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PISTONLESS PUMP

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ABSTRACT

The application of a piston less pump to a launch vehicle or spacecraft can provide cost and reliability improvements over standard pressure fed or turbo-pump fed designs. Calculations show that in a first stage launch vehicle application, a system which uses the piston less pump has comparable performance to gas generator turbo-pump designs.

The performance can be improved by using low pressure liquid helium which is pumped using a piston less pump to high pressure and then heated at the engine. This allows for lower pressurant tankage weight. This system uses lessthan1%of the fuel mass in liquid helium, which offers a performance advantage over comparable gas generator turbo-pump powered rockets. A complete over all 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 proposed ump is also applicable to pumping gelled propellants.

KEYWORDS: Autogenous, Pressurization, CFD, Cryogenic Pumping, FMECA

INTRODUCTION

This paper proposes a piston less pump1as a alternative to turbo-pump and pressure fed systems in both boost and upper stage applications and also for space vehicles. The piston less pump offers significant cost, reliability and performance advantages. These advantages are related to the simplicity of the design. A discussion on how to optimized vehicle which uses the proposed pump is presented in terms of chamber pressure. A comparison using this optimization procedure is also presented for pressure fed and turbo-pump systems. Any pressurized as 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 (he) which is stored in a low pressure Dewar, pressurized by a piston less pump and vaporized at the rocket engine. The pump may also be used for space propels on, where it offers a number of advantages in performance, safety and flexibility for space vehicle designers.

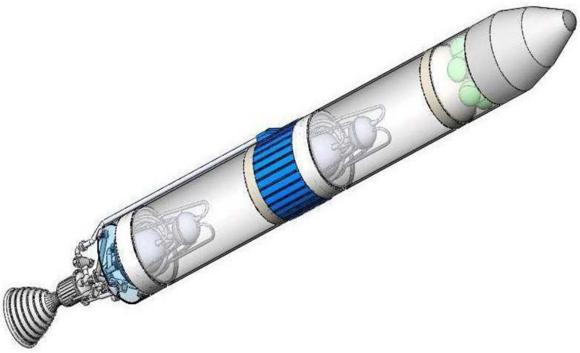

Figure 1: Piston Less Pumped Stage

DESCRIPTION OF THE PUMP TECHNOLOGY

The piston less pump system is basically a pressure fed pump chamber that is periodically vented and refilled from the propellant tank through a check valve, and then pressurized to deliver propellant to the engine through another check valve. Two chambers, a main chamber and an auxiliary chamber with overlapping cycles provide steady output pressure. A diagram of the pump operation is shown in Figure. Two pumping chambers are used in each pump, each one being alternately refilled and pressurized. The pump starts with both chambers filled delivering from the main chamber (Step1.Once the level get slow in the main chamber, the auxiliary chamber is pressurized; and flow is there by established from both sides during a short transient period (Step 2) until full flow is established from the auxiliary chamber. Then the nearly empty chamber is vented and refilled. (Step3) Then flow is against a blushed from both chambers, (Step4) the auxiliary chamber is refilled and finally the cycle repeats. This results in steady flow and pressure. In general only one chamber needs to have flow margin, so that is why the chamber sizes are a symmetrical. A diagram and photo liquid nitro gen pump that was developed for an LOX Methane RCS thruster's application for NASA Glenn**.**

The pressurant gas can be supplied from a source of liquefied gas that is heated at the engine, such as liquid helium, or by heating the propellants themselves (autogenous pressurization).This basic pump design has been around for many years 3, 4, 5, and systems last a very long time, in fact one pump come with a 25yearguarantee.The pump is much larger than an equivalent turbo-pump, but since it starts full of propel ant, there is node crease in overall propellant volume. A Diagram of a Pump that was Build and Tested is shown in Figure 2. This System includes all the necessary parts to test the Pump.

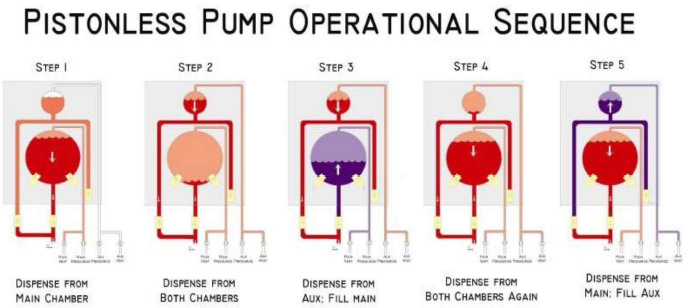

Figure 2: Operational Cycle

PUMP DESIGN PROCESS

Chamber Pressure

The first step in the development process is to determine the best combustion chamber pressure. For a piston less pump system, the pump weight is proportion alto the pressure, but the pump weight does not drive the system design. Instead, the weight of the pressurant which drives the pump is the key factor, just as it is for a gas generator turbo pump system. For a turbo pump operating with a chamber pressure of 1000 psi and LOXHC propellants, the gas generate or burns about 2.5%of the of the propellant in the gas generator. At higher pressures, proportionally more propellant is burned, and although the ISP increases with pressure, the optimum chamber pressure is on the order of 1000 psi. For a piston less pump, the pump can run on helium stored at low temperature and heated at the engine, so the pressurant weighs only5% of the propellant mass at1000 psi. Therefore, the optimum output pressure for a piston less pump system is approximately 1700 psi, which results in an increase in ISP as compared to a gas generator system. At this pressure, the helium weighs about 1% of the propellant mass and the pump weighs about 1% of the thrust. For details on this launch vehicle optimization process, see Ref. 2. Of course a staged combustion system has higher ISP, but it is quite expensive and the higher operating pressures lead to decreased reliability. The other extreme of their liability and performance curve is a peroxide powered turbo-pump, as used on the Soyuz launch vehicle, which uses a larger percentage of the propellant to run the turbo-pump, but has an excel entre liability. The precise chamber pressure for the flight vehicle should be a compromise between performance and reliability, with reliability being more important.

Pump Chamber Design

The pump chamber scan be spheres, cylinders or any other pressure vessel shape. In order to minimize the mass of the pressurant gas, it is best to use heated gas pressurant. This leads to a requirement to use metallic chambers, and stainless steel is best for heat resistance and specific strength. The optimum shape for a metallic pressure vessel is asp here. The mass of the pump chambers is easily determined based on the pressure and volume requirements. The pump chamber volume is based on the cycle time and the required flow rate. The next step is to determine the required cycle time.

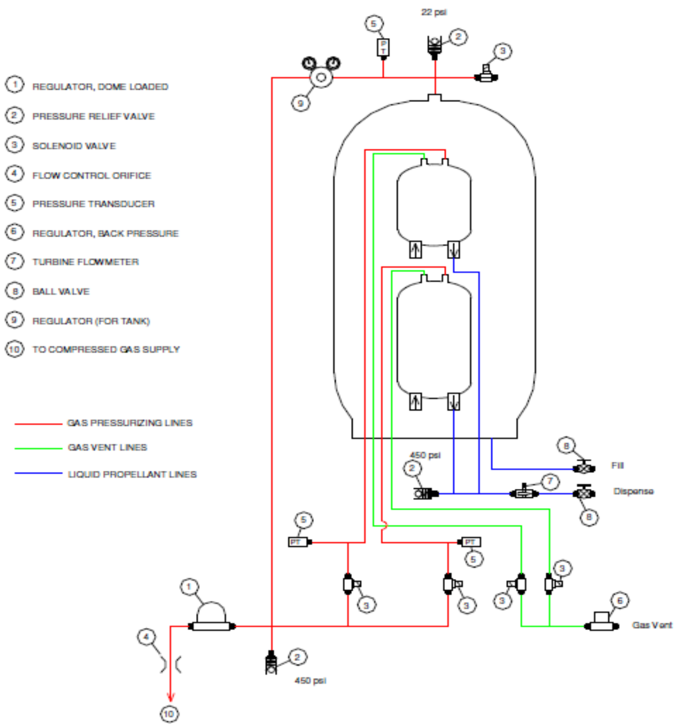

Figure 3: Chamber Pump

The pump cycle time should be as fast as possible to minimize the volume and there by the mass of the pump chamber. However, the cycle time is limited by the response time of the valves and the time required to vent, fill and the pressurize pump chambers. The time required to dispense from the chamber should be longer than the other times, so that the main chamber can vent, refill and pressurize during the time that the auxiliary chamber is dispensing. The vent time is the time required for the pump chamber pressure to fall below the tank pressure so that the chamber can begin filling. Assuming that we are starting with an early empty pump chamber which is still full of pressurant gas, the first step is to open the vent valve, which takes a bout30ms. Then the pressurant gas flows through the valve under choked and then subsonic conditions. The vent valve is designed to open under a high delta pressure and then close under low delta P, so the valve actuator power is low for a given valve flow area. For the given design, the vent valve diameter is 20inches.The time to vent is ~100ms.The next step is the fill process, where in propellant flows from the tank in to the pump chamber, In this step, the key is to diffuse the flow entering the pump chamber so as to minimize foaming or bubble entrainment of the incoming flow. We have developed a proprietary method of doing this which works very well. The time required to fillan8 Ft diameter pump chamber is approximately 300ms, with 224 inch diameter check valves. Just before the propellant reach the top of the pump chamber, the flow is halted by the pressurization step. The propellant level can be sensed by a float based or capacitive level sensor. The pressurize time is a function of the flow rate of the pressurize valve and regulator, and if the pump chamber is nearly full of propellant at the end of the fill cycle, the mass of pressurant required is small, so this is can be a fast process, taking less than 100ms. Then the dispense step can proceed while the auxiliary pump chamber is vented refilled and repressurized. Ideally the dispense process is much longer than the vent, fill and pressurize process. A3 second dispense time works well. This allows us to determine the main pump chamber volume, in this case it is 1800 gallons ($7m^3$). The auxiliary pump chamber size is approximately 2/3 of the main chamber volume. The exact volumes can be determined based on optimization of the various portions of the cycle.

PLUMBING DESIGN

The duct size scan be quickly determined by the requirement that the dynamic pressure be much less than the static pressure, a few percent at most. Placing the pump chamber inside the tank can solve the issue of water hammer; fill duct sizing and thermal conditioning. This will require high pressure plumbing to the engine, but this problem has been solved for various pressure fed systems.

VALVES ANDREGULATORS

The piston less pump valve design nor selection process is as follows. For the check valves, they operate slowly, with predictable changes In pressure, so the valves may be selected based on weight and reliability, and chatter is easily avoided. The out let check valves need to be sized for low-pressure drop at the out let flow rate, perhaps 2 to 4 psi. (less than 1% of the output pressure) The inlet valves need to be sized for about twice the flow rate of the out let valves, so that the pump chamber scan fill more quickly than they dispense. The pressure drop for the inlet check valves is based on the tank pressure and the desired in let dynamic pressure. A check valve which is too small and has a high operating delta may require an elaborate diffuser to allow the pump chamber to fill without entraining residual pressurant gas, so the best solution is to use valves of excess capacity on the inlet check valves.

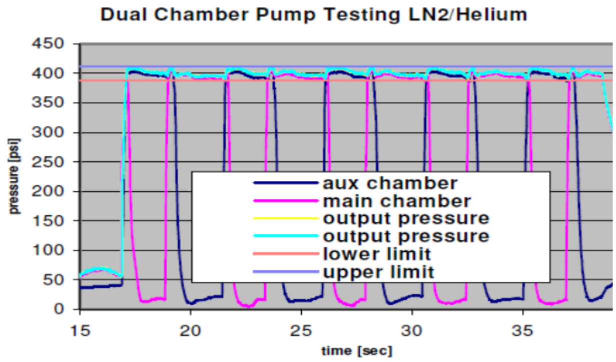

Figure 4: Cryogenic Pumping (LN2with Helium) at 2 gpm

If the pump is placed inside the tank, the valve se at can be built in to the pump chamber wall, so the weight penalty for a large valve is low. The check valves need not be bubble tight, as a small check Valve leak will not negatively impact the pump operation. A stain less valve with a brass or Kel-F sealing surface will work with most propellants. A system which uses two check valves in parallel in the main chamber allows the propellant to flow in evenly, so this is preferred arrangement. The pressurize valve s may be sized based on a pressurant flow rate of about twice the average flow rate so that the tank may be pressurized quickly. All of the gas valves shut under a low pressure differential, so a valve actuator may be designed to take advantage of the situation, and use the force of the upstream as to open the valve. The vent valve must be larger than the pressurize valve, because in need to have a high flow rate of low pressure, low density gas in order to vent the chamber quickly. The vent valve may be sized based on the requirement that the chamber needs to vent in about 100 ms. A sonic/subsonic flow calculation can easily deter mine the required valve opening area. Balanced poppet valves must have large balance flow ports, because sudden changes in pressure are normal for the pump chamber, and balanced poppet vent valves may burp when the chamber is pressurized. As the vehicle achieves high altitude, the vent system will need to maintain an adequate back pressure to prevent boiling of the propellant. The back pressure regulator must have a sufficient capacity to allow for quick venting of the pump chamber. The pressurize regulator needs to be able to handle the sudden changes inflow rate as the pump cycles, without excess overshoot. During the pump chamber pressurization process, the flow will increase and then suddenly reduce as the chamber reaches the target pressure. The regulator needs to be able to handle the sudden changes in flow rate. One way to deal with this is to use a regulator with a much greater flow capacity than is indicated by steady state flow conditions. This will reduce the required poppet movement and inertia, so that the over shoot and there by the pressure spikes in the flow output will be minimized. Also, the demand curve of the pump is very predictable, so the regulator dynamics can be designed to minimize over shoot. For example the poppet mass and spring may be selected so that as the pressure reaches the target value, the spring and poppet are just rebounding towards the valve seat. The dynamics of dome loaded pressure regulators are well known.

GAS GENERATOR DESIGN

The piston less pump is a positive displacement system so the pump runs on gas volume, instead of dynamic pressure as a turbine does. Therefore, the lightest gas will result in the best performance. The preferred system uses a Dewar of liquid helium which is maintained at a pressure of approximately 100 psi. A gas powered piston pump pressurizes the supercritical helium to deliver it to the engine mounted heat exchanger. Liquid helium pressurization was used successfully in the Apollo Lander and it currently used in the LOX tank pressurization system for the Ariane 5. For a launch vehicle, the pump system can be started with GHe from GSE equipment. The Helium can be heated using a nozzle mounted heat exchanger, or it can be heated by contact with the fuel. The nozzle mounted heater will provide the helium at approximately 500 F (260^{o}C) The heater will be located in the aft portion of the nozzle, the exact switchover point from fuel cooled to helium cooled nozzle will be determined based on heat transfer calculations. There is some concern that this vehicle will consume too much helium, but even at 12 launches per year it would consume less than 1% of the US helium production9. Helium used during ground test can be reclaimed.

CONTROL SYSTEM

The control system uses information about the chamber levels, pressures and flow rate to determine when to actuate the pressurize and vent valves. Using more sensors than absolutely necessary allows the system to implement integrated vehicle health monitoring. For example the pump would normally actuate the valves based on the level in the chambers, but if propellant volume rate of change based the level sensors did not agree with the turbine meter output, the system could verify the flow rate based on the thrust chamber pressure and determine which sensors to ignore. It could then utilize the turbine meter signal, the level sensor signal or just timing to actuate the valves. The control system could also be redundant, or have a backup system based on timing alone. The control system would also be able to conduct preflight tests of the pressurization and vent valves. Slow valve actuation times could indicate that valves are becoming sticky. Shorter than normal cycle times could indicate leaking check valves, or longer than normal fill times could indicate sticky inlet check valves.

TANK PRESSURIZATION SYSTEM

A vent valve would be placed in between the pump chamber and the tank so that the pump vent gas could be used to maintain tank pressure. This valve would be placed in parallel with the auxiliary or main vent valve so that both valve could be open at once in order to maintain the quick vent operation. The tank pressure could be determined based on structural considerations, since the pump only needs 3-5psi of pressure to fill quickly.

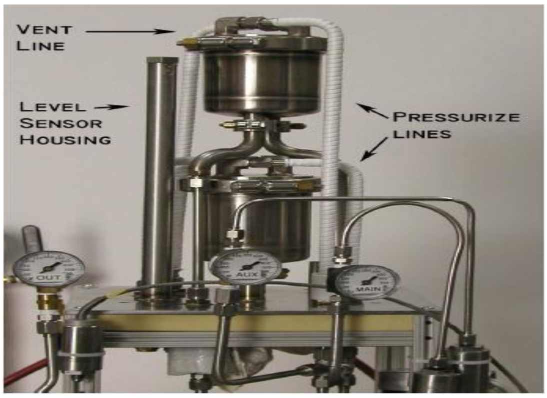

Figure 5: Dual Chamber Pump with Insulated Pressurize and Vent Lines, and Less Tank

HEAT TRANSFER

The heat transfer from the heated pressurant to the propellant should be limited in order to maintain consistent propellant density at the thrust chamber. The heat transfer to the propellant can be minimized by diffusing the pressurant gas as it enters the pump chamber in order to reduce the velocity and turbulence at the liquid to gas interface. In addition, during the initial pressurization process, the gas which is initially in the chamber will be heated by adiabatic compression. If the propellant is close to its boiling point, it may be subject to heating by adiabatic compression as well. At the end of the pump cycle, the chamber will be subject to adiabatic expansion of a larger sample of pressurant gas, so then et effect will be one of cooling. The exact amount of cooling or heating can be calculated based on computational fluid dynamics.

PUMP CALCULATIONS SUMMARIZED

The pump chamber volume can be sized based on a cycle time of 3seconds. The auxiliary chamber should be about 2/3 the volume of the main chamber. The wall thickness of the pump chamber can be determined based on the pressure and required safety factor.

Composites, aluminum, stainless steel or titanium can be used depending on propellant compatibility and heat resistance. For the current case of a 2 MLbF(MN)LOX kerosene system, the LOX flow rate is 30,000 gpm (2 m3/sec) so the main LOX chamber diameter is 8ft (2.2m) with a volume of 1500gallons (5.7m3).

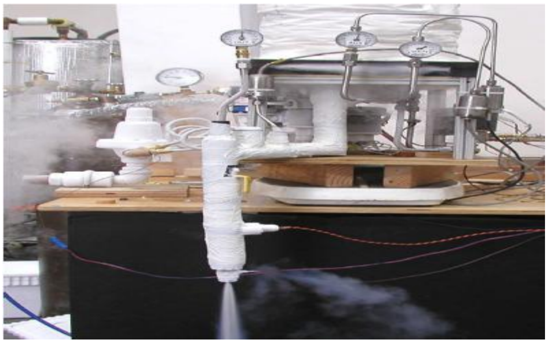

Figure 6: Dual Chamber Pump Undergoing Cryogenic Testing

A 16 inch duct can flow the required amount of LOX with a dynamic pressure of 5 psi. The Cv for the outlet check valve can be determined, it is about 15000. A 20 inch valve with this Cv is available. 2 of the 24 inch valves can be used as the fill valves on the main chamber. For the auxiliary chamber, one 24 inch valve could be used for the fill line, and one 20 inch valve could be used for the dispense line. The output from both chambers should be connect together such that the head loss from either chamber is the same, this will minimize the change in output pressure as the flow is switched from one chamber to the other. The Cv for the pressurize valve can be determined to be such that the pressure drop through the valve is also less than 1%of the static pressure. The required orifice size is about 8 inch to flow the required 42kg/sec of helium with a low pressure drop. For the vent valve, the calculation of vent time is more involved. The flow through the vent valve is initially sonic, and then becomes subsonic. A step-by-step calculation of pressure vs time is required For this case, a 20 inch valve will reduce the tank pressure to less than 50 psi in092 seconds.

Pressure Regulator Design

A dome loaded pressure regulator can be used to supply the pressurant to the pump. The regulator design may be guided by the steady state flow and the need to pressurize the pump chamber without excess over shoot. When the pressurize valve first opens, the pressure downstream of the regulator falls quickly and the regulator responds by opening abruptly. Once the space above the propellant in the pump chamber fills, then the regulator needs to switch to a steady state flow. If the regulator does not respond to the decrease in flow, pressures pikes will be the result. Ideally the volume in the lines leading to the pump chamber from the pressurize valve will be small and the pump chamber will be nearly full.

Pressurant Gas Calculation

The pressurant gas quantity can be determined based on the volume flow rate of the pump and the pressure and temperature of the pressurant. Because the pressurant is only in contact with the propellant for a short time, not much heat will transfer. For a large pump the time constant for the gas temperature is more than 10times longer than the cycle time. This way the pressurant will stay hot for the duration of the pump cycle, and less pressurant mass is needed than for a pressure fed system of similar pressure and flow capacity. The pressurant flow rate needs to be increased by the large volume in the pump chamber, but this can be less than 5%.

Pump Development Process

As discussed above, the cycle time, sizes and specifications of all the pump elements such as valves and regulators can be determined based on the required flow and pressure. One area that will need to be investigated more carefully is the filling process, to ensure that the liquid fills the entire chamber quickly with a minimum amount of gas entrainment and surface waves. This process can be optimized using CFD, and it can be tested with a low pressure pump chamber model, since the dispense process is largely independent of the filling process. During this process, baffles and diffusers can be developed and tested to keep the phases separate. Once the fill process has been optimized using a low-pressure model chamber, a workhorse pump can be assembled and tested. Pumping fuel is quite easy, because there are no thermal issues.

For cryogenic testing, the pump can be connected to a orifice and tested with LN2 at first, and then switched over to LOX with no design changes. Integration with the thrust chamber is straight forward because the pump provides full pressure at any flow, so there is no need to tune the pump and the engine together because as far as the thrust chamber is concerned, it is hooked upto a pressure fed system. The entire propulsion system can be designed based on a number of parallel paths for the pump, the thrust chamber and the gas generator, with well-defined interfaces to facilitate final integration.

Pump Design Summary

The pump for a 2 million lb LOXRP engine would have the following characteristics. (LOX pump)

Table 1

MainChamber Dia.	90 in	2.2m
AuxChamberDia	62 in	1.6m
InletCheckvalveDia	24 in	.61m
OutletCheckvalveDia	20 in	.51m
PressurizeValveDia	8 in	.2m
VentValveDia	20 in	.51m

Pump Component Sizing for LOX Pump for flow rate of 30,000 GPM (2 m3/sec)

Safety and Reliability

This type of pump is not new; in fact it has been used to pump groundwater out of basements for over 100 years, where reliability is critical. The present design operates much more quickly and works in space and in a zero gee environment, but the key to reliability is the slow moving parts and wide operational tolerances, which allow the pump to work regardless of contamination, leakage or sensor failures. A complete FMECA analysis has shown that many of the failure modes of the pump involve reduction in performance and no single point failure can cause explosion or fire. If the valves on one of the chambers fail, there will be a few seconds in which to execute a safe shutdown of the affected engine.

Pump Advantages

Increases Safety, Reliability and Performance while reducing cost and development time.

- The pump can be scaled up or down with similar performance and minimal redesign issues.
- Low risk development; pump technology has been demonstrated and prototypes have been built and tested.
- The manufacturing tolerances need not be tight. Pump and vehicle use inexpensive materials and processes in their construction.
- The pump is failure tolerant. A small link in one of the check valves will only increase the pressurant consumption of the pump; it will not cause a pump failure.
- A software can be designed to keep a pump with redundant valves and sensors operational, despite failed sensors or valves.

CONCLUSIONS

The piston less pump system provides a pump for a reliable and safe rocket propulsion system. This pump, combined with a modestly uprated F-1 thrust chamber, can provide a 2 mlbf engine for the heavy lift needed to mount a Mars expedition, without an expensive and difficult turbo-pump development program. It can do this while improving the performance, safety and reliability of the vehicle.

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