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406 N. Cedros Ave
Solana Beach, CA 92075
www.flometrics.com

Pistonless Pumps for Reliable, High Performance Propulsion Systems.

A flexible, robust, high performance propulsion system is a critical element of the proposed CEV. In-space propulsion systems generally use pressure fed systems that drive up tank cost and mass and limit engine performance and design choices. This paper describes a low cost pump technology, the pistonless pump, to improve CEV performance and design flexibility and increase damage and fault tolerance.

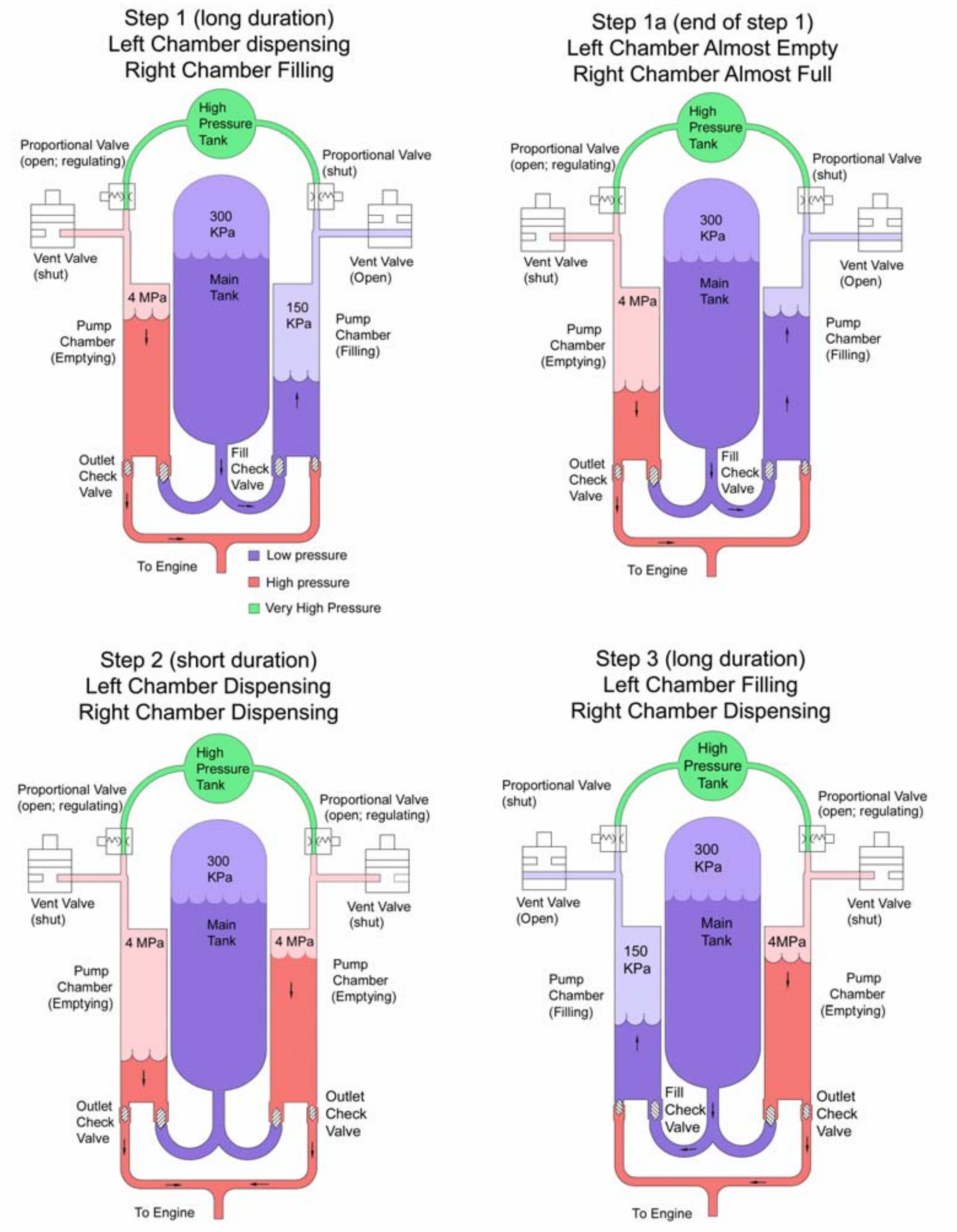

Figure 1, Pistonless pump operational cycle

Relevance to RFI

In order to be adaptable, the CEV needs to have flexibility to use pre-positioned propellant tanks or drop tanks, and these should be low-pressure tanks to avoid the mass and complexity of high-pressure systems. The CEV needs to be safe, and low-pressure propellant systems are safer. This drives the system design toward a higher performance pumped propulsion system. CEV systems need to be scalable and the pistonless pump is scalable. CEV components need to be sustainable, and the pistonless pump is a robust design that could be built by a wide range of manufacturers using standard machining and welding techniques. The CEV needs to be affordable, and the pistonless pump is inexpensive.

Pump description

The pistonless pump is similar to a pressure fed system, but instead of having the a main tank at high pressure (typically 300-500 psi) the proposed pump system has a low pressure tank (5 -50 psi) which delivers propellant at low pressure into a pump chamber, where it is then pressurized to high pressure and delivered to the engine. A diagram of the pump operation is shown in Figure 1. Two pumping chambers are used in each pump, each one being alternately refilled and pressurized. The pump starts with both chambers filled (Step 0, not shown). One chamber is pressurized, and fluid is delivered to the rocket engine from that chamber(Step 1). Once the level gets low in one chamber, (Step 1a) the other chamber is pressurized; and flow is thereby established from both sides during a short transient period(Step 2) until full flow is established from the other chamber. Then the nearly empty chamber is vented and refilled. (Step 3) Finally the cycle repeats. This results in steady flow and pressure. The pump is powered by pressurized gas which acts directly on the fluid. Initial tests showed pressure spikes as the pump transitioned from one chamber to the other, but these have since been eliminated by adjusting the valve timing. For more details on the pump and a discussion of the second-generation design see reference 1 or 8. This pump is more robust than a piston pump in that it has no high pressure sliding seals, and it is much less expensive and time consuming to design than a turbopump and a system which uses the pump has far lower dry mass and unusable residuals than turbopumps do. For more info, see www.rocketfuelpump.com

Pump Technology Readiness Level

The pump development to date has been self-funded The pump is currently at TRL 4. It has been tested with water at 450 psi and 20 gpm, it has been tested with LN2 at 8 GPM and 150 psi, and it has been used to pump kerosene at 485 psi and 20 GPM in an Atlas Vernier rocket engine test. (see Figure 2.) A CAD design of a workhorse pump for LOX, RP, NTO, hydrazine or HPT has been completed. (see Figure 3.) Valves and sensors have been specified. Materials and manufacturing processes (standard welding and machining processes) have been identified, and vendors to fabricate such a system have been qualified .

Figure 2 Atlas Vernier Engine Running with Fuel Pumped and LOX Pressure-fed.
(Test facility courtesy Reaction Research Society)

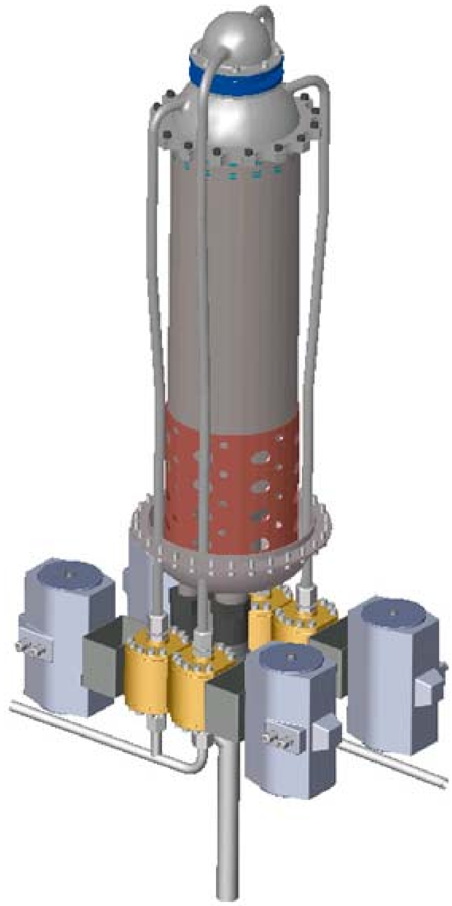

Figure 3. Pump design using off-the-shelf space-qualified valves.

Spacecraft Applications of the Pump.

This pump offers substantial performance and flexibility improvements for a space vehicle such as the Crew Exploration Vehicle. Space vehicles currently use spheroidal tanks pressurized to 200-300 psi. These tanks are somewhat heavy, are very expensive and require propellant management devices to keep liquid propellant at the tank outlet for engine starting in a zero gee environment. The pump allows for lightweight, low-pressure tanks and the pump can be stopped with one chamber full of fuel so that when the spacecraft starts, the fuel will settle to the bottom of the tank and no PMDs are required in the tank. The spacecraft tanks need not be spheroidal, and options such as low pressure drop tanks, flexible composite tanks etc. become feasible. The low-pressure tanks can be lifted to LEO empty and then filled from the upper stage, thereby limiting the structural loads on the tanks. Low-pressure tanks can also be more easily jettisoned or connected, and low-pressure plumbing, valves and fittings are lighter, less expensive and more reliable. For lunar and mars missions, fuel can be pre-positioned by robotic spacecraft at the destination for the return trip. These tanks can be more easily integrated with the spacecraft, and the dangers associated with handling propellant tanks and transferring propellant are lower at low pressures. We imagine a system that utilizes aircraft drop tank style operations. Since ascent stages from the moon or Mars need not be streamlined, concepts for use of propellant produced locally on the moon or Mars may benefit from fiber reinforced external flexible bladder tanks. This will reduce delivered vehicle size and mass.

The pump works well at flow rates from zero to full flow, so it can be used to provide pressurized propellant for attitude control or for landing rockets, as well as for main engine burns. Because the flow and pressure are decoupled the pump uses no pressurant at zero flow. The pump can also be vented to a low pressure so as to reduce loads on propellant valves with seals subject to creep or degradation for long duration space flights. In some missions, it may make sense to use a gas generator to supply pressurant for the pump, to save weight on helium tanks. A fully optimized system might condense the pump pressurant exhaust in a radiator in order for it to be pressurized, vaporized at the engine and reused.

Listed below are a number of pump advantages of pistonless pumps in CEV applications.

Safety:

- Negligible chance of catastrophic failure because typical failure modes are benign.
- Leaks from the main tank involve lower pressures, coarser atomization, and lower explosion hazards than from high pressure propellants
- Easy to start up and shut down, similar to pressure fed systems. No spool up time required.
- Thrust can be modulated quickly, to steer, rendezvous, or reduce start/stop transient loads
- The pump can be run dry with no adverse effects. The pump can even purge the lines leading to the engine.
- Minimal pogo effect as tank pressure is decoupled from engine pressure.
- The pump is failure tolerant. A small leak in one of the check valves will only increase the pressurant consumption of the pump, it will not cause a pump failure. Software can be designed to keep a pump with redundant valves and sensors operational, despite failed sensors or valves.
- Unlike other pumps, no problems with seals, cavitation, whirl or bearings.

Reliability:

- Check valves, level sensors and pneumatic valves can be made redundant if necessary. The check valves in particular can be made very reliable, while the pressurant supply and vent valves are small enough to allow redundancy. All these components are currently available as space qualified COTS components.
- The gas and liquid valves are only required to operate for about 100-1000 cycles, so the valves would not be subject to significant wear.
- No sliding parts, no lubrication, may be started after being stored for a long time.
- Not susceptible to contamination. Our prototype has been sitting in a rusty steel tank for a year and it still works fine.
- The pump can be started after being stored for an extended period with high reliability because it can use valves which have already been flight qualified.
- The pump can also be vented to a low pressure so as to reduce loads on propellant valves with seals subject to creep or degradation for long duration space flights.
- Overall vehicle reliability in emergencies should improve, because pump chambers allow limited propellant storage near the engines, that can be used even if upstream feedlines are damaged.

Performance:

- It can be installed in the propellant tank to minimize vehicle size. Will not reduce volume of propellant tanks because pump chambers hold displaced propellant.
- Allow for design flexibility, arbitrarily shaped tanks can be located to control CG
- For application in a weightless environment, the pump can be designed to have at least one chamber full at engine cutoff, thereby allowing for zero G restart with the propellant in the pump chamber providing the ullage thrust. This means that the propellant settling maneuvers and propellant control devices in the main tank are not required.
- The pump also allows for efficient motor throttling with a response time on the order of the pump cycle time, that is 2-5 seconds, with much faster thrust ramp-up with a full chamber (<0.1 second if desired), and tail-off, if it is acceptable to waste a modest amount of pressurant). The pump works well at flow rates from zero to full flow, so it can be used to provide pressurized propellant for attitude control
- If the pump is combined with an injector which can be partially shut down, very deep throttling can be achieved.
- The pump vent gas can provide roll control or be diffused and/or vented to both sides of the vehicle to minimize inadvertent application of thrust. The fraction of the pump gas vented at high pressure is more than enough to pressurize the main tank, for tank pressures less than roughly 1/3 of pump discharge pressure).

Cost

- The pistonless pump is much less expensive than turbopumps.
- The pump can be scaled up or down with similar performance and minimal redesign issues.
- Low risk development; pump technology has been demonstrated and prototypes have been built and tested.
- The manufacturing tolerances need not be tight.
- Pump and vehicle use inexpensive materials and processes in their construction
- Due to the simplicity of the pump design the engineering and test costs are low. The pump fluid dynamics can be proven with low cost materials, which can then be replaced with flightweight components.
- With the right choice of materials, the pump will be compatible with NTO, MMH, LOX and RP-1. This means a few pump designs can be used in many applications.
- Easier to integrate than turbopumps; provides constant, controllable pressure, regardless of flow.

Disadvantages:

- The pistonless pump uses about 10-15% more pressurant than pressure fed systems. However, the pressurant can be heated to save 30% on pressurant mass.
- The pistonless pump system uses more valves and is more complex than pressure fed systems, however, spacecraft valve design is a mature technology, so this is not expected to be a problem

If a spacecraft were designed as a pressure fed vehicle, the pump could be a straightforward upgrade, with no major system changes. Alternatively, the pump could be coupled to a high-pressure engine for increased performance as described below

<u>High performance storable propellant engines.</u>

Pump technology is also crucial for increasing specific impulse of chemical (either bipropellant or monopropellant) rocket engines using earth-storable propellants by means of higher combustion chamber pressure. Higher chamber pressure increases performance while making engines more compact. Aerojet has been studying and has demonstrated the possibility of increasing the performance of interplanetary and apogee insertion propulsion by employing the pump fed system

The total engine firing time for a typical interplanetary mission is on the order of 60 minutes. The resulting total impulse could approach or exceed one million lbf-sec. If a pump-fed system were available, the rocket engine specific impulse could be improved and the propulsion system mass reduced.
In a 1993-1997 study funded by NASA[5], Aerojet demonstrated that when the combustion pressure is increased, the rocket engine specific impulse could be improved and the overall propulsion system mass reduced.

In the above-mentioned Aerojet study, the baseline engine performance was 327 sec Isp at 100 psia chamber pressure and 100-lbf thrust. The engine used NTO/N2H4 propellants at O/F = 1.15 with a nozzle area ratio of 300:1. When the chamber pressure was increased to 250 psia, the Isp increased to 333 sec. Although the test at 500 psi was not conclusive, extrapolation of data indicated that the Isp would have been around 340 sec. A TRW study in 1995-6 using NTO/N2H4 propellants at O/F = 1.0 showed Isp = 337 sec at 500 psi a chamber pressure with a 150:1 area ratio nozzle producing 50-lbf thrust. Predicted performance increases are shown below in Figure 4. Note that the propellant mass includes both fuel and oxidizer.

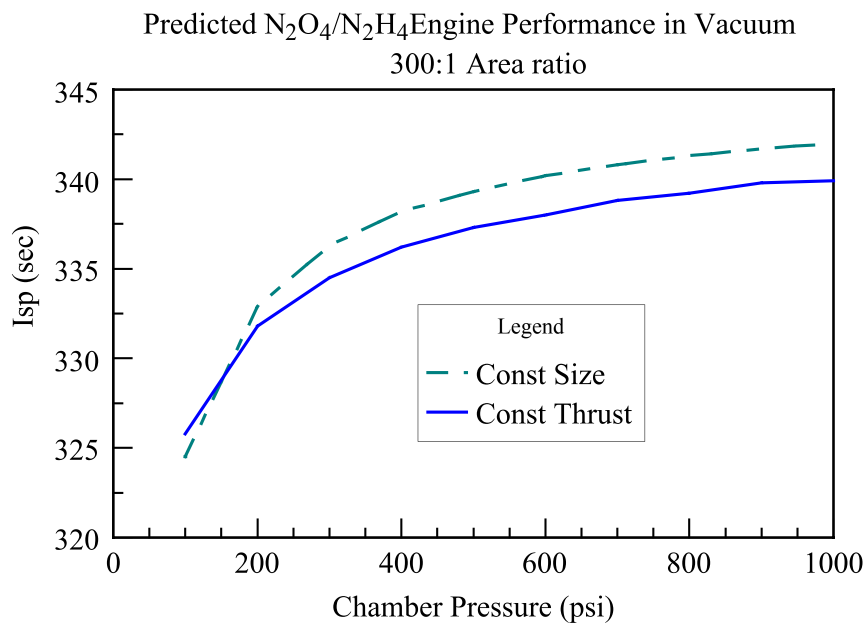

Figure 4. Aerojet engine performance as a function of pressure. Courtesy Aerojet General Corp. The engine tradeoff is normalized for either constant thrust or constant throat size

The pump and high pressure NTO/MMH engine will lower the weight of in-space propulsion systems by 6-16%, or more for high delta V missions. Calculation results for a typical mission are shown in Tables 1 and 2. Two spacecraft configurations are considered and compared. The pressure fed case assumes a tank pressure of 300 psia and an Isp of 323 sec. The pump fed case assumes a tank pressure of 50 psi, a pumped pressure of 700 psi and a specific impulse of 340 seconds. The payload is 4000 kg and the burn times are on the order of an hour The thrust is assumed to be 300 lb, the engine T/W is assumed to be 50 and weight growth on the pump is assumed to be 1000% to account for extra reliability and redundant systems. The analysis is not sensitive to pump weight. The mixture ratio is assumed to be 1.36, but the results are not sensitive to mixture ratio. If pumped LHe (which could be vaporized at the nozzle) is used for pressurant to leave earth orbit, or if the pressurant tanks are jettisoned as they are used up, the performance increase is much greater.

Table 1. Expected Performance of Pressure Fed Propulsion System
Pressure fed system (300 psi (2.1 MPa) tank pressure, 323 second Isp)

Delta V	1000 m/s	2000 m/s	4000 m/s	6000 m/s
Propellant mass (kg)	1511	3669	11462	30357
Tank mass	45.6	110.8	346	916.4
Helium and tank mass	22.7	55.2	172.3	456.4
Engine mass	2.7	2.7	2.7	2.7
Total propulsion system	1582	3838	11983	31732

Table 2. Expected Performance of Pump Fed Propulsion System
Pump fed system: (50 psi(300 KPa) tank pressure, 700 psi(4.8 MPa) pump pressure 340 second Isp)

Delta V	1000 m/s	2000 m/s	4000 m/s	6000 m/s
Propellant mass(kg)	1421	3407	10273	25543
Tank mass	7.2	17.1	51.7	128.5
Helium and tank mass	51.6	123.8	373.2	928
Engine mass	2.7	2.7	2.7	2.7
Pump mass	2.1	2.1	2.1	2.1
Total propulsion system	1485	3553	10703	26605
Mass saving (%)	**6.1**	**7.4**	**10.7**	**16.2**

The design of the pump allows for much higher safety factors than are currently used (4 instead of 1.25), so a space vehicle which uses the pump will be much safer and more reliable than the state of the art. A graphical representation of the data in tables 1 and 2 is shown in Figure 3

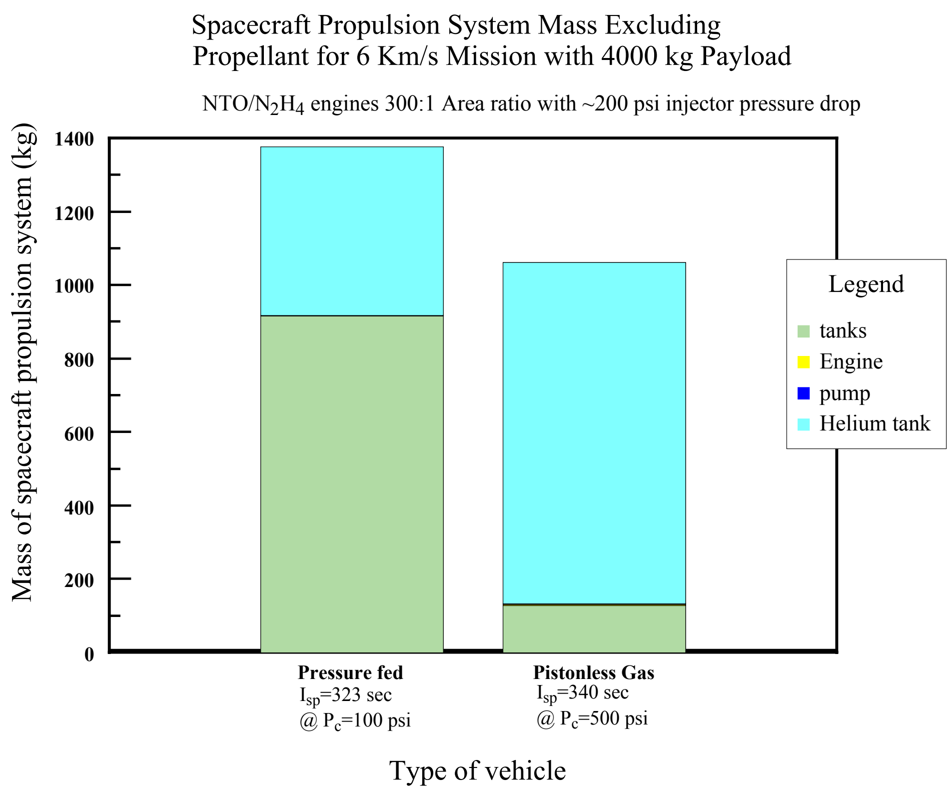

Figure 3, Spacecraft system weights. (Pump and engine are negligible)

<u>Vapor Cycle Pumped Spacecraft.</u>

For a spacecraft which uses the pump, the pressurant weight becomes an issue. If we can recover the pressurant used to run the pumps, then the burnout mass of the propulsion system would be very low. The ideal solution would be to use a closed cycle system which recovers the pressurant used to drive the pump, condenses it in radiators, pumps it up to the required pressure, and vaporizes it in a heat exchanger mounted to the combustion chamber to be used in the pumps again. This adds mass to the spacecraft for radiators, but the mass savings in pressurant is significant. In addition, the working fluid for this system could be nitrous oxide to pump nitrogen tetroxide and propane to pump hydrazine. Then, once the main fuels are exhausted, the nitrous and propane can be burned in a small rocket engine to extract more delta V.

Pumping Gelled Fuel

The pistonless pump may also be used to pressurize gelled propellants which may then be stored in a lightweight main tank at low pressure. Gelled propellants provide a potential increase in ISP due to the inclusion of suspended fuel particles. They also slosh less, and may offer a higher density impulse. They are also safer and more environmentally friendly, due to the smaller spill radius and greater difficulty of atomization. However, the atomization of the gelled propellants requires higher pressures so an optimized propellant system for in-space propulsion or other applications should run at 1000 psi or greater. This pressure level is higher than normal for pressure fed systems, and would require excess tank weight. Pumps would allow for low-pressure lightweight tanks and higher specific impulse, but high-speed piston or centrifugal pumps cause cavitation in gelled propellant.
The pistonless pump runs at slower cycle speeds than standard pumps, thereby eliminating the cavitation problem. The pistonless pump is robust and lightweight, resulting in a reliable low cost propulsion system.

We have also done some preliminary experiments pumping a non-toxic gelled propellant analogue. A plexiglas model was created to demonstrate how the pump works. This pump was used to pump a food starch based gel. The gel was the consistency of yogurt. The pump worked well, but the need for propellant management devices to collect the gel from the walls of the tank and the pump chamber was identified. Also, we saw the need for optimized check valves that would work well with the gel. In some cases, the pump chamber might use a bladder. A design of this type of system, with a bladder and wall scraper, has been completed. And depending on the propellant and mission, unusable residuals in the main tank might be reduced by warming that tank up near the end.

Conclusions

The gas powered pistonless pump has been shown to offer substantial performance and flexibility increases for space vehicles. The pump design is not complex and the pump can be developed using low cost materials and upgraded to spacecraft quality materials late in the design process to save costs.

About Flometrics

Flometrics is an engineering firm specializing in solving problems in fluid dynamics and thermodynamics. We design, build, test and improve products for customers in industries from consumer products to medical devices to spacecraft hardware. Our customers range from SC Johnson to Cardinal Healthcare to Northrop-Grumman. We have also built and launched a number of LOX/Kerosene powered rockets and developed aerospace systems.

About the Author.

Steve Harrington, Ph. D. is the founder and president of Flometrics. He has 20 years of experience in the field of applied mechanics. His skill sets include an extensive knowledge of fluid dynamics, thermodynamics, propulsion, electronics and data acquisition. Dr. Harrington has consulted for the semiconductor, medical device, aerospace and other industries. He also is a part time faculty at San Diego State University where he teaches fluid dynamics, undergraduate and advanced thermodynamics, rocket propulsion and engineering design
Prior to starting Flometrics, Dr. Harrington worked for Unisys, Rohr and Puritan-Bennett as an engineer specializing in fluid dynamics and heat transfer for computers, aerospace and medical devices.
Dr. Harrington has been working on the rocket pump[8] as a self-funded project since October of 2001. He has presented conference papers at the AIAA Responsive Space Conference in February 2003 and in April 2004 and at the Joint Propulsion Conference in July 2003. Dr. Harrington is also working with students from San Diego State University on a LOX/RP liquid fueled rocket as a student project.[9]

Acknowledgements

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