of all kinds depended on PMDs to meet increasingly difficult operational requirements. PMD designers and developers conducted Computational Fluid Dynamics (CFD) analyses to design PMDs from as early as 1970s. Thousands of successful space flights had already proven the functionalities and capabilities of surface tension PMDs, and along with them the validity of using analysis-only approach to design PMDs.

The focus of this summary paper is to explore the development of PMDs and the evolution of industry-accepted standards that led to the current design practice in the United States and Europe. We take a holistic approach integrating historic, numeric, and technical perspectives using both qualitative and quantitative data. In addition, we introduce a body of evidence to validate the analysis-only methodology in PMD design. The summary paper has four sections. Section 1 contains background information on the evolution of PMDs from their inception to the present day to dispel some common misconceptions associated with PMDs. In Section 2, we draw upon project experiences, documentation from the literature, and customer feedback to provide a body of evidence in support of the analysis-only PMD design approach. In Section 3, we discuss the appropriate methods of safeguarding high-quality PMD designs using analysis-only techniques on a long-term basis. In Section 4, we conclude.

1. Introduction
Surface tension PMDs have been a common feature in space propulsion systems from as early as 1960s. Space systems operators use propellant tanks with PMDs to reach orbit and support orbital mission maneuvers on Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO) satellites. Other applications include propellant storage and supply for space exploration missions such as Cassini, Juno, Mars explorers, and the upcoming James Webb Space Telescope (JWST) mission. In a 2016 tally, the estimate for the total number of PMDs made in the United States and Europe was about 3000 [1]. This estimate did not include PMDs manufactured in Japan or other market segments. Currently, most of the GEO satellites from the United States, Europe, and Japan use PMD tanks for orbital transfer, orbit insertion, and station keeping functions. PMD tanks, along with diaphragm tanks, are the two primary tank groups in space propulsion systems. For example, Orbital ATK in the United States had delivered over 1560 PMD tanks and 1210 diaphragm tanks as of April 2018. Other manufacturers in the United States might have delivered a few hundred more in the past 50 years. In Europe, the combined delivery of PMD tanks exceeds 800.

Propellant management device designers and developers had been using analytical techniques to design PMDs from as early as 1970s [2]. Thousands of successful space flights had already proven the functionalities and capabilities of PMDs, and along with them the validity of analysis-only PMD design approach. In many propulsion systems, surface tension PMD tanks are the only option, or the option that presents the best overall value. The extensive use of PMD tanks on many bi-propellant propulsion systems on GEO commercial satellites are prime examples [3] - [20]. Nevertheless, there are still pockets of resistance against using PMD tanks or using PMDs designed by the analysis-only approach. Some reasons behind this resistance include:

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• Unlike the simple functionality of diaphragm tanks, the surface tension phenomena are not intuitive for anyone whose only exposure to fluid behavior is at 1 g. People unfamiliar with the science behind zero g fluid behavior might not be comfortable with the concept or the notion of a PMD.

• There are elements of a PMD that could undergo ground testing in 1g, but not all PMD elements are ground testable. Without test validation, the perception of risk associated with PMD tanks is typically higher than that of diaphragm tanks. This factor is especially potent given that space missions are expensive and mission planners prefer to have test validation for hardware.

• For some people, believing in PMD functionality might require a leap of faith. For example, administrators in charge of multi-million dollar missions often require physical proof, and this physical proof of PMD functionality is not available for PMDs designed to function in a zero g environment.

• On many satellite and space exploration programs, the end of mission often do not take place until 15 to 20 years after the initial PMD design review. The many involved principles at mission start might have already moved on to other endeavors, and there might be insufficient interest or continuity to document end-of-life PMD performance.

• Some PMD users, notably GEO commercial satellite integrators, had used PMD tanks on multiple generations of satellite buses. They are familiar and comfortable with PMDs. However, new comers to space systems or single-spacecraft developers might not be as familiar or as comfortable with PMDs and their functionalities.

• Besides uses on satellite and exploration missions, PMDs are capable of enhancing mission capabilities on upper stages such as engine restart. In addition, PMDs might provide enhanced mission flexibilities on new constellation missions. However, because propellant settling maneuvers are easier to understand and appear less risky as compared to a PMD solution, mission planners often prefer settling maneuvers to PMD solutions.

Given the large disparity in comfort level towards PMDs amongst current and potential PMD users, it is vital that we present the scientific foundation of PMDs and their developmental history. An examination of the literature indicates that while flight history has already provided overwhelming proof on the successful uses of PMDs, the link between CFD application and PMD performance is absent from the literature. In this summary paper, researchers from Europe and the United States address this knowledge gap. To accomplish this goal, we explore the various defining phases of PMD tank development from the earliest days of fundamental research to the modern era of efficient design practice, and conduct an organized presentation of a body of evidence focusing on the use of analysis-only approach in PMD design and development. We present our findings holistically from historical, numerical, and technical perspectives using both qualitative and quantitative data.

1.1 Background

From a historical perspective, the maturation of PMD design methodologies evolved in two distinctive phases. Phase 1 was the research, development, and validation phase consisted of the following:

• Conducting fundamental research and collecting raw data from flight experiments or drop tower tests
• Studying the physics and developing the principles of fluid behavior in zero g
• Developing the basic hardware geometries that enable the movement of fluids in zero g
• Developing the basic PMD elements that suit different mission scenarios
• Developing the CFD elements to design and analyze PMD functionality and performance

In the United States, the phase 1 study started in the early 1960s. Researchers from more than a dozen technology organizations, including Bell, General Dynamics, General Electric, Lockheed, Martin Marietta, McDonald Douglas, National Aeronautics and Space Administration (NASA) Glenn Research Center, NASA Marshall Space Flight Center, RCA, Rockwell, and TRW participated in the basic research. Some researchers collaborated with the academia. For example, engineers from Lockheed at Sunnyvale, California spent around four years conducting drop tower tests at the University of Santa Clara to collect raw data using movie films as the media. Likewise, engineers from Martin Marietta at Denver conducted drop towers tests from the late 1970s and into early 1980s. The reviewing and processing of the raw data took many more years to complete. This initial phase of data collection and fundamental studies continued for two decades from the 1960s
through the 1970s and even into the 1980s as PMD concepts evolved. As engineers gained a thorough understanding of the fundamental physics, they were able to develop the basic PMD concepts and elements that are still in use today [21] - [24].

In Europe, an organized study of surface tension phenomena started with the launch of Spacelab onboard the Space Shuttle STS-9 in 1983 [1]. The technology maturation took an independent path under European Space Agency (ESA) and national funding, but nonetheless followed the same developmental sequence as their American counterparts. Importantly, the fundamental study is still ongoing in countries around the world, extending benefits to both the academia and the space industry [25] – [35].

The investments in time, resources, and intellect during Phase 1 led to the systematic application of advance space propulsion tank technologies in Phase 2. The defining characteristic of phase 2, generally understood as having started in the 1980s, is the widespread use of CFD tools for PMD design and propellant slosh analysis. Phase 2 also includes a process of refinement and affirmation consisting of the following:

- Developing and refining CFD codes and customized software
- Designing PMDs using analytical techniques
- Collecting validation data on the flight performance of PMDs designed by analysis-only approach
- Improving PMD designs with advancements in analytical tools

The phase 2 technology advancement coincided and benefited from the microcomputer revolution. Early PMD developers conducted their calculations using slide rules and mainframes. The task was labor intensive and time consuming. The rapid advancements in computing technology in the 1970s and 1980s had led to exponential increases in computing power. This improved computational capability not only enabled the advancement of CFD tools and their wider use, but also enabled PMD developers to conduct increasingly sophisticated analyses with high degree of granularity at ever-increasing speed.

The current generation of PMD developers can rely on powerful lap top computers to perform design calculations hundreds of millions of times faster than tools used by PMD developers in the 1960s. The dynamics of PMD development also changed. During the early days of PMD design, it required a team of engineers to design and analyze a new PMD. The process typically took more than 9 months. In the present day, an experienced PMD designer with proven CFD and custom designed software can design a PMD and validate functionality in as short as 3 months. Nevertheless, it still requires experience to generate a viable and competitive PMD solution, thus driving the need for continuous education and a close link to universities for research support.

Besides CFD tools, PMD developers continue to benefit from the increasing volume of empirical data accumulated during the past decades on the basic PMD elements such as vanes, baffles, and screens. Numerous quantitative data are available to support a wide range of scope, including quick analytical assessments at initial trade to full PMD analysis. Some examples include pressure losses of screens and vane performance characteristics. In references [1] and [20], we provided overviews on some of these tools and experiments.

On the academic side, the fundamental research had led to the understanding of the laws of physics in zero g. Researchers published articles and books on fluid behaviors at zero g and spurred on new fields of study by students and scholars. Today, this fundamental research continues at academic institutions and often in collaboration with space organizations throughout the world. Some notable fundamental fluid dynamic studies include drop tower tests [25]-[39]; parabolic flights; Space Station experiments [40] - [42]; and suborbital flights such as sounding rocket experiments [43] [44].

1.2 PMD Designer Lineage

Throughout the 50 plus years of space flight, there had been few PMD designers and developers. Their small number is the result of a small niche market with infrequent demand for relatively small number of new PMDs. The competitive nature of the free market and the economic realities of modern corporate structure make it difficult to sustain many PMD designers. Thus being a PMD designer is indeed a rarity throughout the space age.

Prominent first generation PMD designers include Robert Grove from Lockheed at Sunnyvale, California [2] - [6] [45] – [50]; James Tegart from Martin Marietta at Denver, Colorado [51] – [70]; and Gaston Netter from ERNO (now ArianeGroup) at Bremen, Germany [7] – [9] [71] – [75]. All three made their marks in space systems and contributed to the literature throughout their long careers. Mr. Grove had a long career designing PMDs from late 1960s through mid-1990s. His protégé, Don Jaekle, has been designing PMDs from early 1980s through the present day. Mr. Tegart designed PMDs from 1970s through late 1990s. His successor, Carey Parish, continues to design PMDs at the same
Lockheed Martin Denver facility. Dr. Netter is the pioneering PMD designer in Europe. His PMD design activities span from late 1970s through 2016. Although retired, Dr. Netter remained involved in PMD design activities for many years until 2016 by serving as adviser to and collaborator with his protégés, Dr. Philipp Behruzi and Dr. Jörg Klatte.

PMD designer lineage is important to space systems integrators and end users. It ensures the continuity of design philosophy, the consistency of design methodology, the assertion of design and product heritage, the use of previously proven design software, and the assurance from decades of mission success. The customers’ insistence that what worked before should be in the baseline has its merits in PMD design because cumulative lessons learned is a critical component of mission success. It mitigates a risk factor that is controllable by imbedding factors contributing to past mission successes in new PMD designs.

1.3 GEO Commercial Satellite Platform PMD Tanks

The commercial sector has the largest number of users of PMD tanks. GEO satellite platform providers such as Airbus, Boeing, Lockheed Martin, Mitsubishi Electric Corporation, Orbital ATK, Space Systems Loral, and Thales Alenia all use PMD tanks in their GEO commercial satellite platforms. The cumulative number of PMDs in this application sector is nearing 1500. More importantly, successive generations of bus platforms all use PMD tanks. For example, Lockheed Martin’s S3000, S5000, S7000, and several variants of A2100 platforms all use PMD tanks to meet mission objectives. Other satellite integrators also take the same approach and use PMD tanks on successive generations of bus platforms. The literature has many examples of GEO commercial tanks containing custom-designed PMDs, and references [1] and [20] contain summaries of a majority of PMDs designed in Europe and the United States.

1.4 Other Uses of PMD Tanks

Governments around the world are the second largest end user of PMD tanks. End uses include civil services such as earth monitoring and weather monitoring, military and defense communications, space observers and space telescopes [76] [77], and space explorers. Orbital ATK provide PMD tanks directly to governments in the United States, Japan, and Korea, and Airbus is the largest provider of PMD tanks to European institutional or governmental programs.

2. Validation of PMDs Designed by CFD Tools and Custom Software

Space missions are long duration programs. Typically, final validation of a GEO PMD does not take place until the end of the space mission. For GEO satellites, it could be 15 years or longer after launch. However, there are now programs that had completed the typical 15-year service life and reached propellant tank depletion. In addition, there are circumstances that validated PMDs or the use of analysis-only methodology soon after launch. In this section, we draw upon project experiences, documentation from the literature, and customer feedback to provide a body of evidence in support of the PMD design using analysis only approach.

2.1 The ETS VIII PMD

Japan’s Engineering Test Satellite ETS VIII is a test satellite based on Mitsubishi Electric Corporation’s DS2000 platform. The ETS VIII propulsion system has state-of-the-art PMD tank and xenon tanks custom designed for the mission [14] [78]. JAXA launched ETS VIII in December 2006 and terminated the mission in 2017.

The customer feedback on the ETS VIII PMD performance included the following two pieces of data:

- Initial MON-3 propellant load at 1806.5 kg
- Liquid MON-3 remaining in the tank was 4.1 kg

The above figures correspond to 0.2% residual, or 99.8% expulsion of the propellant. The demonstrated expulsion efficiency exceeds the 99.5% target established by the customer. The PMD development relied on CFD analysis and custom software programmed by the PMD designer, and required no ground testing for functional validation.

2.2 Orbital Express Space Experiment PMD

Orbital Express was a 2007 Defense Advanced Research Projects Agency (DARPA) program to conduct flight experiments and demonstrate autonomous on-orbit refueling technology. The Orbital Express PMD tank is capable of both fluid and gas transfer. Both the servicing satellite (ASTRO) supply tank and the serviceable satellite (NEXTSat) receiver tank have identical large sponge PMTs [79]. The PMD functioned as predicted throughout the Orbital Express mission. The predictions of the fluid and gas behavior had been accurate and precise. Impressively, the PMD designer had predicted the fill fraction whereupon the pressurant transfer could no longer take place, and the flight experiment had validated the prediction stated at the design review.
The Orbital Express on orbit experiment was a rare opportunity to attain PMD design validation within only a few years of PMD design. The successful flight experiment had served as a definitive proof of the analysis-only PMD design approach.

2.3 MESSENGER PMD Baffles

Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) was a NASA planetary explorer that orbited planet Mercury from 2011 to 2015. The MESSENGER propulsion system included three custom designed bi-propellant tanks for dual mode operations. During tank design, the PMD designer made extensive use of CFD and customized analytical tools and custom developed software to design the anti-slosh baffle rings. These rings were specifically for nutation damping during spinning upper stage operation [80] [81]. The two ring baffles had divided the tank bulk space into compartments. During the cruise to Mercury, PMD designer conducted CFD analyses to help the spacecraft operators generate operational sequences that extract trapped propellant in the compartments.

After orbit insertion, MESSENGER conducted its science mission and operated through two extended missions that consumed the majority of the propellant. During on orbit operations, the PMD designer conducted CFD analyses in real time to help the spacecraft operators generate optimal thruster operation sequences in support of eight orbit correction maneuvers (OCMs). These OCMs minimized propellant trapped by the ring baffles, optimized propellant extraction, and preserved the extended missions by enabling the spacecraft to operate with the propellant tanks at very low fill fraction [81].

The analysis predictions of propellant behavior had been accurate and precise. For example, after a benign gas-ingestion event during the third OCM, the PMD designer was able to simulate the event using analysis tools. The cause of the brief gas-ingestion event was a droplet of oxidizer falling upon a thin pool of propellant at the tank outlet and causing a brief exposure to gas at the propellant port. Follow on analyses also predicted a similar recurrence at the seventh OCM, thus prompting the spacecraft operators to take appropriate precautions to minimize potential negative impact. Importantly, the mission planners did not have the luxury of time to design a validation test. They relied on analysis results exclusively to formulate updated operational strategy and enable mission extension. The MESSENGER experience once again confirmed the validity of analysis methodology and their high value during real-time mission planning.

2.4 GEOStar 1 GEO Commercial Satellite PMD Tank

GEOStar 1 is an Orbital Sciences GEO satellite developed in the late 1990s. ATK designed the propellant tank to carry 113.85 kg (251 lbm) of hydrazine [82]. The GEOStar 1B retired with 3.3 kg of propellant onboard [83]. The 97.1% expulsion ratio is far less than the design goal of 99.6%. The feedback from the mission planner was that the satellite was becoming obsolete in orbit, and it was necessary to replace the satellite before propellant depletion. Nevertheless, the example is an indication that the PMD, designed by analysis-only methodology, is at least capable of 97.1% expulsion. In addition, the example highlights the fact that, although many PMDs have high expulsion efficiency capabilities, some satellite owners or operators may not take advantage of these capabilities because of other mitigating circumstances.

2.5 The HS601 Satellite PMD Tanks Off Nominal Mission Support

The HS601 spacecraft is the most popular GEO spacecraft in the 1990s. Both the HS601 and the HS601HP platform buses incorporated PMD propellant tanks [84] [85]. When a launch vehicle underperformance left an HS601 spacecraft in an undesirable orbit, the PMD designer worked with mission planners in real time to raise the satellite into a usable orbit [86]. The recovery mission planners, supported by extensive analysis effort, had the PMD operating at performance levels beyond the original design specification. The values of the analysis approach were many. First, the analysis support was in real time, thus providing timely support during crisis management. Second, the analyses examined different scenarios, thus providing optimized solution. Lastly, the analysis methodology did not require test validation, thus saving time and money.

Another documented example is the rescue mission of a HS601HP spacecraft. A launch vehicle 4th stage failure had left the spacecraft stranded in the geosynchronous transfer orbit. The PMD designer worked with mission planners to execute a lunar flyby to place the satellite into a usable geosynchronous orbit [87]. The successful rescue mission was in fact the first commercial spacecraft lunar flyby.

A third example is the recovery of Tracking and Data Relay (TDRS) 9 satellite. The initial failure occurred soon after the launch vehicle delivered TDRS 9 into a transfer orbit. Fuel from one of the propellant tanks had stopped flowing because of an incorrectly wired valve that prevented the flow of helium into a fuel tank. To recover the spacecraft, the PMD designer...
collaborated with the mission planners to design a workaround plan that fed helium gas through the propellant port to enable tank pressurization [88]. Throughout the recovery mission, the PMD designer made extensive use of the analysis tools to analyze how to keep the PMD functional after introducing gas through the propellant port. The recovery mission was a success thanks to the robustness of the PMD design, the ingenuity of the engineers, and the accuracy of the analyses.

In all three documented off-nominal missions, the PMD performance was beyond the nominal mission capabilities. The PMD designer performed extensive analysis support to recover the spacecraft and achieve mission success. More importantly, the value of the recovered hardware was in excess of hundreds of millions of dollars. These successful recovery missions did not happen by chance. An entire generation of researchers and engineers had worked hard to lay the foundation for this success.

2.6 Custom Confidence

Continued customer confidence is one of the most important reflections of product quality, reliability, and performance. In the GEO commercial satellite market, all the major satellite manufacturers have been using the same PMD developers or the same PMD design teams to design successive generations of PMDs [1]. The summary below is a list of GEO commercial satellite platform integrators with multiple generations of PMDs:

- Airbus: 3 generations of PMDs [1] [89] [90].
- Boeing: 3 generations of PMDs [19] [20] [84] [85].
- Lockheed Martin: 5 generations of PMDs [17] [18] [20].
- Mitsubishi Electric: 2 generations of PMDs: [14] [20].
- Orbital ATK: 3 generations of PMDs: [13] [15] [16] [20].
- Space Systems Loral: 3 generations of PMDs [20].

Tank manufacture for most of these GEO platforms started in the 1980s or 1990s. The continuing customer trust well into the late 2010s reflects an unwritten confirmation that the PMD tanks meet the requirements of the customer base. In addition, the continuing patronage from these customers is an affirmation and approval on the use of analysis techniques to design PMDs.

2.7 CFD Tool Validation

The literature is also a very important source of non-project based evidence. Many researchers have dedicated their careers developing and publishing quantitative and qualitative data, and the literature now includes empirical evidence in support of CFD tool validation. CFD tools had reached the high standard required to enable analysis-based PMD design approach around the year 2000. From this time forward, CFD codes such as FLOW-3D by Flow Science Inc. or FLUENT by ANSYS Fluent had maintained sufficient maturity and sophistication to enable the following aspects of PMD design with acceptable accuracy:

- Capillary dominated sloshing (low Bond number regime)
- Capillary transport processes including contact angle and surface tension modelling
- Gravity dominated sloshing (high Bond number regime)

To validate capillary dominated low Bond number flow regime, researchers had conducted thousands of drop tower experiments to benchmark CFD tools during the past two decades and published their findings [35] - [37]. To examine propellant surface tension and contact angle properties, researchers conducted a series of benchmark experiments and provided a thorough overview [35]. For example, when modeling contact angle, researchers had determined that PMD design should take into account the effect of hysteresis by considering advancing or receding contact line [35]. Given all the available data, capillary phenomena of storable liquid propellants had become well defined and well understood. From a scientific point of view, we now consider CFD design tools on liquid propellants behaviors state-of-the-art.

Finally, high Bond number gravity dominated sloshing had been standard for CFD tools. For example, in Konopka et al. [91], the authors compared experimental and numerical results and discussed active sloshing control based on CFD. These tools could be useful for assessment of slosh during ground transport and wind-induced oscillation. While new technology developments continue to underline the maturity of CFD codes in this regime, few in the industry would dispute the use of CFD and its validity in the high Bond number regime.

The study of liquid behavior has effectively reached a major milestone. Basic research is taking on a new direction. The focus in Europe is now progressing towards understanding the capillary phenomena of cryogenic liquids and advancing the technology towards cryogenic propulsion system applications [37]. We foresee the continuing study to benefit future cryogenic systems just as it had on storable propulsion systems.
3. Discussion

The application of analysis methodology using CFD and custom software in PMD design has gone through the life cycle of research, design, fabrication, test, flight, and flight validation. Nearly 60 years of space flight with thousands of flight programs have confirmed that PMDs are functional, and PMD designed by analysis methodology is appropriate.

The use of CFD analysis has effectively eliminated the need for PMD functional testing. Nevertheless, it is often necessary to include component level ground testing such as flow tests or bubble point tests to validate PMD components during PMD manufacture. In addition, successive bubble point tests of porous elements are good insurance to prevent the inclusion of defective parts in the final PMD assembly. However, the purpose of these component functional tests is product assurance and not functional validation. Designing a PMD that functions in zero g but must pass ground level functional test in 1 g is not an optimal approach. Such a ground level PMD functional test could be time consuming, costly, and unnecessary given the demonstrated success of analytical tools.

To safeguard high-quality PMD designs using analysis techniques, the industry should focus on the following key aspects:

- PMD developers should continue their collaboration with academia to gather empirical data on traditional storable liquid propellants, new green propellants, and cryogenic propellants,
- PMD developers should provide continuous feedbacks to software makers to ensure continued improvement of analysis tools,
- Software developers should continue developing and improving CFD analytical tools and taking advantage of the ever increasing computing power,
- Software developers should provide continued training to ensure proper use of the design tools,
- PMD developers should ensure the consistent inclusion of proven design parameters and practices into future PMD designs.

CFD tools are in a mode of continuous change and development. It is advisable for researchers to repeat basic benchmark test cases on regular basis to reconfirm that predicted physical phenomena are still within the desired range of accuracy. To the customer base, this continuous refinement and validation is the means to provide additional assurance of high quality PMD design for both PMD developers and end users.

For PMD designers, it would be important to take into account the range of CFD accuracy margin during the initial tank layout. A long-term goal would be to reduce accuracy margin by optimizing the modeling capabilities of the codes. Some example follows.

Capillary dominated sloshing is gathering increased interest in recent years. It is the focus of attention whenever key requirements include high pointing performance and stability, and often together with competing requirements such as fast re-pointing slew maneuvers and quick settling time. This is the case for several cosmic vision missions such as Euclid, Plato, LOFT, Athena; GEO missions including MTG and Geo-Oculus; as well as all the agile LEO missions (SAR and optical) such as SARah and Jason-CS/Sentinel 6. The slosh motion for these high pointing maneuvers is frequently in a low Bond number regime where the liquid behavior is capillary dominated. However, at the system level, the propellant center of mass (CoM) shift could have a significant effect on satellite motion [92]. These aspects of the phenomena, coupling propellant slosh with Guidance, Navigation, and Control (GNC) and rigid body dynamics, go well beyond the task of designing PMD tanks. It reflects the current state-of-the-art in CFD tools that could enable further mission optimization in support of satellite system design and planning.

Furthermore, we also recognize some limitations of CFD codes with respect to low Bond number slosh. An example is the random noise generated in the range of ±0.05 N for a Spacebus tank analysis using Volume of Fluid (VoF) CFD models that are standard features in CFD today [92]. After confirming that the desired limitations for low Bond number sloshing is achievable using CFD analysis, PMD developers were able to verify that a standard Spacebus tank can meet mission objectives. In this example, PMD developers had originally assessed additional stabilization means but eventually discarded the planned PMD change. The tank solution became cheaper and lighter because the PMD developers were able to avoid over-designing the PMD.

The above examples indicate that the need to verify the quality of CFD tools continuously drives the need to select appropriate benchmark experiments used in crosschecking tool capabilities. In the paragraphs below, we discuss a number of these benchmark experiments. Note the choice of the appropriate benchmark experiment is case specific.
**a) Surface Oscillation Experiment**

In this drop tower experiment, researchers released the drop capsule to expose a low contact angle liquid to a step reduction in gravity from $g_0$ to $\approx 10^{-5} g_0$. The liquid-gas interface reoriented from a gravity-dominated configuration towards a low $g$ $Bo \ll 1$ interface configuration. The drop duration was only 4.7 seconds, but it was sufficiently long to observe the reorientation during the drop. Details of the benchmark test case are in references [35] and [38]. Figure 1 is the general view showing the reorientation process.

![Figure 1. Reorientation process during step reduction in gravity from 1g to 0g: a) equilibrium condition in a 1g environment; b) - d) reorientation of the free surface in 0g (liquid phase in grey) [39]](image)

The following aspects of the experiment are of interest to CFD benchmarking.

- **Frequency of reorientation:** The reorientation process results in a low Bond number damped oscillation. It is of interest to see if the code is able to detect the oscillation frequency.

- **Damping of the oscillation:** With respect to the duration oscillation damping, it is of interest to analyze the damping of the system modelled in CFD.

- **Pinning contact line:** At a certain point in time, the contact line may be pinned at the tank wall. It is of interest to evaluate whether the CFD codes were able to represent this feature or not.

- **Liquid layer at the wall:** A liquid film will form at the tank wall that is detaching from the bulk liquid during the reorientation process. It is of interest to know if the CFD codes can detect this phenomenon.

- **Motion of the centerline interface point:** It is of interest to analyze the movement of the centerline point with respect to time. In addition, deviations with respect to the final condition at the end of the drop are essential. Furthermore, volume errors based on the VoF CFD numerical model are detectable.

- **Symmetry of the liquid-gas interface when modelled in 3D:** Generally, it is possible to model the problem in 2D. However, it is of interest to model this case in 3D to check mesh dependent inaccuracies of the wetting behavior.

Recently, researchers extended the scope of benchmarking to include the study of cryogenic liquids behavior, including liquid hydrogen [37]. At the time of this publication, it is possible to state that researchers had reached satisfactory accuracy for the isothermal case. However, examination of non-isothermal cryogenic conditions is continuing because the current contact angle model is insufficient as temperature gradients change could result in a change in contact angle.

**b) Capillary Rise Experiment**

In another drop tower experiment described by Dreyer [35], a liquid meniscus rose in a Plexiglas tube after the release of the capsule. See Figure 2 below.

![Figure 2. Schematic representation of the drop tower test geometry [35]](image)
Test liquids were FC-77 and two silicone fluids. All liquids perfectly wet the tube (static contact angle is 0°) [35]. In this experiment, the following parameter is of interest.

- Capillary rise velocity. The main characteristic dimensionless number is the Ohnesorge number:

\[ Oh = \sqrt{\frac{\nu^2 \rho}{\sigma d}} \]

The Ohnesorge number is a function of viscosity \( \nu \), the liquid density \( \rho \), the surface tension \( \sigma \) and the tube diameter \( d \) (see [35] for more details). In addition, the advancing contact angle model plays a major role. It is of interest to evaluate whether the capillary rise velocity is reproducible, and how the grid resolution in the mesh affects the CFD result. Modeling both in 2D and 3D are of interest even though the problem is 2D rotational symmetric.

c) Slosh Damping Experiment for High Bond Number Conditions

A well-known database for this kind of experiments is the fundamental work described by Dodge [93] and Abrahamson [94]. Their experiments are state-of-the-art and accepted world-wide. Both slosh damping with and without baffles were examined. Generally, it is of interest to evaluate slosh damping in comparison to this data basis for high Bond number sloshing.

4. Conclusion

Space-based systems are prevalent in modern society and critical to the modern way of life. The development of PMDs is a small but vital part of space systems development. The foundation of PMD development is the application of scientific knowledge based on a thorough understanding of the physical behaviors of liquid propellant in space. There is no sorcery or black magic! Importantly, the fundamental scientific knowledge has been accumulating for more than 50 years, and the practice of PMD design and development for storable propellants is mature.

The practice of PMD design is foreign to many people, even for those who have been working on space systems for many years. It is a highly specialized skill performed by a handful of individuals only. Similar to most professional endeavors, it requires a firm grasp of fundamentals, training, mentorship, frequent repetition and exercise, wide exposures to multiple flight scenarios, and performance feedback in order to become proficient in the trade.

The purpose of this paper is to enable the authors, the individuals with deep involvements in the day-to-day activities associated with PMD development, to present a body of evidence in support of analysis-only PMD design approach. We summarized our program experience and cited sources from the literature to validate the practice of designing PMDs using analysis-only methodology. Currently, the space industry has two camps: one that embraces the analysis-only methodology starting in the 1970s, and one that continues to require ground level functional testing. While we believe it is a customer’s prerogative to choose the qualification method, we also believe the presentation of pertinent facts on PMD design history and practices are keys to making informed decisions.

While the examples provided in this paper are published accounts of PMD performance, it is important to note that thousands of PMDs are in service or have supported missions through depletion. The design validation of a majority of these PMDs was analysis only. The requirement of ground testing, prevalent in the early PMD development years, is no longer necessary today. Billion dollar space vehicles such as Cassini and the upcoming James Webb Space Telescope rely on analysis-only PMDs. The physics of liquid behavior in space is well understood, and to date no flight failures are known to have occurred. We believe the validity of our position is self-evident.

To ensure high quality PMD design into the future, stakeholders must continue to support the collection of fundamental data to narrow the design margins of error. We recommend expanding the fundamental research to include data collection for cryogenic and green propellants. There are many lessons learned in the last five decades that are applicable to cryogenic propulsion and green propulsion systems. Nevertheless, a solid set of fundamental data is essential for enabling PMD design and development.

References


