Space 2004 Conference and Exhibit
28 - 30 September 2004, San Diego, California

AIAA 2004-6130

Launch Vehicle and Spacecraft System Design Using the Pistonless Pump

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The application of a pistonless pump to a launch vehicle or spacecraft can provide cost and reliability improvements over standard pressure-fed or turbopump-fed designs. Calculations show that in a first stage launch vehicle application, a system which uses the pistonless pump has comparable performance to gas generator turbopump designs. The performance can be improved by using low-pressure liquid helium which is pumped using a pistonless pump to high pressure and then heated at the engine. This allows for lower pressurant tankage weight. This system uses less than 1% of the fuel mass in liquid helium, which offers a performance advantage over comparable gas generator turbopump powered rockets. A complete overall vehicle design is presented which shows how the various systems are integrated and how much each component weighs. The vehicle uses LOX/hydrocarbon propellants at moderate to high pressures to achieve high performance at low weight and low cost. The pump is also shown to have significant performance and flexibility increases for spacecraft when combined with high-pressure storable propellant engines. The pistonless pump is also applicable to pumping gelled propellants.

Nomenclature

a	=	factor for portion of vehicle mass proportional to payload
b	=	factor for portion of vehicle mass proportional to propellant mass
c	=	factor for portion of vehicle mass proportional to propellant mass time chamber pressure
g	=	acceleration of gravity
I_{sp}	=	specific impulse
K	=	pump design efficiency (Currently .5)
M	=	average molecular weight of combustion products
P_0	=	Chamber Pressure
P_e	=	External ambient pressure
R_u	=	universal gas constant
ρ_f	=	average propellant density
ρ_c	=	pump chamber material density
σ_c	=	pump chamber material acceptable design stress
T	=	Thrust
T_{cycle}	=	cycle time of pump
V_e	=	Ideal exhaust velocity
W	=	Weight of vehicle

I. Introduction

This paper describes a pistonless pump[1] as an alternative to turbopumps and pressure fed systems in both boost and upper stage applications and also for space vehicles. The pistonless pump offers significant cost, reliability and

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performance advantages. These advantages are related to the simplicity of the design. A discussion on how to optimize a vehicle which uses the pistonless pump is presented in terms of chamber pressure. A comparison using this optimization procedure is also presented for pressure fed and turbopump systems.
Any pressurized gas which is compatible with the propellant may power the pump, but this paper will focus on two possibilities: gaseous helium which is stored in composite tanks or Liquid helium (Lhe) which is stored in a low pressure Dewar. The liquid helium, pressurized by a pistonless pump and vaporized at the rocket engine.

The pump may also be used for space propulsion, where it offers a number of advantages in performance, safety and flexibility for space vehicle designers.

II. Pump description

The pistonless pump is similar to a pressure fed system, but instead of having the a main tank at high pressure (typically 500-1000 psi)(3-7Mpa) the pistonless pump system has a low pressure tank (35 -70 psi)(.2-.5Mpa) which delivers propellant at low pressure into a pump chamber, where it is then pressurized to high pressure and delivered to the engine. Two pumping chambers are used in each pump, each one being alternately refilled and pressurized. The pump controls are set up so that when the level in one side gets low, the other side is pressurized; and then after flow is established from both sides, the low side is vented and refilled. 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. This reference includes a derivation of an equation to determine pump mass. The mass is based primarily on the mass of the pump chamber, a pressure vessel. The thrust to weight ratio of a given pump used with a particular fuel at a given can be calculated by:

$$\frac{T}{W} = \frac{K \cdot \rho_f \cdot g \cdot I_{sp}}{P_f \cdot \frac{T_{cycle}}{\sigma_c} \cdot \rho_c} \qquad (1)$$

Note that the pump weight scales linearly with the thrust, so it can be scaled up or down as required.

Using equation 1 with a cycle time of 5 seconds, and density and specific impulse data from Huzel and Huang[2] for engines running at 600 psi (4 Mpa) at sea level, pump thrust-to-weight ratios were computed for typical rocket fuels (see Table 1). Aluminum (alloy 2219) was assumed to be the pump material. Higher thrust to weight ratios can be attained by using other high performancematerials such as titanium or composites.
In a system which uses the pump, the performance is not sensitive to pump mass. The most important factor is the weight of the pressurant. The gas powered pistonless pump offers significant advantages over pressure fed systems and is shown to be equivalent in performance to gas generator turbopump systems. Due to the reduction on high-pressure tank mass, the liquid powered system performance matches staged combustion turbopump systems. The gas powered pump system is at TRL 4 and the liquid powered system is at TRL 3. (TRL=technology readiness level)

Table 1: Pump Thrust-to-Weight Ratios

Propellant	Average Propellant Density (kg/m^3)	Mixture ratio	I_{sp} (sec)	Pump Thrust/ Weight
LOX/RP-1	935	2.58	285	732
LOX/LH_2	250	5	370	263
H_2O_2/RP-1	1200	6.5	276	657
N_2O_4/N_2H_2	1220	1.36	277	929

III. Pistonless Pump Advantages

Turbopumps are the status quo, but they are expensive and prone to failure. For example, it cost over $1 billion to change vendors on the Space Shuttle turbopump[8]. Furthermore, in 1999 there were two of Proton[9] and one HIIA[10] rocket failures all due to turbopumps. Piston pumps have been developed and flown[3], however these pumps are mechanically complex and would be expected to be heavier and more expensive than the pistonless pump described herein, especially for larger pump sizes. Furthermore, piston type pumps may run into trouble pumping reactive oxidizers such as LOX or NTO, as the sliding seals will tend to remove the oxide layer which protects metal components.

The pistonless pump is easier to integrate into a launch vehicle than a turbopump. Turbopumps are expensive and difficult to develop and are not easily scaled up or down. Turbopumps must be started carefully, and tuned to work with a particular engine because the engine pressure and flow characteristics fluctuate during ignition. The pistonless pump can deliver full pressure or a programmed pressure profile from zero flow up to the maximum flow rate. A rocket which uses the pistonless pump can be tested and optimized at small scale and then scaled up without having to completely redesign the pump. This keeps engineering costs to a minimum especially if a range of vehicle sizes are needed. Furthermore, it is less expensive for a small rocket to fail than a large one. The low cost and scalability of the pump will allow for vehicles of various sizes to be built and stored for use as needed. A pumped rocket uses propellant tanks which are much lighter and easier to manufacture and test than those in a pressure fed system. A rocket powered by a pistonless pump will have the same tank mass as a turbopump rocket, but the gas powered pistonless pump system will be slightly heavier due to the pressurant tank weight. In order to minimize pressurant tank weight, the pump can run on LHe heated at the engine. In this configuration the pistonless propellant pumps run on high-pressure helium which is derived from a LHe supply. The LHe is stored in a low pressure Dewar. A pistonless pump designed to be used with LHe is used to pressurize the LHe to approximately 1000 psi (6.9MPa), and it is piped to a heat exchanger on the rocket engine nozzle where it is heated to 300-800 °K. To heat the helium to 300K will require approximately 0.4% of the heat energy of a rocket engine which runs at 1000 psi (6.9 MPa). Large, high-pressure engines may require that the helium be heated by combustion of the propellants. The heated helium is used to operate the LOX and RP-1 pumps. Heat transfer calculations show that the thermal time constant of the helium in the pump is more than 10 times the pump cycle time for a pump with proper thermal design. The LHe pump runs on a supply of gaseous helium, which is stored in the LOX tank to keep it at low temperature and high density. This gaseous helium which is used to operate the LHe pump may be temperature controlled to prevent excess vaporization of the LHE in the pump. This system uses less than 1% of the mass of the fuel is used as pressurant, instead of the 2 to 3% used for turbopump rockets. Startup of a Lhe powered rocket can be accomplished with the use of ground support helium. The pump will work fine on cold helium until the heat exchanger warms up. Furthermore, the United States controls most of the world helium reserves, so a launch vehicle which requires significant amounts of helium will give us an advantage over our adversaries and competitors.

Some advantages of the pistonless pump for a reliable, low cost launch vehicle are:
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. 3 sigma processes are easily acheivable.
- 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.

Safety:

- Negligible chance of catastrophic failure because typical failure modes are benign.
- Easy to start up and shut down, similar to pressure fed systems. No spool up time required
- 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 the pump operational with failed sensors or valves.
- No problems with 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.
- The gas and liquid valves would only be 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.
- A flight ready pump can be developed using 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.

Performance:

- The pump can be installed in the propellant tank to minimize vehicle size. Will not reduce volume of propellant tanks because pump chambers hold displaced propellant.
- 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 motor throttling with a response time on the order of the pump cycle time, that is 2-5 seconds. 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 amount of pressurant consumed by a propulsion system will be similar to that used by a pressure fed system with a slight increase in pressurant volume to make up for the ullage in the pump chamber at the beginning of each cycle. Heating of the pressurant can reduce the usage by 30%
- The pump vent can be recycled, or designed to provide roll control or it can be diffused and/or vented to both sides of the vehicle to minimize inadvertent application of thrust.

Many of these advantages also apply to the use of the pump in spacecraft.

IV. Launch Vehicle Optimization

The optimization of a launch vehicle which uses the pistonless pump is slightly different than the same process applied to one which uses a turbopump or a pressure fed system. In the following discussion, the performance of a LOX/RP1 powered first stage with a DeltaV in the neighborhood of 3500 km/s is examined. This design point is similar to the Saturn V first stage. The component masses used in the following discussion are based on the S1-C first stage[4].

For any rocket design, higher chamber pressure results in greater specific impulse, but at a cost. For a staged combustion turbopump rocket, the cost is in the engine development, for a gas generator turbopump the cost is more propellant used in the gas generator. For a pressure fed rocket the cost is higher tank mass, and for a pistonless pump powered rocket the cost is the pressurant weight. In all cases, the cost is reduced if the chamber pressure is selected on the low side of the optimum performance range.

Turbopump rockets with staged combustion cycles have high performance but are very expensive and difficult to design, build and test. The working pressure for this type of rocket engine, such as the RD-180 is about 3700 psi (25 MPa).

In a gas generator turbopump vehicle the engine which runs at 900 psi (6.2 MPa) is assumed to use 2.5% of its propellant mass to run the turbopump. This means that the turbopump engine has 97.5% of the Isp of an equivalent pressure fed engine. The amount of propellant used in the gas generator is proportional to the chamber pressure, i.e a turbopump at 1800 psi (12.4 MPa) will use 5% of its propellant to run the turbine. An estimate of the specific impulse for this type of rocket engine includes the reduction in impulse due to the gas generator flow. The result of this is that gas generator turbopumps generally run at less than 1300 psi (9 MPa), because the additional propellant mass to run the turbine does not significantly increase the overall specific impulse at higher chamber pressures. The pump mass is much less than the fuel necessary to run it. As for the vehicle design of a turbopump rocket, the tanks are about 1.2% of the propellant mass, the residual propellant is about 1.4% and the engines and pumps are about 2% of the propellant mass. The large residual propellant is due to the requirement of having significant pressure at the pump inlet to prevent cavitation.

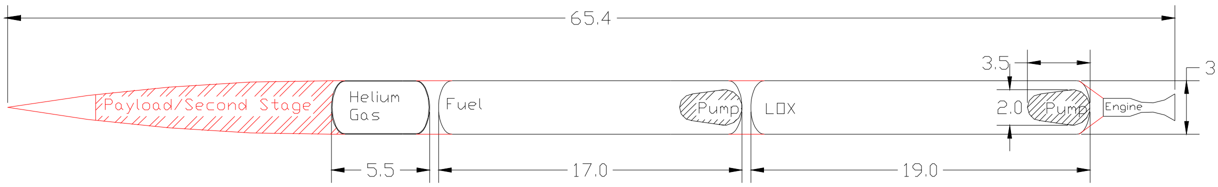

Figure 5a 25,000 lb GLOW Gas Powered Proposed Rocket Design. (Dimensions in ft.)

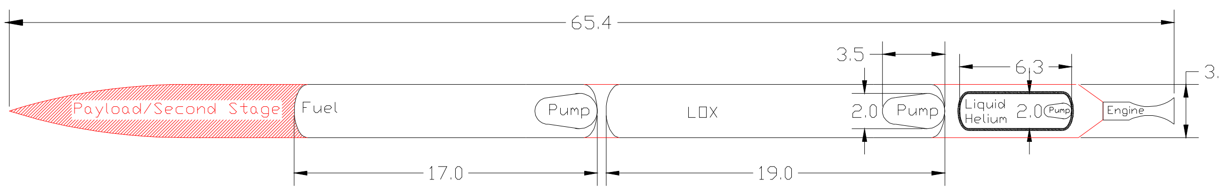

Figure 5b 25,000 lb GLOW Liquid Powered Proposed Rocket Design. (Dimensions in ft.)

The pressure fed launch vehicle requires a pressurant tank and heavy propellant tanks which must be carried all the way until burnout. As the mass of these components is proportional to the chamber pressure, pressure fed rockets run at less than 600 psi (4 MPa). For such a vehicle the engines are about 1% of the propellant mass, the residual propellant is about .2% (it can be run dry). Aluminum tanks for 1000 psi (7 MPa) are about 10% of the propellant mass, and the pressurant and its tankage add up to about 3% of the propellant mass.

The designer of launch vehicle that uses the pistonless pump will need to consider the weight of the pressurant first, because that will drive the empty weight of the vehicle. The vehicle performance is not sensitive to the pump weight. The aluminum pistonless pump is assumed to have a T/W of 200 at 1000 psi (7 MPa). This includes a safety factor of two. The gas driven pistonless pump vehicle works best at about 700-1000 psi (5-7 MPa), so it can be used with thrust chambers which were designed for gas generator turbopumps. If the pistonless pump vehicle is powered by LHe instead of high pressure compressed helium, the vehicle works best at about 1200-2200 psi(8-12MPa). This vehicle uses very little pressurant weight, because LHe is much lighter than the average propellant. For a vehicle which runs at 1000 psi (7 MPa), the pistonless pump is about .7% of the propellant mass, and the tank mass is the same as for the turbopump rocket, 1.2%. The Dewar has a volume of 9% of the propellant volume at 1000 psi (MPa) fuel pressure, so the Dewar is about .3% of the propellant mass The LHe mass is about .93% of the propellant mass, and it is constantly discarded, so the use of the helium can be accounted for by an I_{sp} reduction proportional to the percentage of the propellant mass. The helium is just counted as one more of the propellants as it is used up during the flight. This means that the engine performance is 99.1% of theoretical, instead of 97.5% for the gas generator turbopump rocket. Both types of pistonless pump vehicles have about .2% residual propellant. The helium usage is based on a helium average temperature of 25 °C and the amount of helium can be reduced by heating the helium.

V. Calculation of Mass Ratio

The mass ratio of each type of vehicle is calculated by determining the optimum chamber pressure for a given system and calculating the mass of each subsystem.

The I_{sp} is calculated based on an ideal rocket expansion for an altitude of sea level, T_0=3850 K, M=25.5, and γ=1.2. This analysis does not include effects due to non-ideal gas behavior, engine performance, finite rate chemistry or ambient pressure changes

$$V_e = \sqrt{2\frac{\lambda-1}{\lambda}\frac{R_u}{M}T_0\left[1-\left(\frac{P_e}{P_0}\right)^{\frac{\lambda-1}{\gamma}}\right]} \tag{2}$$

Mass estimates for the various components are based on the mass of the Saturn V first stage from Whitehead[6]

For each vehicle, the figure of merit is the ratio of gross liftoff weight to payload weight to accelerate a payload to a given velocity. The burnout mass is assumed to be a function of the payload mass, the propellant mass, and the chamber pressure. The dependence of some components on the thrust is included by assuming that the thrust is roughly equal to the propellant mass. The thrust to weight ratio for the rocket engines is assumed to be 70 for turbopump rockets and 100 for pressure fed and pistonless pump rockets. We assume at liftoff T/W of 1.2 and a mass ratio of approximately 5.

The equation for burnout mass, exclusive of the payload mass is:

$$M_b = a \cdot M_{pay} + b \cdot M_{prop} + c \cdot M_{prop} \cdot P_0 \tag{3}$$

a - This factor depends on the mass of the payload, this includes the structure, avionics, etc.
This is about 15% of the payload for the S-1C

b - Depends on the amount of propellant, this includes tanks and residual propellant. Low-pressure tanks weigh about 1.2% of the propellant weight. The amount of residual propellant is 1.4% for the turbopump rockets like the S-1C, and it is assumed to be .2% for pressure fed and pistonless pump fed rockets. Since the amount of propellant is roughly equal to the thrust, the engine mass is included here as a percentage of the propellant mass.

c - Depends on the mass of propellant and the chamber pressure. This is used to determine the mass of the tanks for the pressure fed rocket and the mass of the pistonless pump. This factor also includes the mass of pressurant and pressurant tanks. The pressure fed tank weight is figured based on a 2219 aluminum tank. The units for this factor are 1/1000 psi(MPa), that is they are normalized for a 1000 psi(MPa) chamber pressure. The injector pressure drop is assumed to be 100 psi (0.7 MPa). For an aluminum tank at 1000 psi, the tank weight is 10% of the propellant. The helium tanks are assumed to weigh 3 times as much as the helium they contain. This is based on available spacecraft tanks.

Table 2: Fraction of propellant mass for various components

Type of rocket	a	b	c for 1000 psi (7Mpa)
Turbopump	.15	.04 (tank+residual+ engine)	0
Pressure fed	.15	.012 residual+engine	.13 tank+He +He tank
Pistonless Pump Gas He	.15	.025 tank+residual+ engine	.043 pump+ He+He tank
Pistonless Pump Liquid He	.15	.025 tank+residual+ engine	.007 Pump +Dewar

Assuming a constant payload and variable delta Vee and chamber pressure, each one of these options can be analyzed. The figure of merit is the ratio of the GLOW to the payload mass. Lower is better.

These relationships are shown in Figures 1 through 4 for a range of delta Vs. For each type of vehicle the performance for a range of chamber pressures located near the optimum is shown. For each of the rocket types, the chamber pressure value that is selected is based on a GLOW/Payload ratio that is about 2% less than that for optimum mass ratio and I_{sp}. This reduces the cost of the system associated with higher pressures.

Table 3 Rocket Performance for various pressure and rocket types. 3500 m/s deltaV

Type of rocket	GLOW/ Payload	Engine Inlet Pressure	Specific impulse (Sea Level)
Turbopump	4.8	1200 psi (8.3MPa)	282
Pressure fed	6.0	500 psi (3.4MPa)	257
Pistonless Pump Gas He	5.1	700 psi (4.8MPa)	267
Pistonless Pump Liquid He	4.6	1000 psi (7 MPa)	292

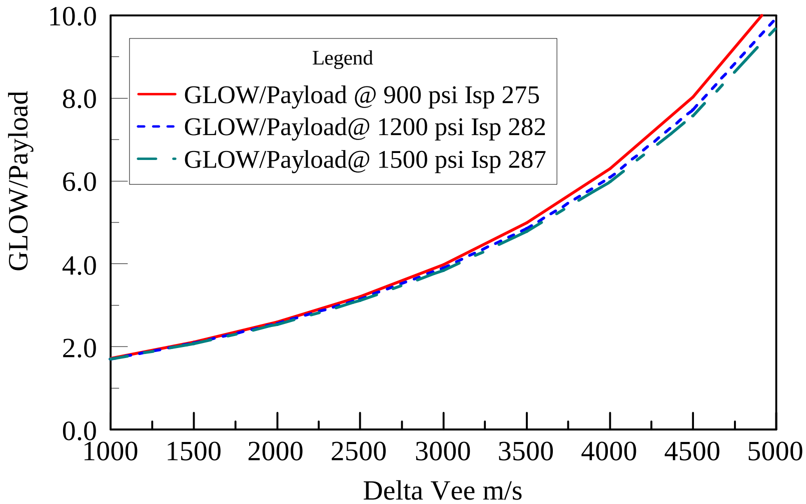

Figure 1. Ratio of GLOW to Payload for gas generator turbopump stage at pressures of 900-1500 psi (6-10 MPa).

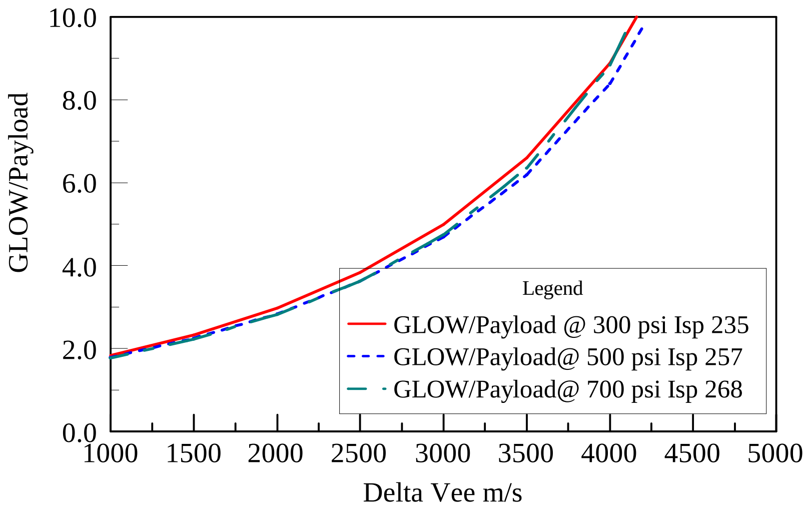

Figure 2. Ratio of GLOW to Payload for pressure fed stage at pressures of 300, 500, 700 psi (2-5 MPa).

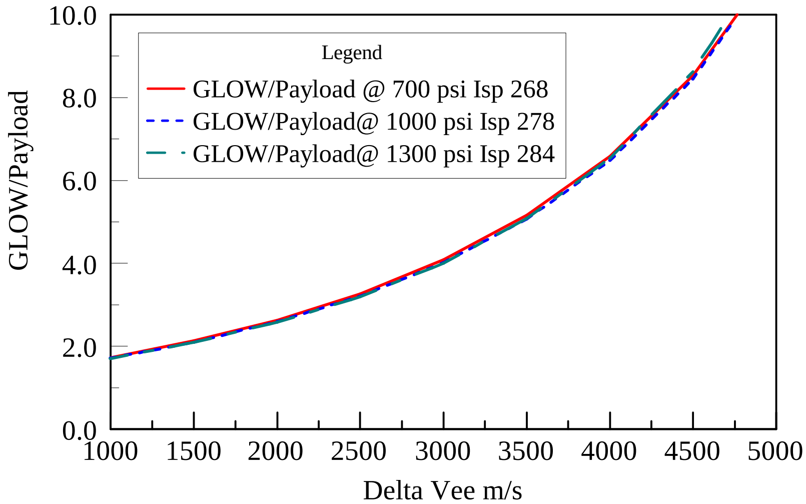

Figure 3. Ratio of GLOW to payload for gas pistonless pump at pressures of 700-1300 psi (5-9 MPa).

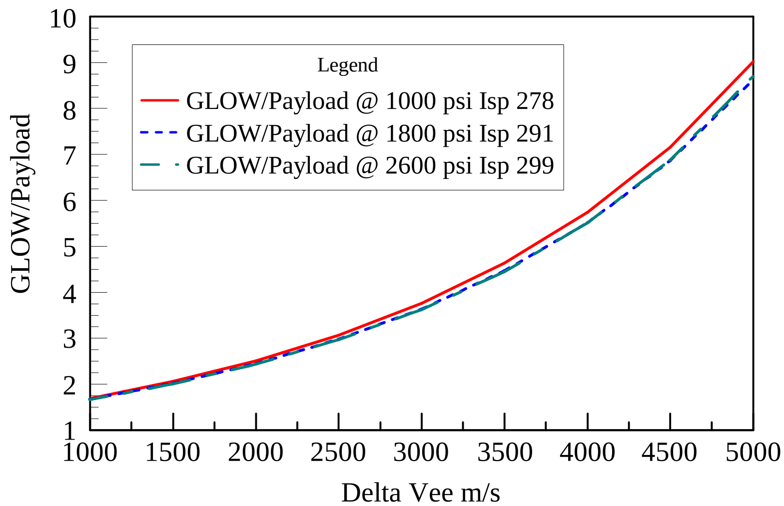

Figure 4. Ratio of GLOW to payload for pistonless pump run on liquid helium at pressures of 1000-2600 psi (7-22 MPa).

Based on these graphs one can see that the optimum chamber pressure for a gas powered pistonless pump is about the same as for a gas generator turbopump engine and that the optimum chamber pressure for a LHe powered pistonless pump is about the same as for a staged combustion turbopump system. This means that the pistonless pump can replace the pump for existing turbopump thrust chambers. Also, thrust chambers currently designed for turbopumps can be used with the pistonless pump. Note that the performance is not strongly dependent on chamber pressure near the optimum.
Furthermore, the vehicle payload/GLOW mass ratio is similar, so design studies of either type of vehicle with a gas generator or staged combustion turbopump can be applied to gas or LHe powered pistonless pump.

The ideal pistonless pump launch vehicle will have at least 6 engines with duplicate pumps and tanks. If any engine experiences a burn-through or other failure, or any tank loses pressure, the opposite engine may be shut down, and the other engines and tanks will allow for safe aborts or orbital insertion. Unlike turbopump systems, the penalties for scaling down are not significant. In fact an optimum pump size may be defined by cost considerations, i.e whatever size is least expensive to manufacture.

The sizing of the pump for various thrust levels and fuel combinations is easily accomplished. For a million pound thrust engine such as the RD-180, the pump would need to be about 4 ft in diameter by 13 feet tall. For a smaller engine, such as the SpaceX Merlin or NASA Fastrac engine, the pump would be approximately 2ft by 5 ft. In both cases the pump would weigh less than .5% of the thrust. Typical vehicle layout for gas and liquid powered vehicles are shown in Figure 5a and 5b. The relative sizes of the tanks are correct for 700 psi (5 Mpa) pressure levels.

VI. Application to LOX/LH_2 Systems

In this section we consider the use of the pump in an advanced technology system. The application of the pump to a LOX/LH2 launch vehicle works best with the Lhe powered design due to the low density of the propellant. An advanced LOX/LH2 system will have composite propellant tanks which weigh 2.6% of the propellant, a pump with a T/W of 100, an engine with a T/W of 140, and it will use 2.7% of the propellant mass in liquid helium to run the pump. The tanks and structure add up to 5.3% of GLOW. These assumptions make a single stage to orbit vehicle possible provided 90% of the liftoff mass can be propellants. Figure 5 shows the gross liftoff weight divided by the payload to a velocity for various chamber pressures. In this case the external pressure is assumed to be .25 bar.

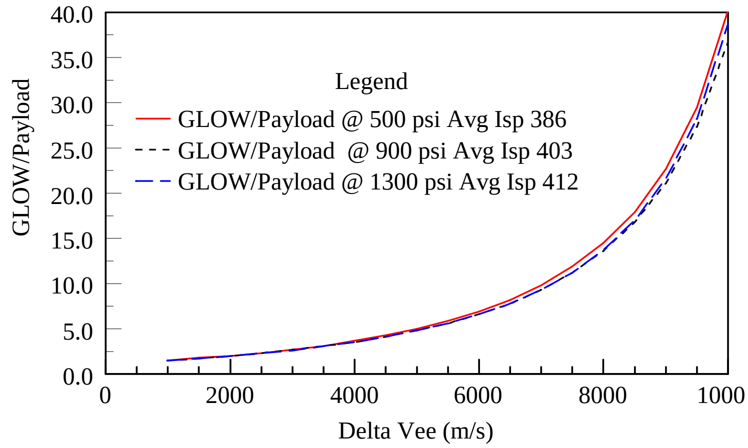

Figure 5. Ratio of GLOW to Payload for pistonless pump run on liquid helium at pressures of 500-1300 psi (4-9 MPa).

VII. Spacecraft Applications of the Pump.

This pump offers substantial performance and flexibility improvements for a space vehicle such as the Crew Exploration Vehicle. Pumps for space vehicles offer advantages beyond mass saving when propellant needs to be transferred from pre-positioned tanks or from in situ propellant plants. Space vehicles currently use tanks pressurized to 200-300 psi(MPa). These tanks are somewhat heavy, are very expensive and require propellant management devices to keep the propellant from sloshing around in the 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. In addition, any leaks from the main tank will involve lower leak pressures and reduced explosion hazards. The spacecraft tanks need not be spheroidal, and options such as low pressure drop tanks etc. become feasible.

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 psi(.7 MPa)a chamber pressure and 100-lbf thrust. The engine used NTO/N_2H_4 propellants at O/F = 1.15 with a nozzle area ratio of 300:1. When the chamber pressure was increased to 250 psi(MPa)a, the Isp increased to 333 sec. Although the test at 500 psi(3.4 MPa) was not conclusive, extrapolation of data indicated that the Isp would have been around 340 sec. A TRW study in 1995[6] using NTO/N_2H_4 propellants at O/F = 1.0 showed Isp = 337 sec at 500 psi(3.4 MPa) a chamber pressure with a 150:1 area ratio nozzle producing 50-lbf thrust. Predicted performance increases are shown below in Figure 6.

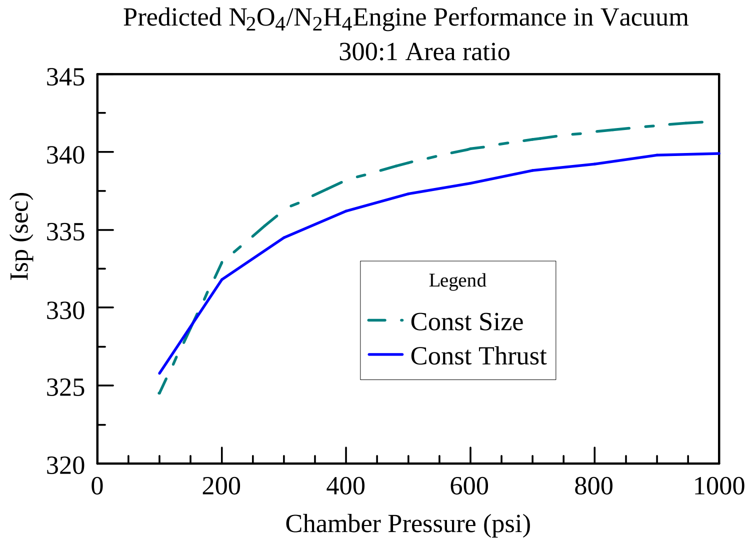

Figure 7. Aerojet engine performance as a function of pressure. Courtesy Aerojet General Corp. The engine tradeoff is normalized for either constant thrust of constant throat size.

The pump also allows for motor throttling with a response time on the order of the pump cycle time, that is 2-5 seconds. The pump works well at flow rates from zero to full flow, so it can be used to provide pressurized propellant for attitude control as the flow and pressure are decoupled and 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. A gas generator could supply pressurant for the pump in order to save weight on helium tanks. 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 4 and 5. Two spacecraft configurations and considered and compared. The pressure fed case assume a tank pressure of 300 psi(2.1 MPa)a and an I_{sp} of 323 sec. The pump fed case assumes a tank pressure of 50 psi(.3 MPa), a pumped pressure of 700 psi(4.8 MPa) and a specific impulse of 340 seconds. The payload is 4000 kg and the burn times are on the order of an hour to a few hours. The thrust is assumed to be 300 lb(1.3 KN), 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 is used for pressurant to leave earth orbit, or if the pressurant tanks are jettisoned as they are used up, the initial mass is up to 12% less, for an overall savings of 27% vs a pressure fed system.

Table 4. Expected Performance of Pressure Fed Propulsion System for 4000 kg Payload
Pressure fed system (300 psi(2.1 MPa) tank pressure, 323 second I_{sp})

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 5. Expected Performance of Pump Fed Propulsion System for 4000 kg Payload
Pump fed system: (50 psi(.3 MPa) tank pressure, 700 psi(4.8 MPa) pump pressure 340 second I_{sp})

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). There is plenty of room for the weight of redundant systems so a space vehicle which uses the pump will be much safer and more reliable than the state of the art.

VIII. 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(7 MPa) 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.
A pistonless pump that runs at slower cycle speeds than standard pumps would eliminate the cavitation problem.

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 we clearly saw the need for propellant management devices to collect the gel from the walls of the tank and the pump chamber.

Pumping gelled fuel can be accomplished by carefully controlling the flow of propellant into and out of the pump chamber so that no bubbles or voids are created in the propellant. This requires that the dynamic pressure of the propellant remain low as it flows through the pump, which is one of the features of the pistonless pump design. The pistonless pump offers a better way to pump gel propellant in that the peak velocity and fluid acceleration in the pump are much lower than those in centrifugal or piston pumps. This prevents cavitation or the formation of voids in the pump

IX. Pump Development Status

The gas powered pump has been built and tested and the liquid powered pump is still being developed. We have developed four different pump prototypes as an internally funded program. A pump data acquisition and control system has been developed to measure pressures and flow rates throughout the pump system and actuate the valves. We have filed a non-provisional patent application on a number of improvements to the basic design. Design studies using the pump for launch vehicles, in-space propulsion, and Mars ascent using various propellant combinations have been completed. The pistonless pump that we have developed has been used to pump water and kerosene at 450 psi(3 MPa) and 20 GPM(75 l/min) We have also used it to pump liquid nitrogen at 150 psi(MPa) and 10 GPM .(37 l/min). It has been used to pump fuel for a rocket engine static test. The pump design has been analyzed and the and potential vendors for the components have been identified. A Plexiglas model has been created to demonstrate how the pump works and allow for flow visualization to determine the internal fluid dynamics inside the pump. The next step is to design, build and optimize a pump for use with cryogenic fluid and then test and optimize it with LN_2 and then LHe. In this pump, heat transfer issues will be critical to prevent helium phase transition in the pump or to deal with the problems of pumping two-phase helium. Although LHe is difficult to work with, the commercial application of superconducting magnets in MRI machines has made the use of LHe more common. We will need to determine acceptable pressurant temperature to avoid excess Helium vaporization in pump. Pumping LHe is difficult due to the low heat of vaporization of the Helium, about 70 times less than LOX or LN2. This means that the Lhe must be pumped with a minimum of heat transfer, turbulence, friction and viscous dissipation. Centrifugal or piston pumps would probably cause the Lhe to vaporize in the pump. The amount of energy in LHe at 1000 psi(7 MPa) is 3 times the energy necessary to vaporize it. A carefully designed pistonless pump can pump the LHe with a minimum of vaporization. This pump may include a float to isolate the gaseous helium from the liquid being pumped. The viscous dissipation in the pump will be less than .1% of the energy required to vaporize the Lhe. Any helium that does become vaporized can be used to pressurize the tanks. These issues are complicated by the fact that the helium will be at supercritical pressures inside the pump.

X. Conclusions

The gas powered pistonless pump has been shown to have similar performance to turbopump based vehicles, and the LHe powered pump has been shown to have better performance than gas generator turbopump vehicles with performance approaching that of staged combustion turbopump vehicles. The optimized chamber pressures have been determined for both types of pistonless pump. The pump has also been shown to offer substantial performance and flexibility increases for space vehicles. The key to high performance rocket pumps is to minimize the mass of the pump and the mass of the pump power supply. Because the rocket thrust chamber can supply plenty of heat, powering the pump with liquid helium heated at the chamber provides the lightest weight pumping option

Acknowledgment

The author would like to thank Joe Carroll, Carl Tedesco, Bruce, Bridges, Frank Lu, John Garvey, Eric Besnard, Jeff West, Tom Mueller, Doug Gaylord, Ryan Butrym, Daryle Dismukes and Dave Crissali for their helpful suggestions and comments about the pump and this paper.

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