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Reciprocating Pump Systems for Space Propulsion

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Small propellant pumps can reduce rocket hardware mass, while increasing chamber pressure to improve specific impulse. The maneuvering requirements for planetary ascent require an emphasis on mass, while those of orbiting spacecraft indicate that I_{SP} should be prioritized during pump system development. Experimental efforts include initial testing with prototype lightweight components while raising pump efficiency to improve system I_{SP}.

I. Introduction

While electric propulsion offers new capabilities, chemical propulsion advances are still desired for missions that require higher thrust-to-weight ratios. Obvious examples are ascending from Mars or landing on Europa, which need accelerations near 1 g (earth gravity). At only 1 percent as much acceleration, chemical propulsion is also relied on for timely orbit insertion maneuvers at planets and into earth's geostationary orbit.

Maneuvering capability can be improved by reducing hardware mass, or by increasing specific impulse (I_{SP}). Rocket propellant pumps reduce the size and mass of hardware, by permitting the use of compact high-pressure thrust chambers, while reducing liquid tank pressures and minimizing inert gas storage. Higher chamber pressures can also improve I_{SP}. For these reasons, turbopumps are found on all the largest liquid stages of launch vehicles.

Past progress has been made toward the development of miniature pump-fed propulsion technology that can offer launch vehicle performance on a tiny scale.[1-4] The potential benefit of pumps is less obvious for orbit insertion, due to the lower acceleration. This paper therefore considers the applicability of small pump technology to propulsion in space.

II. Allowable Mass Changes for I_{SP} Increases

Both hardware mass and specific impulse are affected by propulsion design choices, so a good place to start is to consider the relative importance of mass and I_{SP} for missions of interest. Two extreme examples are compared here. A 100-kg Mars ascent vehicle (MAV) needs approximately 1000 N thrust, to reach orbit efficiently from a standing start in Mars gravity.[5] The much larger 5-ton Cassini spacecraft recently arrived at Saturn with its two 445-N thrusters.[6] Although one of the latter is just a backup, the similar total thrust indicates that the two vehicles would have essentially the same engine mass, if identical technology applied. Cassini has 500 kg of propulsion hardware out of a 2500-kg spacecraft dry mass, while the total dry mass of the MAV (including its guidance system and payload) cannot exceed 25 kg. Clearly, engine mass is less critical for Cassini than for a MAV. More generally, engine thrust-to-weight ratios are a lower priority for orbital maneuvers than for ascent and descent.

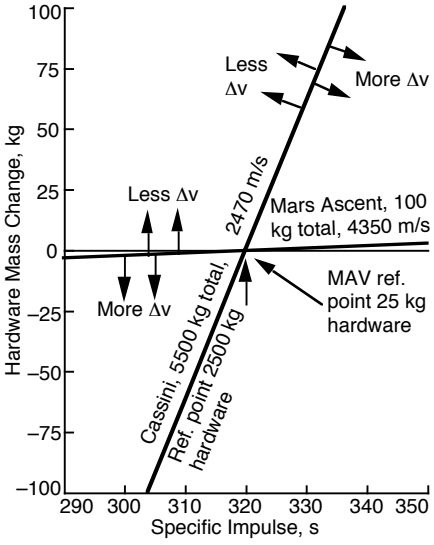

Fig. 1. Mass trades with I_{SP}.

Figure 1 quantifies the sensitivity of mass changes to I_{SP}, for the specific examples. Constant Δv curves were plotted from the rocket equation, with the assumption that initial mass totals are fixed. The curves differ greatly. However, both have positive first derivatives, because improving I_{SP} reduces the propellant quantity, thus increasing the hardware allowance. The latter could be a payload increase. In order to interpret the graph purely as a propulsion design trade, it is assumed here that the mass variations apply to propulsion hardware

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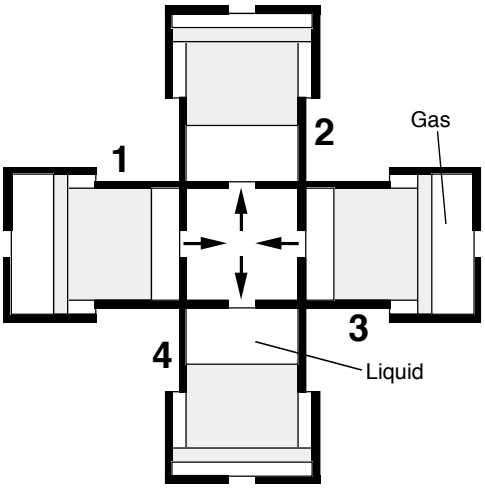

Fig. 2. Quad piston pump configuration.

refilled with propellant. The gas valves are controlled so that opposite pistons always move toward or away from each other in unison to cancel moving mass effects. In addition, the control scheme provides overlap of the power strokes, i.e. cylinders 2 and 4 become pressurized with gas slightly before cylinders 1 and 3 reach their limit and are vented.

A key feature shown in Figure 2 is that the gas cylinders are larger in diameter than the liquid cylinders. This makes it possible for delivered propellant to power its own pump. A small fraction of the liquid is either boiled or reacted in a gas generator. Its flow back to the pump powerhead necessitates a pressure loss, so the stepped pistons are needed to compensate.

The configuration shown here has a low-pressure exhaust stroke during liquid refilling, driven only by the propellant tank pressure. Thus the pump exhaust cannot be injected into the main thrust chamber as is done in some launch vehicle engines. While turbopumps do not require their gas to be vented below tank pressure, reciprocating pumps need a very different configuration to expel high-pressure exhaust. In particular, pistons must be mechanically linked for the power stroke in one cylinder to apply a force that aids the refill stroke in another cylinder. Such mechanical links can be cumbersome, the motion is not balanced, and power strokes cannot overlap for the smoothest flow. Given the advantages of the simpler pump shown, it is worth asking whether low-pressure exhaust is acceptable.

VI. Pump Efficiency Affects I_{SP}

If 5% of the propellant drives the pumps and then is simply vented, the overall I_{SP} of the propulsion system falls to 5% below that of the thrust chamber. This particular number is unacceptable, because it would negate a 15 s gain to 335 s, from the present state of the art. Three things can be done to minimize the loss. Besides reducing the gas density and avoiding powerhead leakage, the exhaust can be controlled by a nozzle directed to produce some thrust.

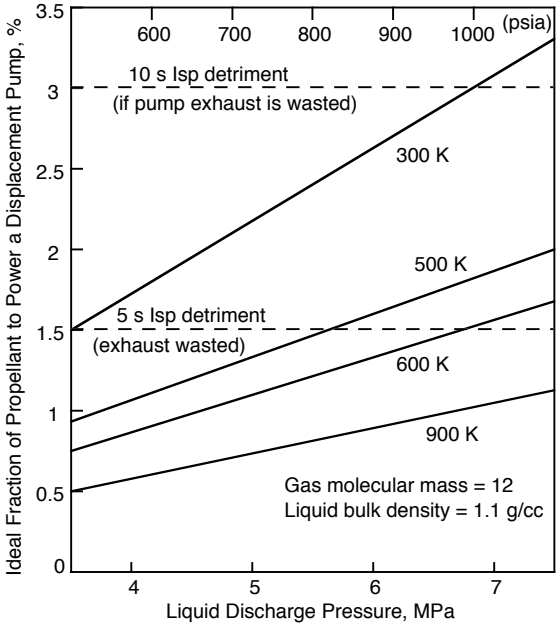

Fig. 3. Ideal gas requirements for pump drive.

Hydrazine (N_2H_4), when decomposed completely, offers a low gas density because most of the resulting molecules are lightweight hydrogen. Hydrazine is also a desirable spacecraft fuel, because it offers a higher I_{SP} than MMH (e.g. when combusted with N_2O_4), while enabling dual-mode systems (bipropellant engines, and monopropellant thrusters for fine control). Figure 3 shows the ideal percentage of propellant needed to power both the fuel and oxidizer pumps. The assumptions are a liquid bulk density of 1.1 g/cc, a molecular mass of 12 (80% NH_3 dissociation), and ideal gas behavior with R=8.31 J/mole-K.

Work is done by the gas, and heat is lost into the hardware and the propellant. Thus what Figure 3 actually represents for a displacement pump is the thermodynamic state of the gas just before the vent valve opens. At pump pressures (e.g. 5 MPa) needed to obtain the high thrust chamber pressures noted above, Figure 3 indicates that a mere 1-2% of the propellant mass would need to flow through the pump drive circuit.

If the pump exhaust is simply wasted, then attaining the 1.5% level amounts to a 5 s I_{SP} decrement. On the other hand, if useful thrust can be produced by the pump exhaust at I_{SP}=130 s or so, then there is only a 3 s decrement from the greatly-improved performance of the main thrust chamber. While the intent of this paper is not to propose exact numbers, the point of this example is that there could be a significant net performance benefit, if using pumps on a Cassini-like spacecraft can offer a 10-15 s improvement by virtue of a high chamber pressure. For more aggressive maneuvering applications like the MAV example, pump efficiency and specific impulse also matter, but they are

less critical than mass is, per Figure 1. Thus the analysis has shown that while pump-fed propulsion on a MAV can be mission enabling for weight reasons, a similar approach might also improve space systems by virtue of raising the specific impulse. These two different reasons for using pumps tend to result in different priorities when actually designing hardware for a pump-fed propulsion system.

VII. Progress Toward Implementation

Past hardware progress was focused toward applications that have requirements exemplified by the MAV mission, so mass reduction was emphasized. A 365-gram hydrazine pump first tested in 1993 would have been more than capable of 1000 N thrust, assuming two such pumps for bipropellants at I_{SP}>300 s.[2] The mass would be acceptable for both missions considered in Figure 1. However, that original quad piston pump was inefficient in terms of gas consumption, primarily due to leakage past high-temperature seals. Moreover, the solid graphite piston rings had a relatively rapid wear rate.

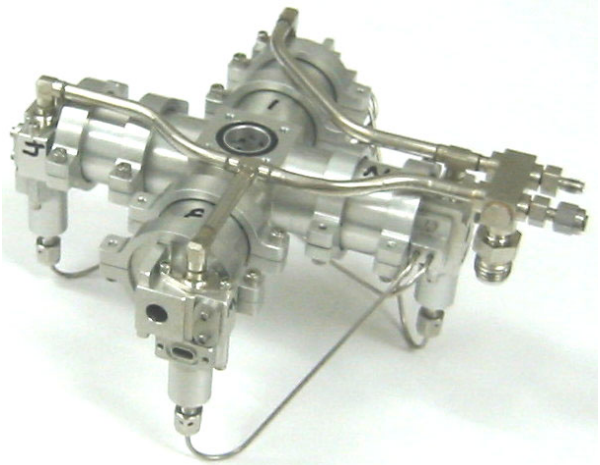

Fig. 4. Leaktight quad piston pump.

More recently, a leaktight design incorporating liquid-cooled gas seals was demonstrated, using decomposed hydrogen peroxide (steam and oxygen) to power the pump.[4] Although gas consumption is not as critical for the MAV application as for space maneuvering, avoiding leakage is desirable in any case, and seal life is greatly improved. Figure 4 shows the 400-gram leaktight pump, which can deliver about 200 g/s liquid at 5 MPa. While it is not optimized for mass and flow, preliminary design work supported by representative structural testing indicates that a lighter 270-gram iteration can reach 250 g/s flow. Realizing these numbers will be a milestone by matching the power-to-weight ratio of the 1993 pump, but with a much longer lifetime and far less leakage. The next logical step after that will be to carefully measure the gas consumption while powering the pump with decomposed hydrazine. While the seals and the metal both operate below the bulk gas temperature, the materials do impose thermal limits. Thus a key testing need is to make a determination of the best operating point in Figure 3.

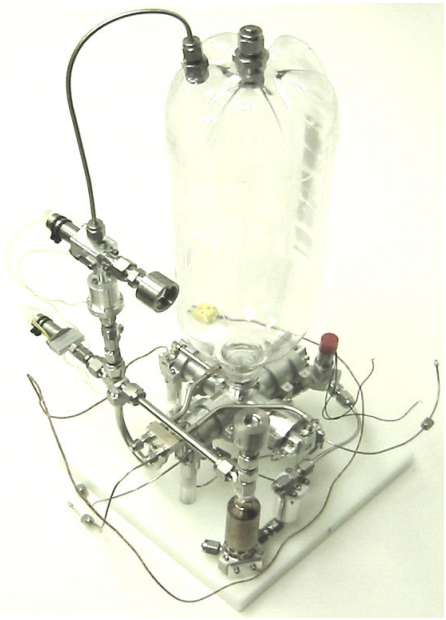

Fig. 5. System test assembly.

Implementing a complete pump-fed propulsion system requires a number of unique associated components. Those used for the original hydrazine work were extremely lightweight, but there were reliability issues. The system testing described in Reference 4 included some heavy auxilliary components, notably an off-the-shelf liquid pressure regulator in the gas generator circuit. More recently, there has been further prototyping of simplified, lightweight versions of the auxilliary components. Figure 5 shows a system assembly which was built recently for H_2O_2, but is not yet fully tested. It includes a simplified liquid pressure regulator as well as tank pressurization components that use some of the pump-drive gas at a reduced pressure (~0.5 MPa).

A nontoxic propulsion system has potential applications in its own right. Hydrogen peroxide can also serve as a nontoxic surrogate propellant for testing hardware, other than combustion devices, intended for conventional space propellants. A prime example is the thermal loading on the tank when it is pressurized using a small amount of gas which starts at temperatures above 500 K. A success with the clear polyester tank in Figure 5 would prove there is a thermal safety margin for metal tanks, while a nontoxic failure is tolerable in the lab.

Partial testing of the system shown has included operation with a water-filled tank, and helium to power the pump. The fast thrust control valve shown in Figure 6 was connected to the pump discharge port. It fed a receiving tank instead of the direct-mounted thruster partially visible toward the left side of the image.

Pressure traces in Figure 7 begin at full pressure in the absence of flow. One pair of opposite pump cylinders is pressurized (represented by the Cylinder 1 trace), while the other pair is vented (Cylinder 2). When the solenoid is actuated (lowest trace), the valve opens and simultaneously two pump pistons begin moving within 10 ms. Thereafter, liquid flows continuously and pressure dips occur when the pump cylinders switch. Overlap of the power strokes is evident, and the switching transients are smoother than for similar data in Reference 4. The valve inlet spike appears to be the effect of a sudden initial rush of fluid slowing down to steady flow. During this test, the tank ullage was maintained within a narrow band (0.45-0.47 MPa) using helium from the pump's fluid power supply, flowing through lightweight components visible in Figure 5. Given that pressures remain steady other than in the pump cylinders themselves, these data underscore the point that a space propulsion system using this technology may be operated in a fashion similar to a pressure-fed propulsion system. Any number of thrusters may be connected to reciprocating pumps, then pulsed or throttled independently (for attitude control or to obtain a precise Δv). Of course, the maximum total flow capability of the pumped feed system must meet mission requirements. In Figure 7, the water flow was approximately 200 g/s.

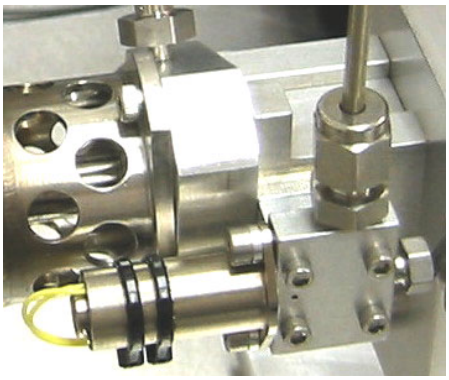

Fig. 6. Piloted thrust control valve.

Some of the actual hardware that may be developed for missions like the MAV might be useful for a pumped propulsion system intended for maneuvering in space. However, it is recognized that certain requirements for the latter type of mission are more stringent, and not all such problems are solved yet. Such differences are addressed next. If it turns out that pump-fed propulsion makes sense for spacecraft like Cassini, a different implementation could be beneficial.

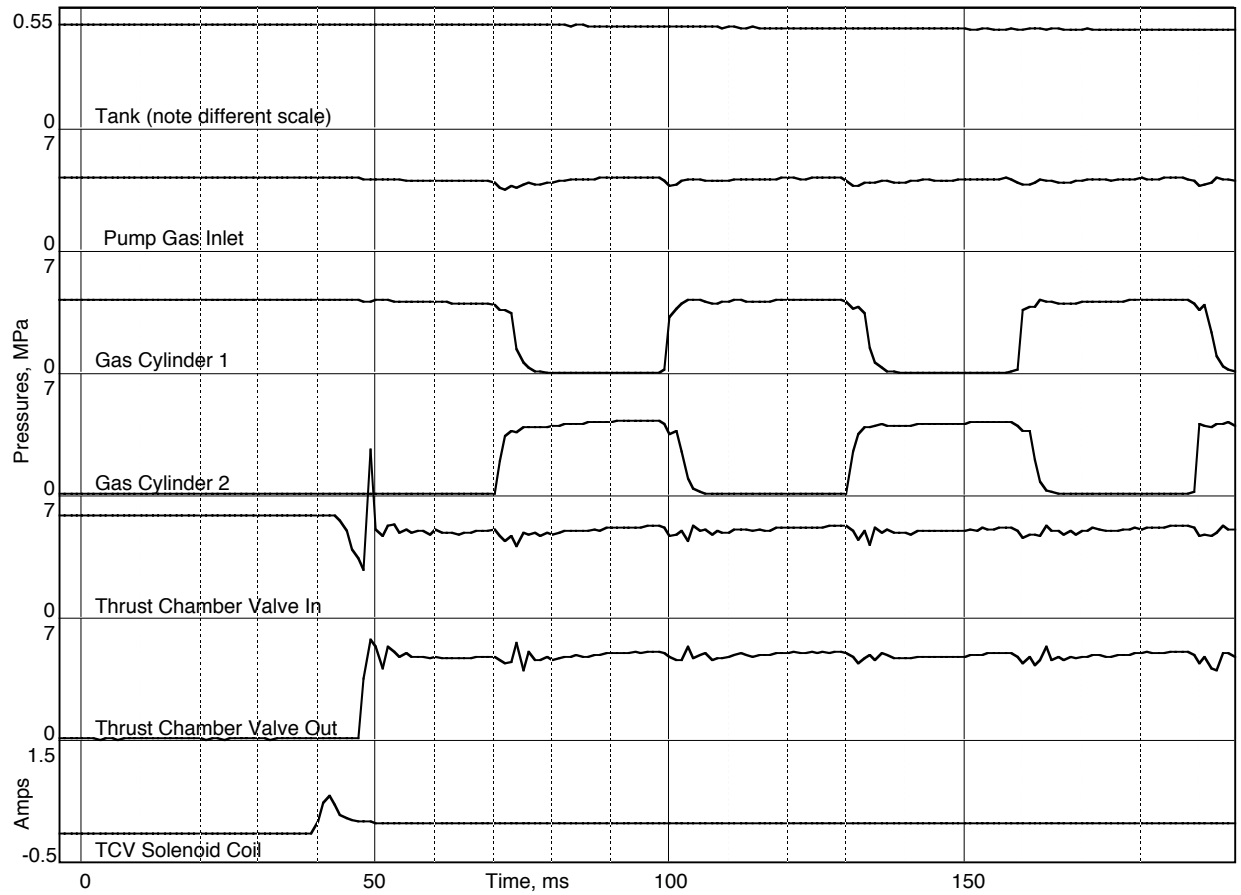

Fig. 7. Pressure data from an inert fluids test using lightweight prototype components.

VIII. Pump System Requirements for Space Maneuvers

Assuming that pumps can improve net specific impulse by 10 s or so on a future spacecraft similar to Cassini, then Figure 1 indicates that 10 kg or so of extra hardware would be a minor concession. Thus it is permissible for spacecraft propellant pumps and their associated components to be several times heavier than existing developmental hardware intended for MAV-like applications. The question to be addressed is whether the relaxed mass budget makes it possible to meet the more stringent requirements mostly related to longer lifetimes. In a similar vein, pump gas consumption might be reduced further by design changes that add hardware mass. Several potential changes are discussed below.

The operating life for a MAV pump is a few minutes, whereas the propellant load on Cassini lasts for 6 hours of total engine operation. Cyclic structural loading and seal wear are two life limiting phenomena which can be improved by heavier hardware, i.e. thicker metal and thicker seals. In one informal test, a 400-gram quad pump lasted for 4 hours of operation before structural failure at 138,000 cycles. This result offers a measure of confidence for meeting long cycle lifetimes with only a modest mass increase. In combination with added strength, larger pump chamber volumes could be used to reduce the total cycle life requirement, which is also of interest for seals and valves.

The propellant-wetted lifetime is another key difference. While a MAV can be loaded with propellants and then complete its objective entirely within an hour, the planned mission duration for Cassini exceeds 10 years. At issue is the effect of propellant, especially nitrogen tetroxide, on elastomer seals in the pump. The relaxed mass budget can help by permitting the use of (relatively large) isolation valves along the large feedline from the oxidizer tank to its pump. Alternatively or in combination, the oxidizer pump could use metal bellows instead of pistons. This change would add significant mass especially for long lifetimes, but again mass is not critical for the space application.

Regarding gas consumption by pumps, the lightest gas valve design used in prototypes to date permits some blowby when switching between intake and exhaust. This loss mechanism might turn out to be a significant fraction of total gas consumption (e.g. >10%) for MAV-like applications. Reducing the cycle life, by increasing pump volume as suggested above, would reduce the total number of valve switching events over the course of the mission. The valve size and its gas loss per event depends on design flow rather than the pump volume, so overall losses would be reduced. Similarly, if there is gas leakage late in a pump's life due to seal wear, reducing the number of cycles per unit quantity of propellant would solve the problem.

If valve poppet blowby during switching turns out to represent an even larger fraction of pump gas consumption, then for space applications it would make sense to consider heavier valve arrangements that prevent flow from the source to the vent during switching. Minimizing non-working head volume in the pump gas cylinders would also be more important to missions that require a primary emphasis on specific impulse.

For the MAV application, as for large launch vehicles, tank pressures near 0.35 MPa (50 psi) or lower are fundamental to obtaining stage propellant fractions in the neighborhood of 90%. However, when considering performance improvements for spacecraft like Cassini, it might make sense to keep the conventional feed system with its higher tank pressures near 1.7 MPa (247 psi). Such an approach minimizes propulsion system design changes relative to the conventional state of the art. More importantly for performance, the pump exhaust could then be expelled at well above 1 MPa (145 psi), thus making it easier to obtain efficient thrust through auxilliary nozzles.

Beyond the pump itself, mass can be traded for I_{SP} in other system components. The use of greater area ratios at the expense of more nozzle weight is well known. To some extent, a larger, heavier injector having larger passageways can reduce the pump pressure requirement for a given combustion chamber pressure.

As a final consideration, there is still the possibility of heavier, more complicated pumps, which can deliver the exhaust at a high pressure directly to the main thrust chamber. Most launch vehicle engines do not do this, to avoid extra complexity and its resulting impact on cost and reliability. Nevertheless, staged combustion cycles using reciprocating pumps should not be ruled out entirely.

IX. Conclusion

It is widely appreciated that relatively modest improvements in specific impulse can significantly improve spacecraft capabilities and satellite lifetimes. One option for doing so in the chemical propulsion development arena is to use pumped feed systems to permit increased chamber pressures. The capabilities of prototype pump system hardware, intended for miniature launch vehicle applications, have continued to improve. Future propulsion systems for maneuvers in space might take advantage of such developments. Actual hardware configurations may differ, in order to meet more stringent needs for lifetime and efficiency. The mass-I_{SP} trade offers an extra mass allowance to address such issues unique to space applications.

Acknowledgment

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