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Piston Pumps for Space Rocket Engines: Review and Design

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Abstract

A high-performance space propulsion system normally uses pressure fed systems that drive up propellant tank mass and limit space engine performance and design varieties. In this paper, the particular specifications and designing factors that should be met by rocket engine fuel pumps are demonstrated, and a comparative study is formed on the suitableness of all the necessary kinds of pumps to be used with rocket engines and their applications. Furthermore, the paper describes low cost and high-performance pump technology. This new piston pump has been improved for space applications. Depending on the type of body of this pump, its various parts should be evaluated at the desired pressure and temperature as well as the speed of fluid handling, leakage from the body, and the strength of the parts. Our review results are expressed to give complete awareness of different situations in space rockets.

Keywords:

Space Rocket, Piston Pump, liquid rocket engine

Introduction

The development efforts towards the main engine for the space vehicle effort were initiated in 1971 by NASA. Rockwell's Rocket dyne division as the prime contractor with NASA, after several years of development and testing, delivered three space shuttles to the space transportation system [1]. All space vehicles included high performance, perfect thrust, and high reliability and reusability systems. Figures 1 depicts a flow Schematic of a space vehicle that is staged combustion and reusable Hydrogen /LOX liquid rocket engine [2].

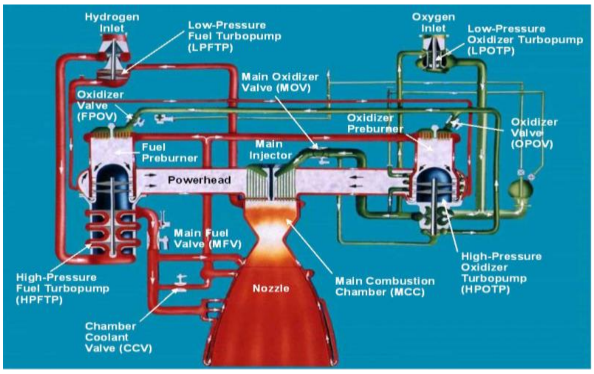

Figure 1: Flow Schematic of propellant for space vehicles [2].

The simplest way to differentiate rocket engines is to categorize them on the basis of their technique of propellant pressurization and delivery. All rocket engines generally can be divided into two categories including pressure-fed engine and pump-fed engine. While small pressure engines use pressurized tanks for propellant delivery, the majority rocket engines use turbo pumps that allow delivering the propellants to the level of desired pressure. Pressure-fed engine uses self-pressurization such that is usually carried out through mono-propellant rocket engines and is obtained through thermal decomposition of the liquid propellants or their vaporization. Pressure-fed system engines usually make use of high-pressure helium bottles. In any case, the thrust stage of pressure-fed engines is confined through the tank technology. A flow schematic of a pressure-fed rocket engine is depicted in figure 2 including staged combustion cycle and gas generator cycle.

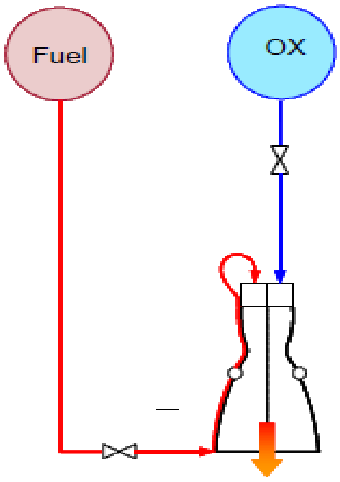

Figure 2. Schematics of different rocket engine cycles [3]- Pressure-fed system

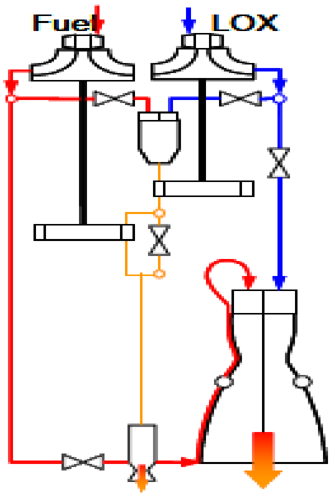

Figure 3. Schematics of different rocket engine cycles [3]. - Pump-fed system

An instance of these engines is the ARIANE 5G and AESTUS engines. Pump-fed engines use a turbo pump to increase the propellants pressure. In fact, a Part of the propellants are fed into a gas generator which typically works at a necessarily high-pressure level. The flow schematics in figure 2 depict the gas generator cycle. Modern liquid rocket engines have required pumping systems to transfer the propellant to the rocket engine. These pumps decrease the mass and size of other hardware by using lightweight high-pressure thrust chambers while decreasing the pressure of the liquid tank and minimizing the storage of inert gas. Figure 4 shows typical rocket engines using high performance pumping systems.

Figure 4. Modern liquid rocket engines with high reliability and reusability- P111 engine

Figure 5. Modern liquid rocket engines with high reliability and reusability- RD-180

The objective of this paper is to survey the status of research in the areas of pumps for liquid rocket engines in order to provide a comprehensive review of the state of the art and understanding important challenges. In this article, the emphasis will be on a reciprocating pump and the pump pistons that are stimulated by gas.

Figure 6. Modern liquid rocket engines with high reliability and reusability- Viking engine

Figure 7. Modern liquid rocket engines with high reliability and reusability- Vulcain 2 engine

Pumping system

The vital parts of a pumping system are propellant tanks, pump, and source of power for the pumps, control valves, and rocket motor. Pump systems are divided into two groups: positive displacement or centrifugal pumps. Piston and gear are classified as the most common positive displacement pumps, while the turbopump is classified as a centrifugal pump [4]. The selection of the kind of pump for rocket engines depends on various factors including the kind of drive available, propellant flow, delivery pressure and suction pressure requirements, required rocket motor thrust, etc. Therefore, a correct analysis of these variables depends entirely on having comprehensive knowledge about kinds of drives and pumps available [5]. Gear pumps as a type of positive displacement pump are dependent on close clearances to evade slippage. Generally, the gear pumps shown in figure 8 are more suitable for high viscosity liquids. Rotational speeds of gear pumps are approximately 2000 RPM.

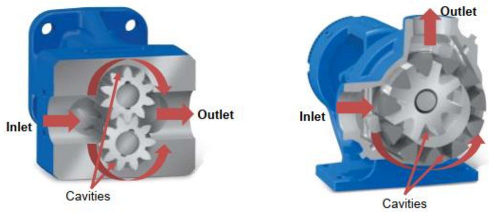

Figure 8. Gear pumps are used for liquid rocket pumps. a) External gear pump b) Internal gear pump

Conventional space launchers essentially use turbopumps that contain centrifugal pumps which are completely incorporated with the thrust chamber. A significant prerequisite is that the pumps and their power supply ought to have a mass in smaller amounts than the liquid inside the tank and rocket engine. Turbines are the main driver for centrifugal pumps and by reducing the scale of these pumps, they become less heavy and effective. Figure 8 depicts an example of turbopump used for a modern liquid rocket engine

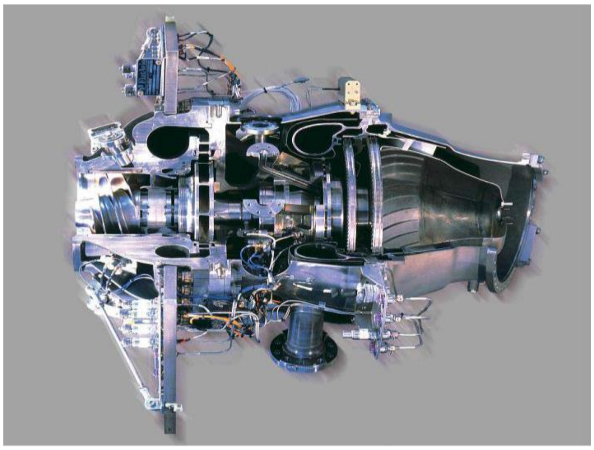

Figure 9. Turbopump of the Vulcain 2 engine [3].

Space engines have devices called turbopumps performing like a gas turbine engine where fuel and oxidizer react in a combustion chamber and then the combustion products pass through a power turbine to rotate the pumping elements. Fuel is pumped by an impeller and the oxidizer is pressurized by a different impeller. The high-pressure propellants are then injected into the rocket chamber to produce thrust. Therefore, it is costly to develop and produce and also decrease reliability. Piston pumps are more reliable than those with turbo-pumps [4]. The engines equipped by piston pumps are less sensitive to start transients, instability, and propellant quality and decrease the improvement cost. The reciprocating pump operates at a pressure much higher than that. Piston pumps are more appropriate for high delivery pressure and low viscosity fluids.

The piston pumps examined in this paper are more appropriate to various applications and those can give wide ranges of pressure and flow [5]. Normally, these pumps are planned as a lightweight pump to attain a high acceleration and also accomplish volume and mass. An electric liquid propulsion engine cannot provide such significant capabilities, since it is a motor where the chemical combustion is performed using one or more liquid oxidizing, therefore the safety factors are decreased significantly. These regenerative fuels and oxidizing factors are named propellants. Launcher tanks store this propellant, and when the rocket engine is turned on, the fuels and liquid oxidizing are injected into the chamber, causing combustion and creating high thrust. Another significant feature of this pump is that the system can provide full fuel flow and pressure at any case. With electric pumps, the fuel is promptly disconnected when the engine power is interrupted. The pressure regulator accompanying the gas generator makes an ensured operation. Piston pumps are simple and can work significantly more effectively than small scale turbopump. In piston pumps, the gas pressure is applied to the fluid, without the utilization of shafts or other parts.

XCOR aerospace company has developed a piston pump depicted in figure 6 for a reusable suborbital space launch vehicle. This pump is powerful enough to deliver the propellant to two rocket engines with high reliability in comparison with conventional turbopumps. XCOR plans were to charge tourists to have space flights of at least 30 min and three minutes of zero gravity while making landings safer [6]. Furthermore, XCOR Aerospace developed a reciprocating piston pump such that each pump delivers the LOX to two rocket engines while the fuel for the same two engines is delivered by the second engine. Each rocket engine produced around 13.3kN of thrust.

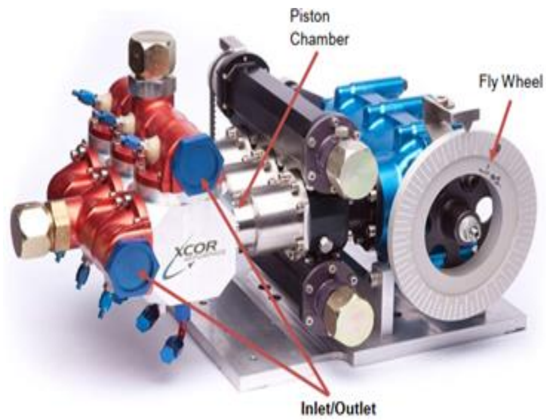

Figure 10. A triplex piston pump is used in the XCOR spaceplane [6, 7].

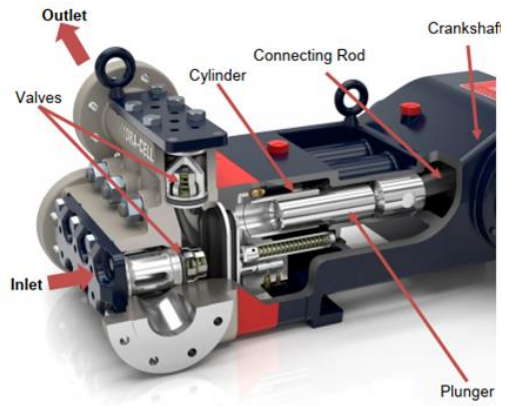

Figure 11. . A triplex piston pump is used in the XCOR spaceplane [6, 7].

The diverse use of piston pumps for different liquid rocket propulsion systems may be found. The most adaptable usage of a piston pump is on satellite that has to make multiple and massive delta V maneuvers shown in figure 13. Any polar orbit satellite and geostationary satellite could have enormous delta V maneuver requirements [2]. Since each polar satellite and geostationary satellites are commonly high-priced and need to perform for several years, they constitute likelihood applicants for performance improvements. However, it must be referred to that the performance supplied using a solid booster could, in a few cases, exceed the overall performance of a bipropellant liquid rocket. The simplest improvement is that the piston pump can offer on/off functionality and throttling as well. Other applications are probes to the moon, interplanetary probes, and near-earth objects commonly require enormous delta V maneuvers [2]. These specific missions have mass budgets and may take advantage of any weight reduction and financial savings while overall performance stays high. Finally, missions to or from the other planets surface, moons will also benefit from overall performance enhancements.

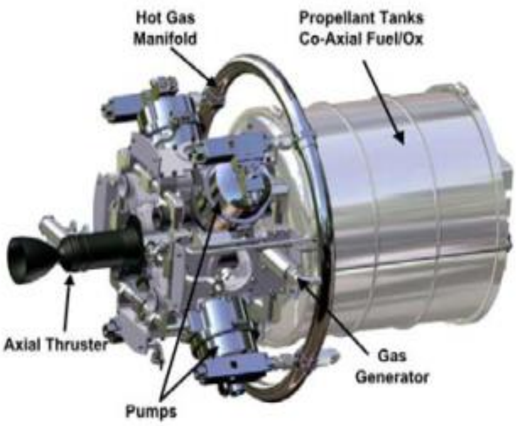

Figure 12. Pump fed propulsion system in satellite [8

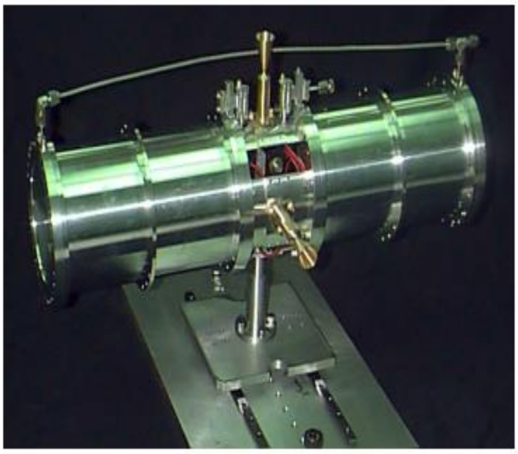

Figure 13. Pump fed propulsion system in satellite [8

One of the significant issues in flying vehicles is the high maneuverability in addition the high ratio of efficiency to weight proportion. This feature can be enhanced by increasing the specific impulse (I_sp) for rocket engine or diminishing the mass. A low-mass fuel pump is being explored which can enhance I_sp by utilizing high-pressure pumps while diminishing the pressure of propellant tank. Besides, chemical developments are required for those missions that need high thrust to weight proportion. In the event that the consumption of the pump is sufficiently low, it won't make a propulsion failure, but it tends to be useful to improve the specific impulse necessitated for in-space propulsion systems. The main objective for this pump is to operate at high pressure and temperature and decrease weight, to diminish fuel utilization [9]. Another feature of the pump is to keep up full pressure in various conditions of space propulsions which is more surveyed. Table 1 lists applications and technical requirements of a high-performance pump.

Today various types of pumps are designed and built to be used in space systems. Such as electric pumps, centrifuge pumps etc. The choice of the pump depends on many conditions, such as operating pressure, overall efficiency, discharge, cost efficiency and etc. A reciprocating piston pump is a new technology of high-pressure pumps, which is mostly used in the space propulsion system. In this liquid fuel pump, it enters the cylinders through the input port, and then compressed by the piston through the output port to the engine.

Table 1. Applications and technical requirement of the pump discussed in this paper

Applications	-Small monopropellant and bipropellant rockets, -The development of enabling technology for the Moon and Mars return missions
Pump type	Positive displacement pump powered by gas
Specifications	Generate a significant increase in pressure while reducing the loss of the driver gas

Whitehead and his colleagues started research in 1990 to fabricate a high-pressure pump for usage in research environments. Their aim was to fabricate a lightweight pump to supply fuels for those spaceships that were planned to be transported to Mars. First, they tested a prototype of their concept in 1991 and 1993[1, 2]. The research findings were not very promising. The hydraulic signal valves were used in the pump and subsequently the control of the piston shaft was replaced by this valve. Gas leakage often resulted in the decision to make improvements to the control system and the pump body design, so they achieved better results. John C. Whitehead in 1995 [3] assessed the latest pump and analyzed the efficiency and outcomes. The outcomes were comparatively more promising than the initial pump design. The pump weight and leakage were lighter and lower respectively, instead of using hydraulic valves and pneumatic valves, which made it simpler to produce and operate. In addition, he analyzed the settings of this pump for the Mars climb in 1997[4]. Whitehead tested, assessed and analyzed his research between 2001-2002 and 2007 [5-10].

The design of the pump as well as the representation of the fluid inside the pump is very difficult, time consuming and costly [19, 20]. Compact Fluid Analysis (CFD) is the best available tool for analyzing flow patterns inside the piston pump and gas generator to predict their behavior under different operating conditions [21, 22]. It also helps optimize pump design parameters by providing the most correct flow patterns along with more efficient pump operation.

Pump design

As shown in figure 1, the pump contains four cylinders and pistons that are joined together. It has a central section which provides the pump with a liquid inlet from the propellant tank. Directions reflect the flows of the inlet and outlet. The liquid propellant's inlet port is the large port in the middle of Fig. 1, and a separate outlet hole is on the opposite side of the piston pump that is evident in Fig. 1. The gas is distributed and operated by valves to the outer cylinders. Liquid cylinders are smaller in diameter than gas cylinders, as seen in figure 8. The area ratio allows the reciprocating pump to be operated by means of delivered propellants.

At the end of every cylinder, the gas cylinder is larger in diameter than the liquid cylinder and the gas entry point. A piston separating the fuel and gas chambers is located among them. As seen in the pump schematic, it is understood that no shaft or other rotating components are required to apply gas pressure to the rocket liquid. The gas inlet valves are retained to cancel the mass effect of movement, so that the opposite movement of pistons is towards or away from each other. Furthermore, because of existing pistons in pump chambers, the control scheme is considered to compensate for the pressure loss. According to Fig. 9, cylinder numbers 1 and 3 reach the end of the stroke, while cylinders 2 and 4 have been refilled with the propellant. A control mechanism provides the continuation of the flow such that cylinders 2 and 4 are pressurized with gas before reaching pistons 1 and 3 to their limit and venting their cylinders

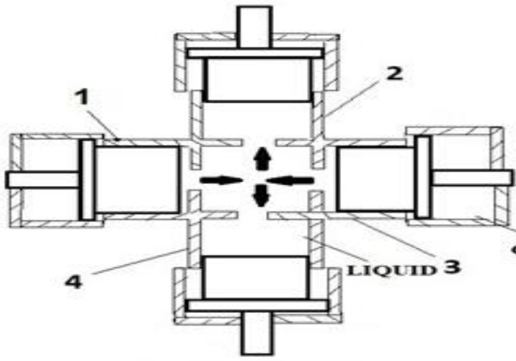

Figure 14. . Primary schematics of the piston pump.

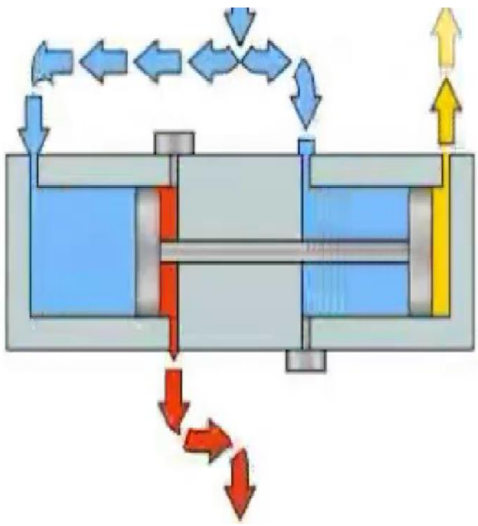

Figure 15. Preparation of fuel injection from propellant tank to engine chamber occurring within reciprocating pump

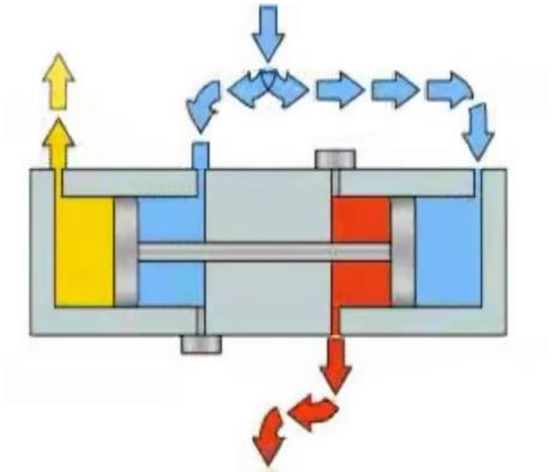

Figure 16. Preparation of fuel injection from propellant tank to engine chamber occurring within reciprocating pump

This pump weighs 470 grams and the blocks and cylinders are all made of aluminum with the exception of the valves and tubes. The role of curved pipes is to send gas to the inlet valves shown in Figure 3 that are used in the design of light alloy metals. The largest hole located in the center of the block is the fuel entry site, and the exit point of the four small holes is situated in the middle of the pump and on the other side. Each cylinder has a perfect displacement of 8 cc between the piston stops, or 32 cc per pump cycle. The valve opening time for fuel input is also less than 10ms, and this is independent of the piston speed. In order to provide the required force to drive the pistons, a key aspect previously mentioned is that the diameter of the gas cylinder is greater than the liquid cylinder. It should be noted that, as shown in figure 15, the gas and liquid cylinders are not combined, but are connected by screws. This pump works at a far higher pressure than those pumps used in conventional launchers.

Signal valve

As mentioned earlier, this pump does not use any shafts to move the pistons and power transmission. But in order to move the pistons, we used a pneumatic valve to control the inlet and outlet valves. As shown in Figure 18, a tap is located at the bottom of each piston. In fact, this valve is driven by the gas used in the system to open and close the gas inlet and outlet. This will control the movement of the pistons in the system and cause the pistons to always move against each other. In addition, such controls reduce friction and damage in the system. Because it causes injection before the piston reaches the end of the motor cycle to prevent its collision with the body. Each cylinder has a standard displacement of 7 cm between the start of motion and the piston stroke per pump cycle. The opening time for the fuel valve is about 9 ms, which is independent of the piston speed.

Figure 17. The primary design of the reciprocating pump.

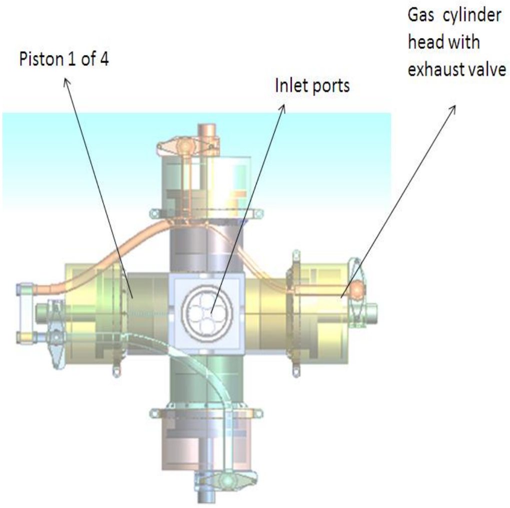

Figure 18. The primary design of the reciprocating pump.

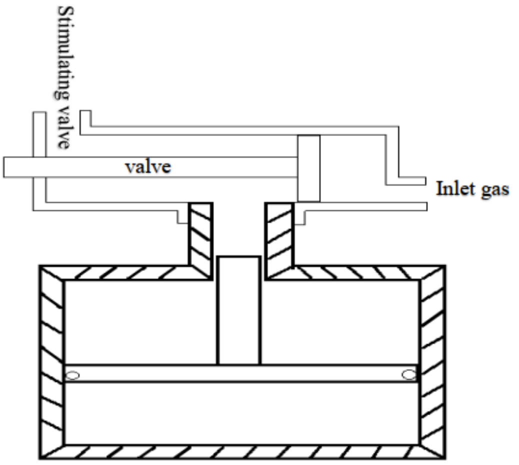

Figure 19. Pneumatics signal valve.

Figure 20 shows the volume of discharge of the pump using water for testing in each cycle. The obtained results in water tests reveal that a pair of cylinders can transfer fuel to about 590 grams per second. The same experiments show a hydrazine fluid volume of 530 grams per second. This means that the output of the pump is reduced by using hydrazine fuel and may react results are also very encouraging and more favorable than many other pumps.

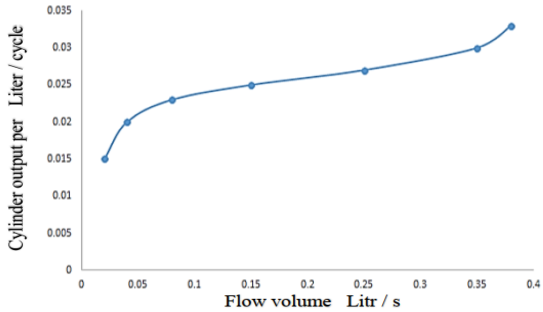

Figure 20. Output flow of volume per cycle of cylinder performance.

Conclusion

Compared with other pumps, this reciprocating pump has a lighter weight and higher efficiency, which can have a positive effect on the launcher 's acceleration and maneuverability. A reciprocating pump as a pressurized propellant feed system is used to feed the fuel and oxidizer to thrust chamber and gas generator. According to the study, the construction of this pump as well as the hydrogen peroxide gas generator should be done carefully. The pump should be prevented from leaking gas to the pumping cylinder. It should be noted that the hot gas has a high escape potential. It is also necessary that the gas pipelines should be made as seamless as possible. Gas pipelines must be able to tolerate extreme heat, which should be tested before operation.

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