

PISTONLESS DUAL CHAMBER ROCKET FUEL PUMP

Steve Harrington, Ph.D.
 Flometrics, Inc.
 Solana Beach, CA 92075

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. 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 low cost and simple construction of the pump allow for low cost, mass producible propulsion systems to fulfill a responsive space requirement.

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 flown¹ and pneumatic diaphragm pumps have been proposed by Godwin² 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 worries 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 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.

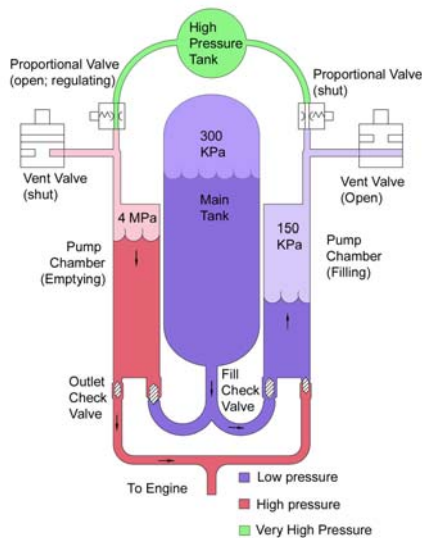


Figure 1 Basic Pump design

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 a steady output 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 pressure⁴. The pressures and flow rates were measured and the data was analyzed to determine how to improve the pump performance.

Pump design Considerations

When considering how to optimize the basic design to work in a rocket vehicle there are a number of issues. Pump chamber size is inversely related to cycle time. The pump chamber volume can be determined by multiplying the required volume flow rate by the cycle time. A smaller chamber will be lighter, but the cycle time will be less and the flow velocities will be higher. 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). The time to vent and pressurize the pump chamber also depends on the density of the pressurant gas; lower density is preferred. The ullage volume in the pump chamber should be small to minimize gas usage, but if it is too small, there will be a water hammer effect at the end of the filling cycle. Furthermore, the pump cycle frequency must not excite any combustion instabilities in the rocket motor. The pump chambers should not be too small for a given flow rate, or the mass of the valves becomes excessive. Given large vent and fill valves, the pump chamber may be filled faster than it can be emptied. Therefore the cycle time may be determined by estimating the time for the valves to fully open and the gas pressure to stabilize and then multiplying that by a factor of five to ten or so in order to minimize fluctuations in engine delivery pressure.

The pump optimization process started with the realization that by placing the pump chamber inside the main tank and increasing the size or number of 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.

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

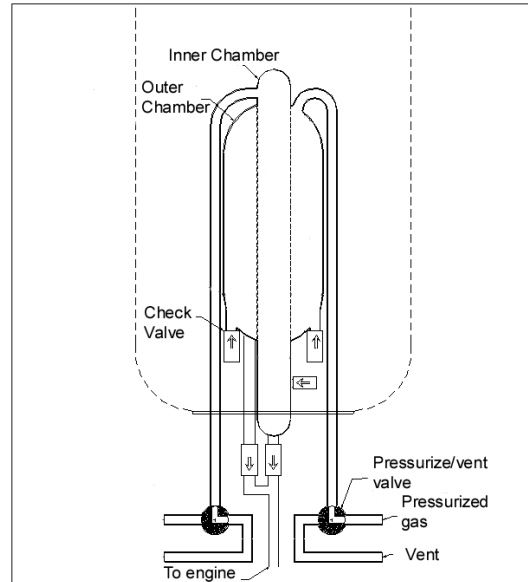


Figure 2 Prototype optimized pump design

of 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 and the valves are brass and the seals are Teflon so that it can be used to pump LOX.

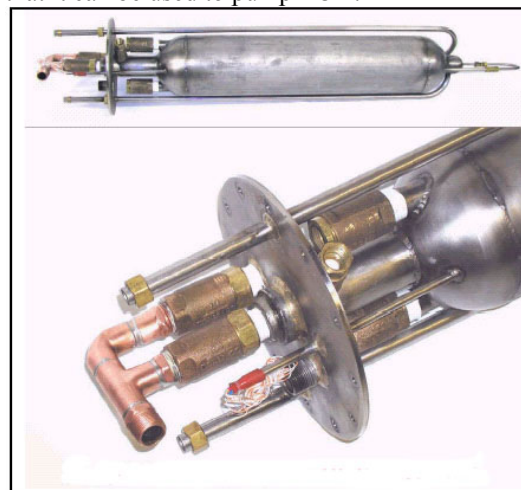


Figure 3 Photo of pump assembly with flange for attachment to tank.

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 factors for pump performance is the 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 weight 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 weight 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 give 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 is:

$$V_c = Q \cdot T_{cycle} \quad (1)$$

Where Q is the propellant flow rate and T_{cycle} is the cycle time of the pump.

The diameter of a spherical vessel is given by:

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

The required thickness for a spherical vessel made from a material with a given maximum stress is given by Roark⁵:

$$t = \frac{P_f \cdot D_c}{4 \cdot \sigma_c} \quad (3)$$

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

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

or

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

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

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

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

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

$$F = Q \cdot \rho_f \cdot g \cdot I_{sp} \quad (6)$$

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 1/4 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 1.25² or 1.56 times the chamber mass. Now we can calculate the thrust to weight ratio for the pump:

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

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 Huang⁶ 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. 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.

Model Design and Test Results

A model has been designed that performs as expected pumping water at 1.2 kg/s and 3.2 MPa. See Figure 4. A conservative cycle time of 6 seconds was used for these preliminary tests. The main chamber supplies fluid for 4.2 seconds and the auxiliary chamber supplies fluid for 2.2 seconds, allowing approximately 100 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 pressure spikes at switchover may be due to the mass of fluid in one pumping chamber slowing down as the other pumping chamber starts to flow during the overlap time when both chambers are pressurized. The pressure spikes can be reduced by more careful valve sequencing or by adding a small accumulator to the pump output.

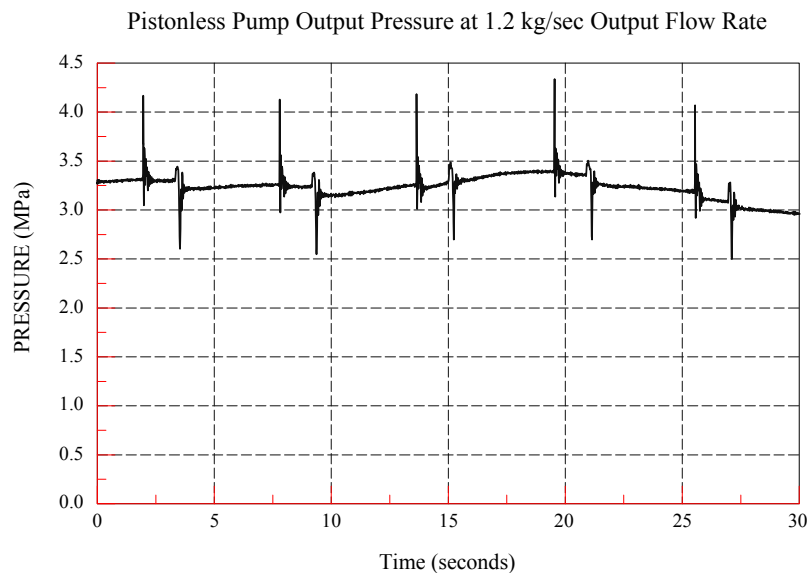


Figure 4 Prototype pump output.

Integration Into Rocket Vehicle

To use the pump into 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 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 insure 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. Analysis of the system and mission will determine the optimum chamber pressure for the vehicle.

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. Further optimization of the pump design will result in reduced cycle times and better pump thrust to weight ratios. Adjusting the valve timing or the addition of a small accumulator will reduce the pressure spikes to an acceptable level. 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. The pump prototype in Figure 3 needs to be tested with liquid Nitrogen (LN2). After the pump has been tested with LN2 and Jet-A, we will use it to pump LOX and Jet-A into an Atlas Vernier to prove that it will work with a rocket engine.

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

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

¹ http://www.llnl.gov/etr/pdfs/07_94.2.pdf

² Godwin, Felix Exploring the Solar System Plenum press 1960

³ Sobey, Albert J. US patent 3,213,804

⁴ <http://www.rocketfuelump.com>