

Design of an External Combustion Engine and its Application in a Free Piston Compressor

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The design of a free piston compressor and an analysis on integrating an external combustion engine into the compressor design are presented in this article. A free piston compressor is a device which converts chemical energy to work on a volume of air through the kinetic energy of an inertia driven piston, which is not rigidly attached to a ground. An external combustion engine serves as in intermediate chamber which transfers combustion gases to a device to perform some work. The following discusses the design and experiments on an external combustion engine, with a focus on eliminating an injection holding force on a free piston compressor's elastomeric membranes. The efficiency of the external combustion engine to transfer energy without significant losses due to heat, dead volume, air/fuel mixtures, and actuated valve speed are also presented.

Introduction

Free piston compressor (FPC) research is brought upon by the need for an improved power source for untethered robots. Current robots utilize battery driven motors, which have strong limitations on the work output and the life of the robot. For example, the Honda P3 Humanoid Robot only lasts 25 minutes while performing work on a human scale. A more appropriate energy source of hydrocarbon fuel could be coupled to a linear pneumatic actuator to provide greater energy density than the standard couple of batteries and electromagnetic motors. Pneumatic actuators are "an order of magnitude more power dense than electromagnetic motors." Also, the energy density of carbon fuels is 46,350 kJ/kg, while battery energy density is at 180 kJ/kg (Free-Piston Compressor for Portable Fluid-Powered Systems). The high difference of energy and power densities of the pneumatic actuator and carbon fuels causes this combination to be advantageous for use in untethered robots. Because of inefficiency of converting energy from carbon fuels to mechanical work, 0.5% efficient, and the inefficiency of the pneumatic actuator, an energy of 725 kJ/kg, 8 times that of batteries, is the a predicted outcome of this combinations of components. A free piston compressor, developed by Vanderbilt University faculty, has resulted in a system efficiency of 9.5% (Dynamic Characteristics of a Free Piston Compressor). Another advantage of the free piston compressor is the ability to couple the mass of the robot to the pneu-

matic actuator. Any combination of pneumatic actuators and masses may be used, resulting in a dynamic robot design with fewer limitations on the kinematic movement of the robot.

Free piston compressors are intended to be used in many different devices and applications due to the small size of the mechanical power source. It could be found in rescue robots, which travel in areas that humans are unable to reach, and in space missions in which a robot needs to perform multiple activities. Also, an FPC could serve as the power supply on the surface of foreign planets to perform heavy lifting, in prostheses to provide a constant pneumatic power source, and in a number of other capacities in which a human is unable to perform a task due to its hazardous nature or required heavy lifting.

Free Piston Compressor

Work on a free piston compressor has been performed by Vanderbilt University faculty in order to exploit the following design features: compact size, inertia driven, automatic cooling, start on demand, low noise, and high pressure combustion chamber.

A.) *Size and Weight*

The total volume of the device should be able to fit inside of a shoe box. Due to the portability goal of untethered robots, a small, lightweight energy source is desired to increase the maneuverability and efficiency of the system. The goal of the project is to mount the entire

FPC on the robot in use, often of small size. The efficiency of the robot is proportional to the weight of which the robot is comprised. Therefore, by making the FPC as light as possible, the overall efficiency of the robot will increase (Design of a Free Piston Pneumatic Compressor as a Mobile Robot Power Supply 2006, 2).

B.) *Inertia Driven*

The FPC manipulates a piston that is not rigidly attached to a crankshaft and uses the kinetic energy of the piston mass to compress air. A free piston allows the entire energy of combustion to be used through the conversion of kinetic energy, created through the isentropic expansion of gas in the combustion process, to potential energy in the form of high pressure air. Whereas, a kinematic device would develop wasted energy in the form of friction due to the crankshaft link pulling the piston back into place. Also, the inertia driven device causes the combustion gasses to exhaust at lower than atmospheric pressure, allowing for minimized exhaust noise (Experimental Operation and Characterization of a Free Piston Compressor 2005, 2).

C.) *Automatic Cooling*

In order to develop the most efficient engine, the FPC must allow the combustion chamber to cool. In many engines this is brought about by some type of separate cooling device, and therefore increases the weight and complexity of the design. For automatic cooling to exist, the pressure inside the combustion chamber must decrease to lower than atmospheric pressure, as shown in part (B), and draw cool ambient air into the chamber through a check valve. By cooling the combustion chamber, the next fire of the engine will pull a greater amount of energy out of combustion than if the combustion chamber was hot (Design of a Free Piston Pneumatic Compressor as a Mobile Robot Power Supply 2006, 3).

D.) *Start on Demand*

In many cases, a robot needs to change from a hibernating mode to an active mode immediately. Therefore, the FPC must be able to begin running without a complicated start up process. A start on demand feature will allow multiple combustion chambers to be coupled together, creating an engine with a faster cycling rate (Design of a Free Piston Pneumatic Compressor as a Mobile Robot Power Supply 2006, 3).

E.) *Low Noise*

Noise is a form of energy loss, and is therefore a factor that should be minimized in order to

increase the efficiency of the FPC system. Because the inertia driven device decreases the pressure of the combustion gasses, the exhaust gas creates minimal noise while exiting. Symmetric combustion along an axis of the FPC also plays a factor in reducing noise by causing the device to remain stationary, lowering friction and noise losses. Magnets, used to control combustion pressure as shown in (F), and the piston also cause noise losses when striking against metal components (Design of a Free Piston Pneumatic Compressor as a Mobile Robot Power Supply 2006, 3).

F.) *High Pressure Combustion Chamber*

The pressure of an air/fuel mixture must be controlled in the combustion chamber in order to create an efficient combustion. There is a linear relationship between pressure and work when a volume of gas is held constant; therefore, the higher the pressure inside the combustion chamber, the higher the subsequent work done on the free piston during combustion. In previous models, magnets have been used as a controlling force to hold the air/fuel mixture during the injection stage and are released during the combustion stage. They are also used as a source of conservative energy to move the final volume of air into the air reservoir. This method is one of the main problems facing the current design of the Vanderbilt free piston compressor. The magnets create a force against the combustion in order to hold in the initial intake pressures, decreasing the engine efficiency. Also, the magnets are difficult to attach to the current fluid and membrane designs due to the variety curvatures and sealing problems associated with attaching a magnet to a rubber membrane. Finally, the magnets create high levels of noise when striking metal walls in the FPC.

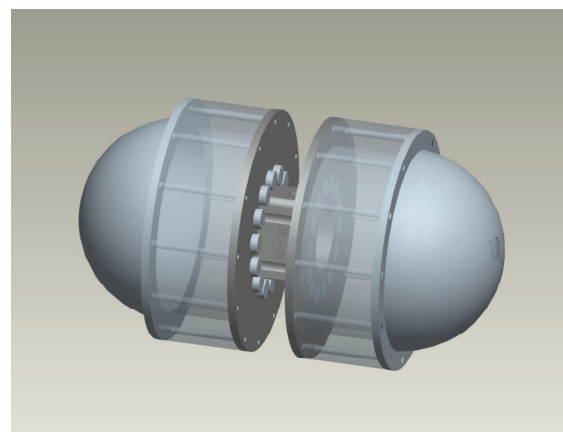


Figure 1: Fluid membrane free piston compressor (*Free-Piston Compressor for Portable Fluid-Powered System, 2006*)

The current Vanderbilt University design of the FPC is performed using elastomeric membranes and fluid inside a pill-like container. The design is shown in Figure 1.

The center section between the two semi-circles acts as a combustion chamber while elastomeric, high-temperature diaphragms press against the sides of this chamber through the use of several magnets of high strength. These are held in place by the magnets on the outside of the FPC, seen as circular disks in Figure 1. The large cylindrical sections are filled with liquid and a rolling diaphragm is placed at the entrance of the hemispherical section. Therefore, a “liquid piston” is created between the elastomeric diaphragm and the rolling diaphragm. Air intakes and an air reservoir are attached to each of the ends of the hemisphere sections as well.

Figure 2 shows the combustion process of this liquidpiston FPC. The air compression stage begins as the ideal air to fuel mixture, 14.7, is injected into the combustion chamber. The magnets hold the elastomeric diaphragms in place to maintain a high pressure in the combustion chamber. These design features are used to eliminate the compression stroke of a typical I.C. engine. A spark plug then discharges and combusts the fuel, causing the magnets to release and the liquid pistons to shift into the air-filled hemispheres. Because the diaphragms are elastic, they expand to form the shape of the container, eliminating dead space (a normal inefficiency) and leakage problems from the design. The momentum of the liquid pistons during this stage causes the air to be compressed into the air reservoirs through a check valve and causes the exhaust gas in the combustion chamber to decrease to below atmospheric pressure. A check valve from ambient air allows cool air to fill the combustion chamber, eliminating the need for a separate cooling process. After the diaphragms have reached the end of the

hemisphere, an actuated valve in the combustion chamber is opened, allowing the membranes’ elastic properties to push the exhaust into the atmosphere. As the membranes are moving towards their equilibrium positions, a check valve opens in each of the hemispheres, causing air to fill the entire hemisphere because the chamber pressure is below atmospheric pressure. The combustion process is then able to repeat.

It is important to note the simplicity of this FPC while meeting the design criteria. The design has eliminated exhaust noise problems by exhausting low-pressure gasses, has no leaking found in typical I.C. engines, has the capability to start and stop at will, has an automatic cooling process, has a small volume, has the ability to be driven by inertia. However, this device does create some problems of its own while fixing conventional I.C. engine problems. The first of these occurs in the return of the liquid piston. Because the membrane return is governed by its elastic property, the movement is limited with a slow response time. This reduces the top speed of the FPC, with no way to manipulate the restriction. Also, the magnets in the design cause two main problems. Firstly, the force with which they hold the elastomeric membranes to the combustion chamber acts against the combustion force, limiting the efficiency of the device. This effect could be minimized if the energy from the magnets was used to help push the liquid piston into the end of the shell after the magnets are released; however, because of the membrane elasticity, the magnets are not able to do appropriate work on the air. The second problem with the magnets is that they create loud collision noises, during the return stroke of the engine, when they strike against the metal side of the combustion chamber.

In order to combat the problems created by the magnetic holding force (the main problem with current FPC design), a few design additions have

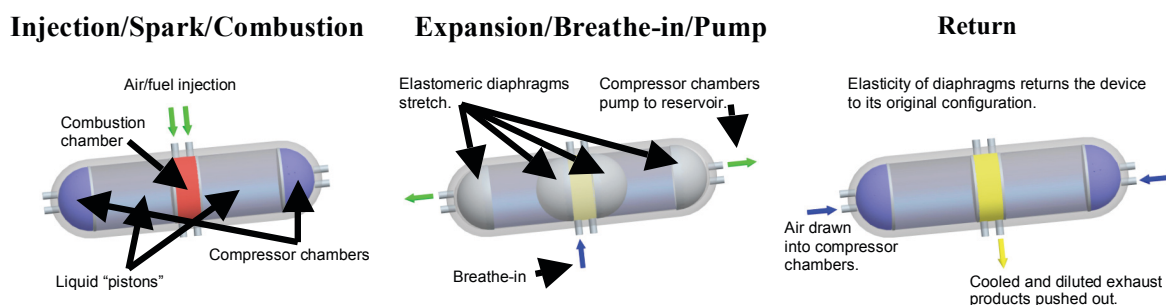


Figure 2: Combustion process of liquid piston FPC (*Free-Piston Compressor for Portable Fluid-Powered Systems*, 2006)

been analyzed, including changing the positioning of the magnets and introducing magneto-rheological fluid into the FPC. However, the approach taken to fix the holding force problem was to eliminate the magnets from the design completely. The concept of an external combustion engine was incurred. In an external combustion engine, pressure-volume (PV) work is performed on a piston after the combustion gasses travel from an external chamber to a chamber containing the piston. Whereas, in an internal combustion engine, the combustion occurs in the chamber containing the piston, and PV work is transferred immediately, without intermediate travel. In the FPC, an external combustion engine would eliminate the need for magnets to hold fuel gasses in place before combustion and would create the ability for coupling the combustion chambers. For example, as one external combustion engine is going through the exhausting stage, another external combustion engine may be combusting and supplying the FPC with combustion gasses. This option is very important as increased coupling allows the FPC to combust in the center and end chambers, providing a force to push the slowly responding elastomeric membranes to their equilibrium position. Therefore, chambers in the FPC can act as both the combustion chambers and air compression chambers. However, there are several concerns with using an external combustion engine. Firstly, the large amount of surface area in the combustion chamber and the tubing that the combustion gasses travel through, create a significant avenue for heat losses in the engine. Also, as numerous valves and connections are necessary to attach the external combustion chamber to the FPC and mixing chamber, large dead spaces result, decreasing thermal efficiency. A mixing chamber and external chamber cause the FPC to increase in complexity and in size. However, this size constraint may be reduced in further models by integrating the mixing and combustion into one chamber. Also, the speed of the fuel injection valves is in question as the resisting force of these valves may be too large to overcome. Lastly, the exhaust valve, which opens to allow combustion gasses to leave the external combustion chamber, must resist high temperature gas flows and open and close at high speeds. The following section discusses the setup and results of experiments meant to test the feasibility of an external combustion engine.

External Combustion Engine

Setup

Figure 3 displays the experiment setup of the external combustion engine. The figure shows the two sections of the engine 1.) Air/Fuel Injection and 2.) Combustion/Exhaust.

In the Air/Fuel injection section, a source of 80 Psig air is connected through plastic piping to a Parker Hannifin Corporation VAC-100 Psig actuated valve. This valve is oriented to open in the direction allowing flow into the mixing chamber and restricting flow back into the air reservoir. This valve is connected to an A-lok connection serving as the mixing chamber. Also connected to the A-lok is a real-time pressure sensor and another actuated valve of 1250 Psig restriction, connecting a source of propane to the mixing chamber. The pressure sensor is used to determine the mass of air and fuel that has entered the mixing chamber using the partial pressures of the gasses. A stoichiometric mixture of air and fuel can be maintained using this sensor. Inside of the mixing chamber, several pieces of metal netting have been placed in order to increase the turbulence of the flow and ensure homogeneous mixing of the air and fuel. The mixing chamber is connected to another 100 Psig actuated valve to hold the air/fuel mixture in the mixing chamber until it is injected into the combustion chamber at the appropriate time. The combustion chamber is an aluminum cube with sides of 1.2 in³ and a hollowed out center. The dimensions of the cube were used to insure that the mixing chamber was much larger than the combustion

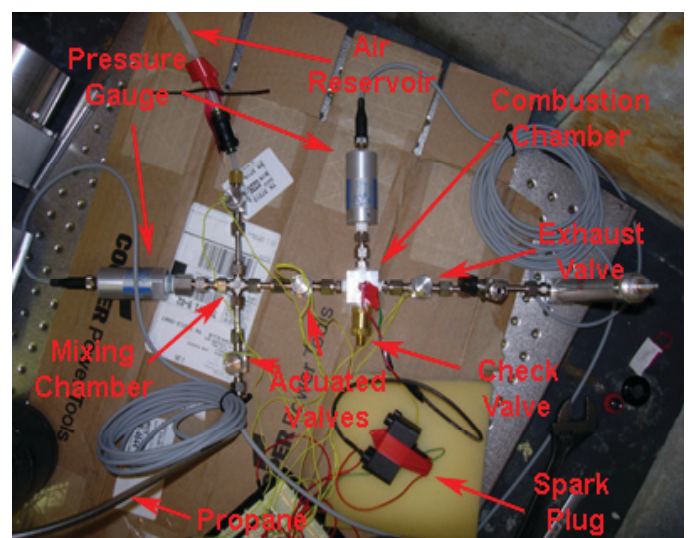


Figure 3: Image of experimental external combustion engine

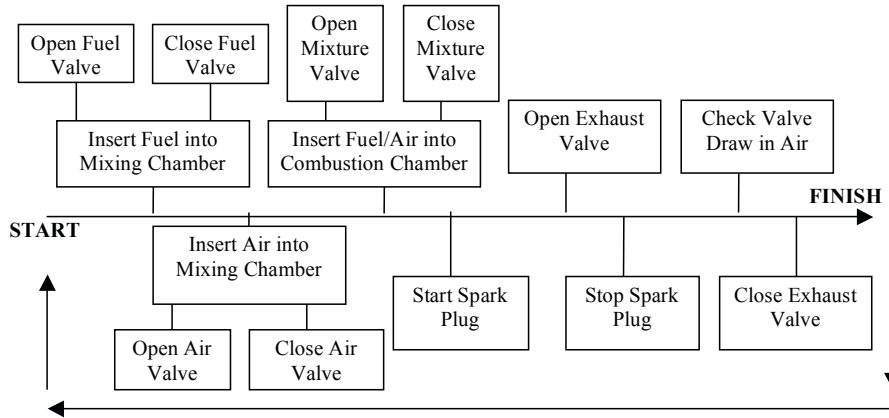


Figure 4: Combustion process timeline

chamber, causing uniform pressure to be maintained while injecting the air/fuel mixture into the combustion chamber. A spark plug is placed towards the center of the chamber to ignite the fuel equally while maintaining structural strength of the aluminum chamber walls. Also, an actuated valve is connected to the combustion chamber to serve as an exhaust valve. This valve is linked in such a way that the valve should be forced open if the combustion chamber pressure is greater than 100 Psig. The other side of the exhaust valve is attached to tubing leading to the atmosphere. Lastly, connected to the combustion chamber is an air check valve used to draw air into the combustion chamber after combustion is completed, cooling the engine. Figure 4 shows a timeline of the process involved in a combustion cycle in the external combustion engine.

Results

The external combustion engine was able to combust after altering the time delays in opening valves and adjusting the air/fuel mixture. Figure 5 shows the gas pressure in the mixing chamber over several cycles of the engine. It is seen from this figure that the mixing chamber pressures are consistent after the first cycle. During the first cycle, the pressure begins at some non-constant value, due to leakage in the mixing chamber from runs performed previously. However, as the run time advances past the first cycle, the leaking rate is slow enough not to affect the mixing chamber pressures. It is seen that when both air and fuel are added into the chamber, they consistently reach a peak pressure of 80 psig.

Figure 6 shows one cycle of injecting air and fuel into the mixing chamber and releasing it into the combustion chamber. A 0.8 Psig bump at 6.1 seconds is seen when the propane valve opens and begins to let propane into the mixing chamber for

0.045 seconds, adding 3.2 Psig of fuel to the mixture. At this point the fuel valve closes and a slight drop in pressure is seen. The line with a small negative slope shows that there is some leakage in the chamber during the time between closing the fuel valve and opening the air valve 0.1 seconds later. At this point, 36.9 Psig of air are added to the mixture and the total pressure peaks at 80 Psig. After

the air valve is closed, a significant amount of leakage is seen at this high gage pressure and 3.9 Psig of pressure are lost. At this point, the mixture valve is opened, allowing the gasses in the mixing chamber to flow into the combustion chamber. There is little resistance in the flow as the mixture valve is open for only 0.025 seconds, and the mixing chamber pressure decreases from 76.4 Psig to 40.5 Psig, losing 46.9% of its pressure. The pressure then reaches an equilibrium of 42.2 Psig again and has negligible fluctuation associated with it during the sparking and combustion in the combustion chamber 0.06 seconds later. At this point the process starts over again. The air to fuel ratio of the gasses in the mixing chamber is important to the combustion process as a stoichiometric mixture is needed to optimize the engine efficiency. The air to fuel ratio of the added gasses, using the partial pressures equation, of the external combustion engine is:

While using a propane fuel, a stoichiometric mixture has an air to fuel ratio of 14.7. Therefore, the external combustion engine has an air to fuel ratio that is 21.5% less than the ideal mixture. However, during this experiment the first cycle of fuel injection is different than the subsequent cycles. For the first cycle, 3.22 Psig of propane and 42.8 Psig of air are put into the mixing chamber. This mixture leads to an air to fuel ratio of 13.29

$$\frac{m_{air}}{m_{propane}} = \frac{\frac{P_{air} V_{air}}{R_{air} T_{air}}}{\frac{P_{propane} V_{propane}}{R_{propane} T_{propane}}} = \frac{P_{air}}{P_{propane}}$$

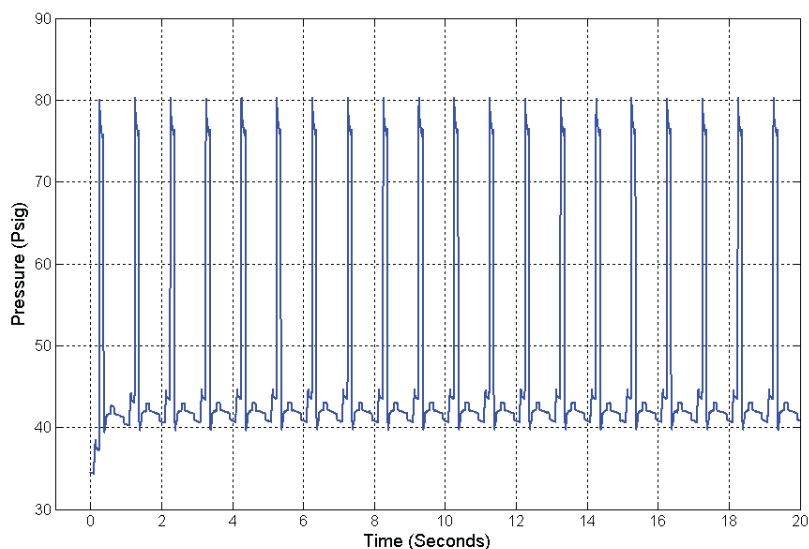


Figure 5: Mixing chamber pressure vs. time over several combustion cycles

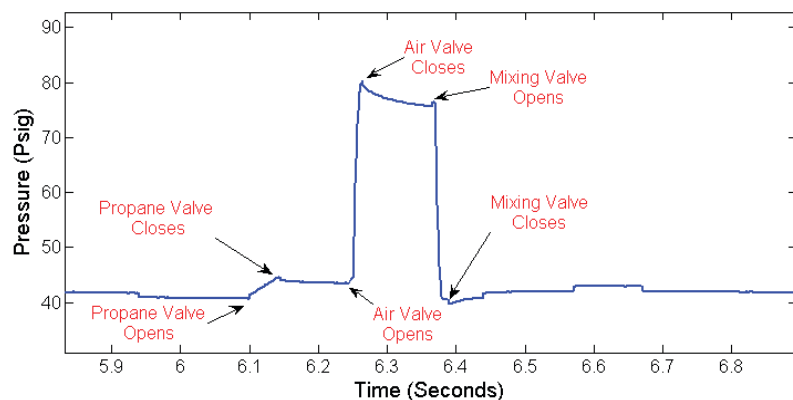


Figure 6: Mixing chamber pressure vs. time for one cycle

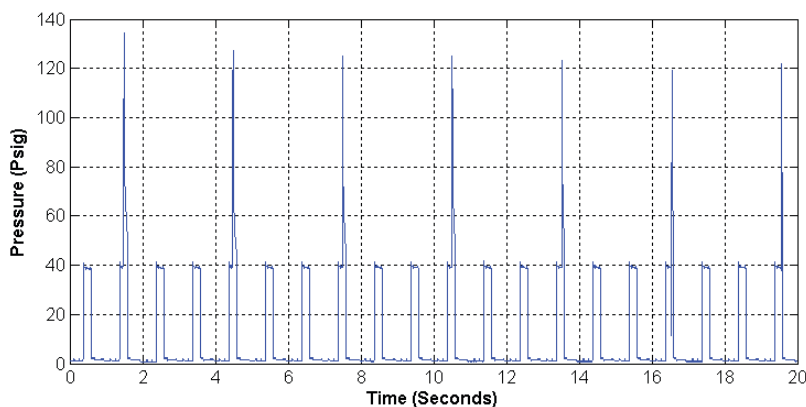


Figure 7: Combustion chamber pressure vs. time

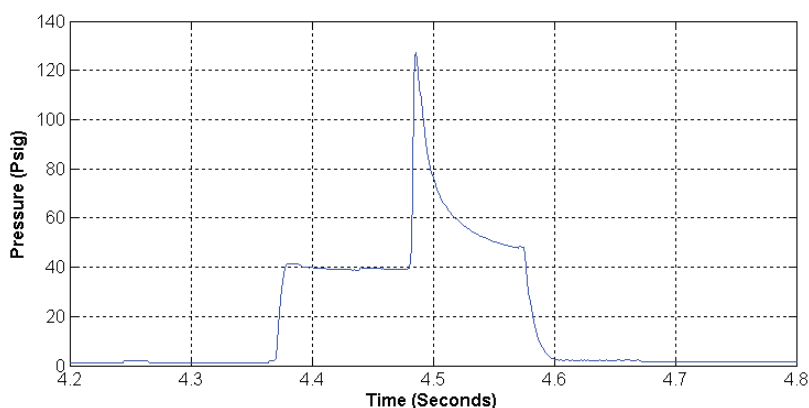


Figure 8: Combustion pressure during the firing of the external combustion engine

which is 9.6% less than the stoichiometric mixture.

The combustion chamber pressure over the run time is seen in Figure 7. It can be determined from this figure that the external combustion chamber does not fire every cycle of injection, sparking, and exhausting. However, it does consistently fire every three cycles. The fact that the chamber fires every three seconds indicates that fluctuations in air to fuel ratios and temperature variations are evening out to create a pressure close enough to ideal that combustion occurs. This could be related to the combustion chamber temperature as the chamber cools for two cycles creating the temperature needed for combustion on the third cycle. It is also seen that the maximum pressure increases from 39.1 Psig to 134.6 Psig an increase in pressure of 244%. The range of combustion peaks is from 119.2 Psig to 134.6 Psig with an average peak of 125.1 Psig. It is also shown in Figure 7 that the pressure leaving the combustion chamber reaches an equilibrium of 1 Psig consistently. In further experiments, as the exhaust gas performed work on some component, the combustion chamber pressure decreased to -4.0 Psig. This is important as the negative pressure allowed the check valve to bring in ambient air, cooling the combustion chamber.

Figure 8 shows an enlarged image of the pressure in the combustion chamber as the engine fires. It is seen in this figure that the combustion chamber starts its cycle at no gauge pressure. The 1 Psig increases and decreases in pressure result from the opening and closing of valves in the mixing chamber. At some run-time, 4.365 seconds in this case, the mixing chamber valve opens and allows a mixture of air and fuel to enter into the combustion chamber. In 0.025 seconds, the combustion pressure increases by 41.46 Psig. Using the ideal gas law at constant temperature, the ratio of the volumes of the combustion

chamber and the mixing chamber can be found, which indicates that the combustion chamber volume is 54.2% of the mixing chamber volume.

$$P_{C.C.}V_{C.C.} = P_{M.C.}V_{M.C.}$$

$$\frac{V_{C.C.}}{V_{M.C.}} = \frac{41.46}{76.4} = 0.542$$

After the air/fuel mixture is put into the combustion chamber, there is a pause of 0.05 seconds where the pressure remains nearly constant, indicating that there is almost no leakage in the combustion chamber. After the 0.05 second pause, the spark plug begins to fire, and combustion occurs 0.04 seconds later. This combustion increases the combustion chamber pressure from 39.7 Psig to 127.4 Psig in 0.006 seconds. Over the next 0.084 seconds, the pressure sees a large exponential decay to 47.8 Psig, losing 90.7% of its gain in pressure. This decrease in pressure could be due to high heat losses to the atmosphere. The high surface area of the cube and the high heat transfer coefficient of aluminum are ideal conditions for this to exist. Also, there could be a small amount of leakage out of the exhaust valve but the resistance of the actuated poppit prevents a large pressure drop. This shows that the combustion force, contrary to the expectation, does not open the actuated valve. The exhaust valve then opens and the combustion pressure drops 46.3 Psig over 0.031 seconds. This shows that while open, the exhaust valve does not restrict the flow of the combustion gasses significantly. However, because of the exponential drop in combustion pressure, little work is done by the combustion gasses.

Finally, the engine speed is important in the application of the FPC as it governs the frequency at which the free piston will be able to move. An appropriate engine for robotics use would have a speed of 20 Hz. Table 1 outlines the time restrictions within the experimental external combustion engine.

It is seen that the spark to combustion time is the limiting factor in this experiment. For the first cycle, the combustion occurs 0.04 seconds after the start of the spark. However, as the run time increases, the air to fuel mixture changes and the combustion chamber temperature increases. While running at an engine speed of 1 Hz, after 20 cycles the factors combine to cause combustion to occur 0.13 seconds after the start of the spark. The engine speed is 3.98 Hz when the total cycle time is conservatively 0.251 seconds. During the first

Combustion Cycle in the Experimental External Combustion Engine			
	Start (Seconds)	End (Seconds)	Time Elapsed (Seconds)
Injecting Fuel	0	0.045	0.04
Injecting Air	0.045	0.06	0.015
Injecting mixture into Combustion Chamber	0.06	0.08	0.015
From spark start to Combustion	0.08	0.23	0.15
Exhaust Exit	0.23	0.24	0.031
TOTAL TIME			0.251

Table 1: Process time restrictions in the external combustion engine

few cycles of combustion, the engine is running every 0.141 seconds, which is a speed of 7.092 Hz. However, even if the spark was an immediate process, the engine would only run at 9.9 Hz.

Conclusion

It is found that the construction of the external combustion engine presented in this paper was completed successfully, and that the engine fired consistently every three cycles of injection, spark, and exhaust. A combustion peak pressure average was found to be 125.1 Psig and the Parker Hannfin Corporation VAC-100 Psig exhaust valve was able to withstand the high temperature and pressure flow presented to it though combustion gasses with minimal restriction. Experiments showed that the time taken to complete one firing of the external combustion engine is 0.251 seconds, giving the engine a speed of 3.98 Hz. Also, it was found that using a separate mixing chamber and combustion chamber can provide an appropriate structure for an external combustion engine, in which accurate measurements of mixing and combustion pressures result.

Many problems resulting from the external combustion engine were also presented in this paper. Leaks in the mixture chamber caused the air to fuel ratio to be inconsistent with the stoichiometric ratio with a large deviation between the first engine cycle and subsequent cycles. However, the main problem of this design is the loss of pressure to heat and leakage after combustion in the combustion chamber. This drastically decreases the efficiency of the external combustion engine as the peak combustion pressure falls from 127.4 Psig to 47.8 Psig before the exhaust valve before the exhaust valve opens only 0.085 seconds later. By opening the exhaust valve earlier, this could be combated; however, as the number of effective cycles increases, the time to combust after the spark began increases from 0.04 seconds to 0.13 seconds. If this problem is due to heat losses or problems with the air/fuel ratio, it could be avoided by constructing the combustion chamber out of a ceramic material and making the device completely absent of leaking. It was also concluded that the exhaust actuated valve was not forced open during combustion, indicating that the valve must be triggered to open as soon as combustion occurs. The speed of the external combustion engine poses a final problem as the maximum performance speed is 7.092 Hz, 64.5% lower than an ideal 20 Hz

engine, and the minimum performance speed is 3.98 Hz, 80.1% lower than a 20 Hz engine.

Future work should include developing a combustion chamber made out of a ceramic material to determine if losses after combustion are due to heat, leakage, or some other unknown factor. Also, experiments need to be run to see how the external combustion engine is affected when it is run for both long and quick time durations. This should include determining how the temperature of the combustion chamber affects performance and if the check valve to insert cool air into the combustion chamber can sufficiently cool the device. Another improvement to the design would be to integrate the combustion chamber and the mixing chamber into one chamber, reducing the overall size of the engine.

Before the external combustion engine replaces magnets in the proposed free piston compressor, many improvements need to be made. Although many variables stand in the way of this integration, further experiments should be run to optimize the external combustion engine performance before it should be eliminated from consideration for use in a free piston compressor.

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