39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
20-23 July 2003, Huntsville Alabama

AIAA 2003-4479

PISTONLESS DUAL CHAMBER ROCKET FUEL PUMP

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Abstract

A positive displacement pistonless rocket fuel pump uses two pumping chambers alternately filled and pressurized in sequence to maintain a steady flow of pressurized propellant to a rocket engine. This pump fills the gap between pressure fed and turbopump rockets by making a lower cost rocket feasible without the weight of a pressure fed design or the high cost and complexity of a turbopump. The pump, combined with a lower pressure tank, saves up to 90% of the tank weight in a comparable pressure fed system. Thrust to weight ratios are calculated for the pump using typical fuel combinations. For a 2219 aluminum LOX/RP-1 pump at 4 MPa the thrust/weight ratio of the pump is ~700. Design and test data for a prototype which pumps water at 3.5 MPa and 1.2 kg/s is presented. The simple construction of the pump allows for low cost, reliable propulsion systems. This pump has been tested with liquid nitrogen and kerosene. It has also been used to pump kerosene with a rocket engine.

Introduction

With the advent of low cost ablative liquid fueled rocket engines and composite tanks, the problem of propellant pressurization becomes the last stumbling block to affordable launchers. Turbopumps are currently used in the majority of launch vehicles, although piston pumps have been designed and flown[1] and pneumatic diaphragm pumps have been proposed by Godwin[2]and Sobey.[3] The pump considered herein is much simpler and less expensive than a turbopump. The pump concept is simple: instead of having the whole fuel tank pressurized to 2-7 MPa, the main tank is at pressurized to 100-400 kPa and it is drained into a pump chamber, and then the pump chamber is pressurized to deliver fuel to the engine. An auxiliary chamber supplies fuel while the main pump chamber is being refilled. This type of pump has benign failure modes, can be installed in the fuel tank to minimize vehicle size and uses inexpensive materials and processes in its construction. With the right choice of materials, the pump will be compatible with all common rocket fuels. The pump can be started instantly, with no spool up time required. It can be run until the tank is dry with no concerns about cavitation or overspeeding. The simplicity and low cost of the pump allows for systems with engine out capability or allows for the use of tri-propellant systems. This pump lends itself to mass production techniques for low cost systems with multiple engines and tanks. The pump can be easily scaled up or down with no loss of performance. The pump can be stored for a long time with no degradation.

Basic Pump Design

The basic pump design is shown in Figure 1. In this design, two pumping chambers are used, each one being alternately refilled and pressurized. The pump is powered by pressurized gas which acts directly on the fluid. The pump is designed so that the time required to vent, refill and pressurize one pumping chamber is less than the time to dispense a given quantity of fuel from the other.

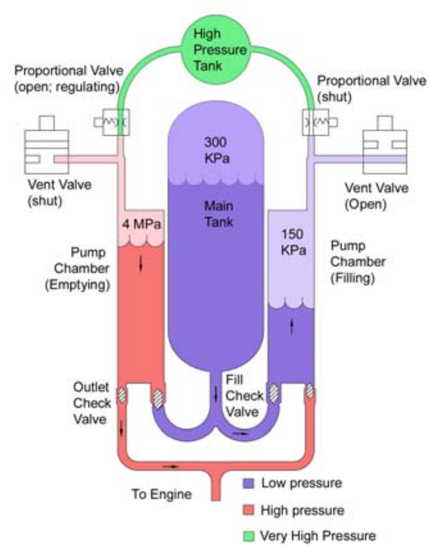

Figure 1 Basic Pump design

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. A model of this pump was designed and built out of clear plastic, and it performed as expected delivering steady flow and pressure[4]. The pressures and flow rates were measured and the data was analyzed to determine how to improve the pump performance.

Pump design Considerations

Although the pump design is simple, the optimization process is not. Making the pump cycle as fast as possible would make it lightweight, but higher flow velocities cause problems. A pump with a small chamber must be filled and vented quickly, with minimal head loss through the gas and liquid valves and plumbing. The maximum inflow rate is limited by the main tank pressure (usually about 300 kPa) and the area of the inlet valves. Also, if the inflow velocity is too high, the propellant will be aerated, which may cause problems with the engine. The ullage volume in the pump chamber should be small to minimize gas usage, but if it is too small, there will be a loss of propellant through the vent. Furthermore, the pump cycle frequency must not excite any combustion instabilities in the rocket motor. The second generation pump design process started with the realization that by placing the pump chamber inside the main tank and increasing the size of the check valves, the pump can be filled very quickly. Once the pump is being filled much faster than it is emptied, it becomes clear that the two chambers do not have to be symmetrical.

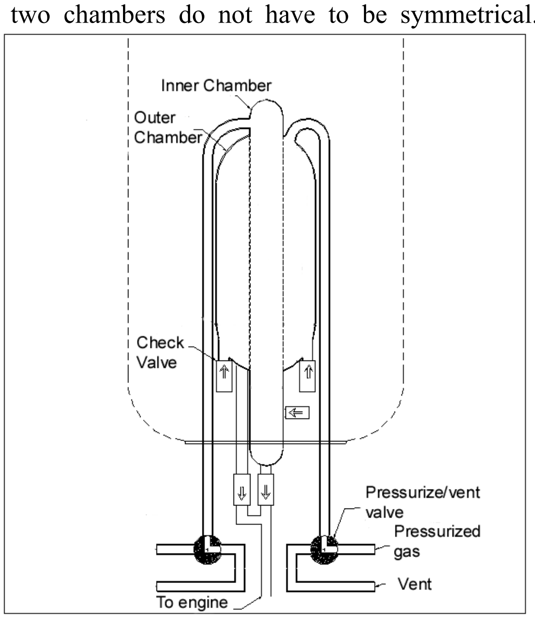

Figure 2 Prototype optimized pump design

Optimized Pump Design

The optimized pump design is shown in Figure 2. Instead of two similar pump chambers, it uses one main chamber which supplies fuel for most of the time and an auxiliary chamber which supplies fuel for the rest of the time. The main chamber is placed inside the tank, and it is filled through a number of check valves so that it can be filled quickly, thereby reducing the size of the auxiliary chamber, which is typically one fourth the size of the main chamber. The optimized design offers a substantial weight savings over the basic design, in that it uses one primary pumping chamber and one auxiliary chamber instead of two pumping chambers. A prototype of this type of pump is shown in Figure 3. The tank is made of stainless steel, the valves are brass, and the seals are Teflon so that it can be used to pump LOX.

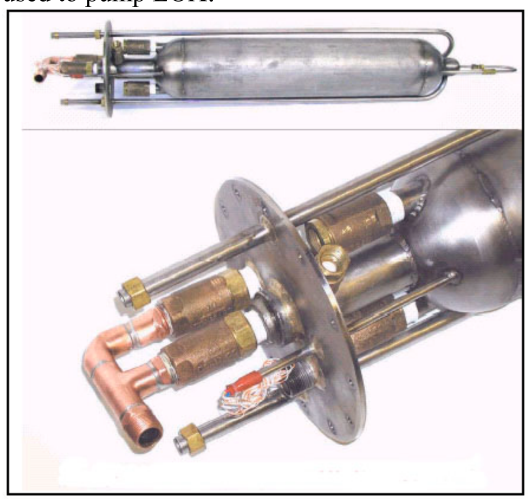

Figure 3 Photo of pump assembly with flange for attachment to tank.

The prototype includes a flange to easily attach it to the bottom of a tank. The prototype uses cylindrical tanks instead of spherical for ease of manufacture. It weighs approximately 6.8 kg exclusive of the air valves and the bottom flange.

Pump Weight

One of the most important benefits of this pump is the low weight for a given propulsion system. The weight may be calculated by determining the weight of the pump chambers and the valves. For valves or chambers, the weight is found to be proportional to the flow rate and the pressure. The weight of the chambers can be easily figured as spherical or cylindrical pressure vessels. The weight of the fluid and pneumatic valves may be estimated based on the weight of commercially available check valves and actuated butterfly valves. For example an aluminum 200 series

Circle Seal check valve flows up to 200 liter/minute at 20 MPa for a 25 mm size which weighs 250 grams. Assuming that the weight is proportional to the design pressure times the flow rate, a valve for use at 4 MPa and 200 liter/minute would weigh 50 grams. If each pump requires 5 valves as in Figure 3, then for a pump which supplies 200 lpm at 4 MPa, the valves would weigh 250 grams. Note that not all the valves will be the same design, but we are assuming an average weight. If the pump supplies rocket fuel to an engine at a given mass flow rate, the weight of the valves may be calculated as a function of the engine thrust. Since the thrust is proportional to mass flow rate, a thrust to weight ratio for a set of valves may be determined. For example, if a set of rocket pumps supply LOX and kerosene at 200 liters/minute to an engine with a specific impulse of 285 s, the thrust would be about 8800 N. This gives a thrust to weight ratio for the fluid valves as 2600. The gas valves will be substantially lighter. Therefore the valves can be considered to be a small percentage of total pump weight.

The weight of a pressure vessel can be found as a function of volume, pressure and the specific strength of the material.

The required volume for the main pump chamber V_c is:

$$V_c = Q \cdot T_{cycle} \tag{1}$$

Where Q is the propellant flow rate and T_{cycle} is the cycle time of the pump. We will use spherical pump chambers in the calculations that follow. Cylindrical vessels would be heavier.

The diameter of a spherical pump chamber D_c is given by:

$$D_c = \sqrt[3]{6 \cdot \frac{V_c}{\pi}} \tag{2}$$

The required thickness for a spherical vessel made from a material with a given maximum stress is given by Roark[5]:

$$t = \frac{P_f \cdot D_c}{4 \cdot \sigma_c} \tag{3}$$

Where P_f is the fuel pressure and σ_c is the allowable stress. The mass of the chamber M_c, can be computed by using the thickness t, the area of the spherical chamber, and the density of the chamber material, ρ_c:

$$M_c = t \cdot \pi \cdot D_c^2 \cdot \rho_c$$

or

$$M_c = \frac{P_f}{4 \cdot \sigma_c} \cdot \pi \cdot D_c^3 \cdot \rho_c \tag{4}$$

Because the chamber size is a function of the flow rate, we can put the chamber mass in terms of the flow rate:

$$M_c = \frac{P_f}{4 \cdot \sigma_c} \cdot \pi \cdot \left(\frac{6 \cdot Q \cdot T_{cycle}}{\pi} \right) \cdot \rho_c$$

or

$$M_c = 1.5 \cdot \frac{P_f}{\sigma_c} \cdot Q \cdot T_{cycle} \cdot \rho_c \tag{5}$$

In order to calculate the thrust to weight ratio, we need to determine the pump required for a given propellant and thrust.

The thrust T is given by the momentum equation for the case of ideal expansion:

$$T = Q \cdot \rho_f \cdot g \cdot I_{sp} \tag{6}$$

where ρ_f is the average density of the propellants, g is the acceleration of gravity and I_{sp} is the specific impulse of the propellants at the fuel pressure.

The optimized pump mass is the mass of one full size chamber, one ¼ size chamber, 5 check valves and three or four air valves. Therefore, the total mass of both pump chambers is 125% of the mass of one chamber. If we assume that the valves and the ullage add another 25% to the pump mass, the total pump mass is 1.25^2 or 1.56 times the chamber mass. Now we can calculate the thrust to weight W ratio for the pump:

$$\frac{T}{W} = \frac{.43 \cdot \rho_f \cdot g \cdot I_{sp}}{P_f \cdot \frac{T_{cycle}}{\sigma_c} \cdot \rho_c} \tag{7}$$

This equation applies to a single pump in the case of a monopropellant, or to a number of pumps for bipropellant systems. Because the pump mass scales linearly with flow rate, the flow can be divided among a number of pumps. If the pumping chamber is made cylindrical instead of spherical the weight will be twice as much, but it may be easier to integrate into a fuel tank. The thrust-to-weight ratio can be calculated for a number of propellant combinations:

Using the equation (7) above with a cycle time of 5 seconds, and density and specific impulse data from Huzel and Huang[6] for engines running at 4 MPa at sea level, pump thrust-to-weight ratios were computed for typical rocket fuels. 2219 Aluminum with a design stress of 350 MPa and a density of 2.8 gm/cc was assumed to be the pump material. The pressure drop through the injectors was not included. Higher T/W can be achieved by using titanium or FRP pump chambers.

Propellant	Average Density (kg/m^3)	Mixture ratio	I_{sp} (sec)	Pump Thrust/ Weight
LOX/RP-1	935	2.58	285	732
LOX/LH2	279	4.13	370	283
H2O2/RP-1	1200	6.5	276	657
N2O4/N2H2	1220	1.36	277	929

Table 1. Pump Thrust-to-weight ratios.

Recent testing indicates that the cycle time may be reduced to 1 second or less. Commercial diaphragm pumps operate with a 1 second (60 RPM) cycle time. Therefore the numbers above are conservative, even as safety factors are added in. As far as the scalability of the pump is concerned, for spherical pumps with a similar time to fill, the flow velocities need to scale linearly with the pump size. The velocity through the filling check valves is a function of main tank pressure, so larger pumps will require more or larger inlet check valves. However, if the pump chamber is made larger in diameter, but not taller, the pump will scale with minimal changes.

Pressure Fed Weight Savings

Pressure fed systems include the weight of a high pressure tank, whereas the pump fed system includes the weight of a low pressure tank and the pump. Assume both systems use a similar high pressure gas supply. The weight savings of the pump fed system can be calculated based on the fuel pressure and the burn time. Note that the pump consists of chambers which hold the same pressure as the tank in a pressure fed system, but the pump is much smaller, and the tanks in a pump fed system are much lighter than in a pressure fed system because they need to hold a much lower pressure but are of the same volume. The weight of any pressure vessel is proportional to the volume of the vessel and to the pressure inside the tank. Higher pressures require thicker, heavier walls.

Given:

- The volume of the pump chamber is equal to the flow rate times the cycle time
- The volume of the tank is equal to the flow rate times the burn time.

Therefore the ratio of the pump chamber volume (or mass) to the tank volume (or mass) is equal to the ratio of the cycle time to the burn time. This allows us to calculate the pump mass for a given fuel volume and pressure as a function of the tank mass for an equivalent pressure fed system. The ratio of the pump chamber mass to the pressure fed tank mass is the ratio of the cycle time to the burn time. The mass of the pump is 1.56 times the mass of one pump chamber. (See eq. 7).

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Furthermore the tank weight is proportional to the fuel pressure, so when we replace a pressure fed system with a pump fed system, the mass of the pump fed tank is equal to to the fuel pressure divided by the tank pressure times the mass of the pressure fed tank.

Therefore we can calculate the ratio of the weight of a pump fed system to the weight of a

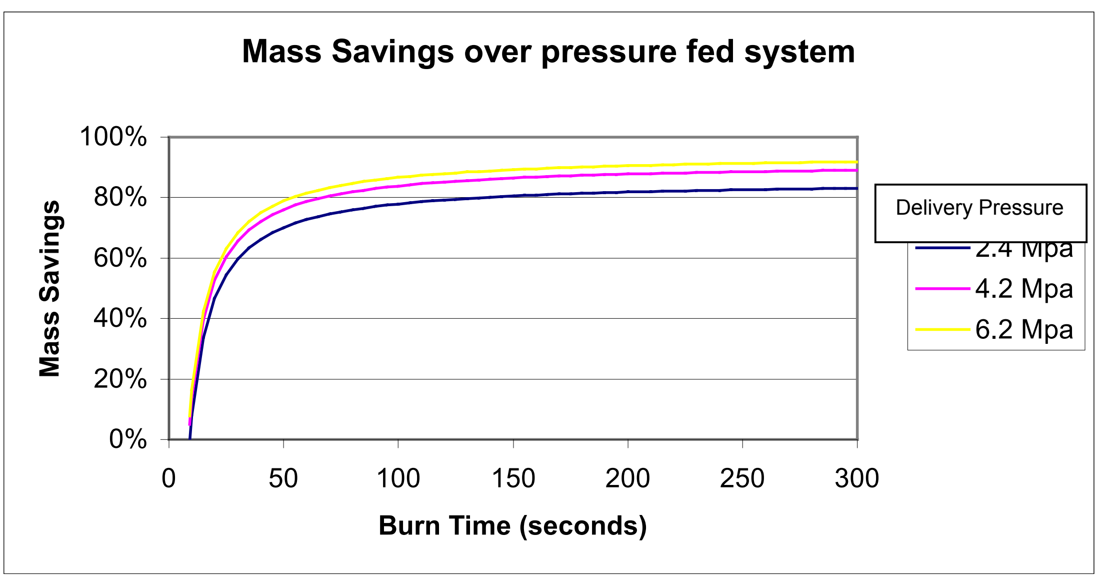

Figure 4: Mass savings as a function of burn time and delivery pressure.

pressure fed system as follows: (the first term is the mass of the pump and the second is the mass of the tank)

$$\frac{M_{pumpsys}}{M_{pressure\_fed}} = 1.56\frac{T_{cycle}}{T_{burn}} + \frac{P_{\tan k}}{P_{fuel}} \qquad (8)$$

Where $M_{pumpsys}$ is the mass of a pump fed system including the pump and the tank and $M_{pressure\_fed}$ is the mass of the tanks in a pressure fed system. T_{cycle} is the cycle time of the pump, usually 1 to 5 seconds and T_{burn} is the burn time of the rocket, usually 120 to 300 seconds. P_{tank} is the pressure in the tank, usually 300 kPa and P_{fuel} is the fuel pressure delivered to the rocket engine, usually 2.4 to 8 MPa.

The pump fed system is 5 to 10 times lighter than the pressure fed system for burn times longer than a minute. The graph in Figure 4 shows the mass savings for a system with a 5 second cycle time and 300 kPa tank pressure.

Model Design and Test Results

A model has been designed that performs as expected pumping water at 1.2 kg/s and 3 MPa. See Figure 4. A conservative cycle time of 6 seconds was used for these preliminary tests. The main chamber supplies fluid for 5 seconds and the auxiliary chamber supplies fluid for 1.5 seconds, allowing approximately 250 ms of overlap during each valve switchover. The model is constructed of off-the-shelf industrial and consumer valves, level sensors and fittings.

The sequencing is controlled by the same computer that acquires data on the pump operation. Note that there are 20 msec wide pressure spikes as the second chamber is pressurized. The minor pressure spikes at switchover may be due to the mass of fluid in one pumping chambers slowing down as the other pumping chamber starts to flow during the overlap time when both chambers are pressurized.

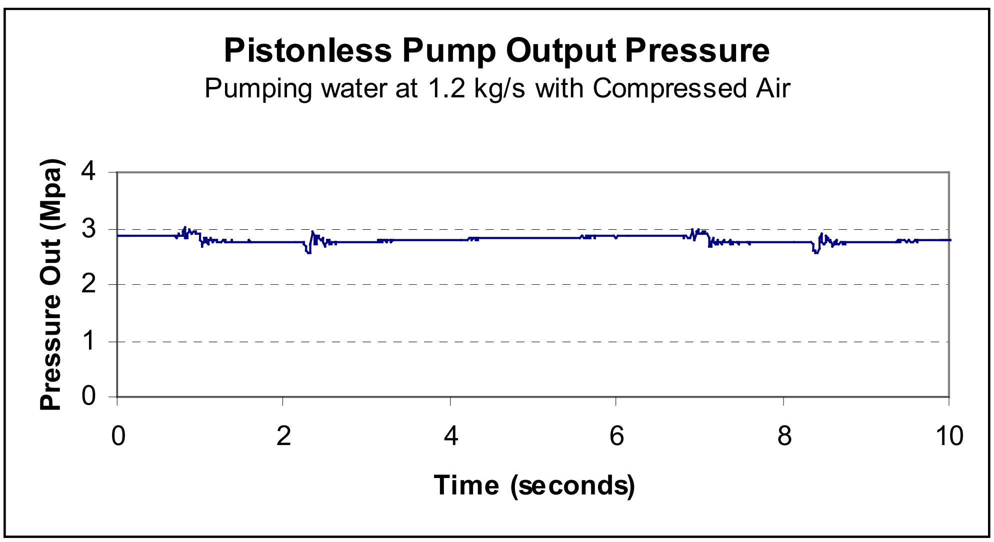

Figure 5 Prototype pump output.

Integration Into Rocket Vehicle

To use the pump in a vehicle, a pump would be placed in both the oxidizer and fuel tanks and a third pump or a set of pumps would be used to supply pressurant to a gas generator. The pressurant pump(s) would run on pressurized helium or air. The pump(s) would either supply propellant(s) to a gas generator or liquefied gas to an engine-mounted heat exchanger. Heavy pressurant tanks would not be required. Because the pump weight scales linearly with flow rate and pressure there is no penalty associated with size. Therefore the rocket vehicle can use a number of independent tanks, engines and pumps to ensure redundancy. For example, there could be 6 or more propulsion modules arranged in a ring, If one system failed, the one on the opposite side could be shut down, the remaining engines could be throttled up and the vehicle could continue. Also, because the pump chamber is relatively small, the fuel pressure can be easily controlled to vary the thrust without having to vent pressurant. Analysis of the system and mission will determine the optimum chamber pressure for the vehicle, which will probably be higher than for a pressure fed vehicle and lower than for a vehicle which uses a turbopump.

Testing with Liquid Nitrogen

The pump has been tested with liquid nitrogen and it works well. Figure 6 shows the test in progress, the pump is inside the tank .

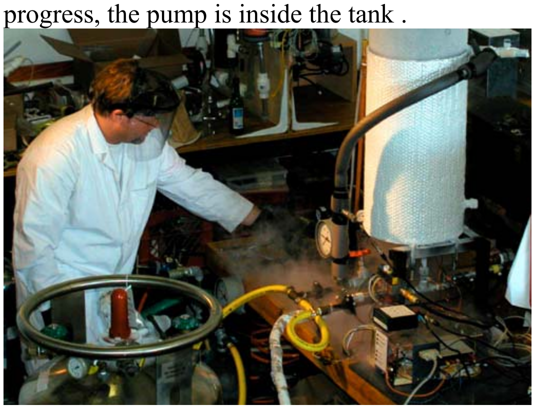

Figure 6 Liquid nitrogen test.

When pumping liquids near the boiling point, the liquid must be prevented from boiling excessively during the vent cycle. This may be achieved by venting through a back pressure regulator or by shutting the vent when the pump chamber pressure falls below a preset level. This is particularly important when the pump is used at altitude or in space.

Testing with Atlas Vernier Engine

The pump has been tested with an Atlas vernier engine as a proof of concept test. The pump worked well maintaining pressure even as the engine suffered an o-ring failure which caused excessive fuel flow. The pump delivered kerosene at 2.8 Mpa and 1.1 kg/s. The LOX was pressure fed for this test. Figure 7 shows the engine running with kerosene supplied by the pump.

Figure 7 Atlas vernier engine running with fuel pumped and LOX pressure-fed.

Conclusions and Further Work

The pump has been shown to be a viable alternative to turbopumps, with a comparable thrust to weight ratio. It is clear that the pistonless pump will cost at least 10 times less than a turbopump. It is also clear that the pistonless pump will be more inherently reliable than a turbopump, with no issues related to bearings, seals or vibration. Further optimization of the pump design will result in reduced cycle times and better pump thrust to weight ratios.. One potential use for the pump would be to pump liquid Nitrogen or liquid Helium through a combustion chamber mounted heat exchanger to provide the gas to operate other versions of the pump which would be pumping propellant.

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[2] Godwin, Felix *Exploring the Solar System* Plenum press 1960

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[4] http://www.rocketfuelpump.com

[5] Warren C. Young, *Roark's formulas for stress and strain* McGraw-Hill, c1989

[6] 1992 Dieter K. Huzel, David H. Huang, *Modern Engineering for Design of Liquid-Propellant Rocket Engines (Progress in Astronautics and Aeronautics, Vol 147);*