DESIGNING, MANUFACTURING, AND TESTING A VALVELESS PULSEJET ENGINE

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ABSTRACT

This paper reports on the design, manufacturing, and testing of a Lockwood-Hiller pulsejet engine. The design of the engine was based on engine-ratios developed by Ray Lockwood in his pulsejet patent [1]. The design was verified using the computer modeling software Solidworks, ANSYS, and MATLAB. The electrical ignition system was modeled using the program Micro-Cap 11 (Evaluation Version). The engine is made of 16-gauge 316-L stainless steel sheets, which were rolled and hydroformed into the proper shape and welded together along with pre-manufactured steel piping. To test the engine, it was mounted atop a trailer that is fitted with all of the fuel tank, controls needed for safe operation, and the instruments used to gather diagnostic data, on temperature, frequency, thrust, and sound levels. Those measurements resulted in an outside temperature between 1,000 and 1600 °F, a frequency of 52.6 to 56 Hz, a maximum force of 28lbs, and sound waves with an amplitude of 135 dB. This project was completed by a group of high schools students participating in an afterschool program run through Power Mountain Engineering. It tested their ability to complete an advanced engineering challenge [2].

INTRODUCTION

Pulsejets are a variety of jet engine that work based on acoustic resonance created through fuel flow and combustion. They can either function using valves that control fuel flow in the combustion chamber (like the German V2 rockets) or as valveless engines. In both cases spontaneous combustion of the fuel generates a resonance dictated by the shape and size of the air columns [2]. This project deals with a valveless pulsejet engine whose general form and parts are shown in **Figure 1**. The size and shape were chosen to produce 150 lbs. of force, employing ratios from Ray Lockwood's patent [1] and equations found in Smith [4]. This design creates thrust by combusting propane in the combustion chamber (A) which forces the hot gaseous products to exit the top and bottom exhaust/intake pipes (C). The resonance of the engine can be divided into two parts The particles that go left from the combustion chamber (A) form a Helmholtz resonator while the particles that go right become the conical resonator (B). These two ends (C) resonate together such that hot gas escapes from both at the same time and fresh air is also inhaled synchronously. This pattern of rapid combustion, thrusting out of hot gases, and inhalation of fresh air creates the complete rhythm of the engine.

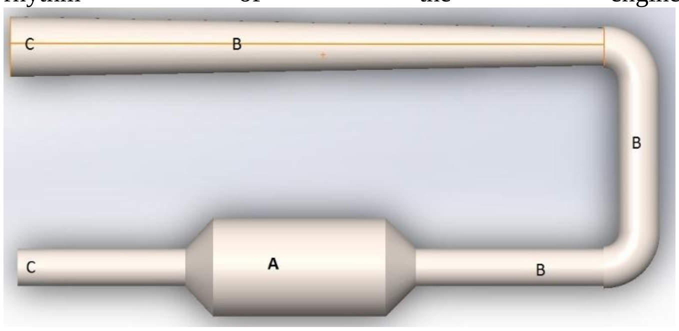

Figure 1 THE PULSEJET ENGINE SCHEMATIC

A Combustion Chamber
B Conical Resonator
C Exhaust/Intake

Pulsejet engines are extremely hot and loud. To ensure the safety of the operators and spectators, all people in close proximity to the engine wore double hearing protection and safety glasses. All spectators farther away wore some ear plugs. The heat produced by the engine is radiated out onto a heat shield that protects the contents of the trailer upon which the engine is mounted, dispelling heat to the environment.

This engine was built in the machine shop of Fossil Ridge High School after school in three-hour sessions twice per week amounting to a total of 105 hours. The following paper contains all the design, modeling, construction and testing details.

NOMENCLATURE

Hydroforming: the process of inflating a metal envelope to achieve the desired shape using high pressure water.

Pulsejet Engine: a resonating steel pipe that combusts propane to produce a rhythm the causes a reprise of the process.

DESIGN

Engine Design

The design process was divided into four steps. The first step was to calculate the volume of the combustion chamber based on the desired thrust. The next step was to ensure that the combustion chamber had a high hoop-stress safety factor. The third step was to determine the Helmholtz resonance of the combustion chamber. The final step was to design the conical exhaust cone from information found in Scavone [5].

Given a desired thrust of 150 lbs, the equations provided in Ray Lockwood's pulsejet patent [1] show that the combustion chamber must have a volume of at least 2.2 x 10^{-2} m^3 (1400 in^3) This project used a combustion chamber has an internal volume of 2.6 x 10^{-2} m^3 (1600 in^3) to ensure sufficient thrust. A thin-wall hoop stress calculation with these dimensions and the conditions created by the internal combustion process show that the combustion chamber experiences 66 MPa (9.6 psi) of stress [6, 7]. At 700°C (1300 °F), 316 L stainless steel has a short-term stress threshold of approximately 320 MPa (46 psi) [8]. Thus, the combustion chamber has a hoop-stress safety factor of 4.85. The frequency equation for a Helmholtz resonator shows that the combustion chamber resonates at 81.4 Hz [4]. This frequency should match the resonant frequency of the exhaust cone. The resulting exhaust cone has a length of 2.82 m (9.25 ft.), an end diameter of 0.16 m (6.3 in.), and a resonant frequency of 81 Hz [5].

To measure the thrust produced by the engine, the engine was attached to one of two right-angle arms via a tab and clevis. The other arm was attached to a force gauge. This converts the horizontal trust produced by the engine to measurable vertical force. There was a slight difference in the lengths of the two arms, but this was considered insignificant.

Control Design

The control system contains two sub-parts that both run off of a 12V lead-acid battery. The first part is an emergency fuel cut-off valve and carbon dioxide "fire" extinguisher. In the event of an emergency a button is pressed and an in-line fuel solenoid closes to stop all fuel flow going to the combustion chamber. At the same time, the carbon dioxide in-line solenoid opens and floods the combustion chamber to stop all chemical reactions. The fuel solenoid remains closed until the "Arm" push-button is pressed which re-arms the system. The second part of the control system is a variable-speed spark (the ignition circuit), because pulsejet engines have been found to start better using a spark tuned to frequency the engine [4]. This circuit uses a 555 timer IC to drive a gate driver IC that controls an IXYS IGBT that switches the current on the spark coil. A spark is created when the IGBT opens. The variation in the spark comes from a potentiometer that changes the on-time of the circuit thus changing the frequency. These properties are described in Fairchild semiconductor data sheet [9] for the 555 timer. The ignition circuit is only needed to start the engine, so it is turned on and off by a switch that takes advantage of the reset pin on the 555. The IGBT is protected from the ignition coil's sudden release of energy by a snubber capacitor and diode-resistor circuit shown in the bottom right of **Figure 2**. All of the timing circuitry is contained inside of a grounded, aluminum box.

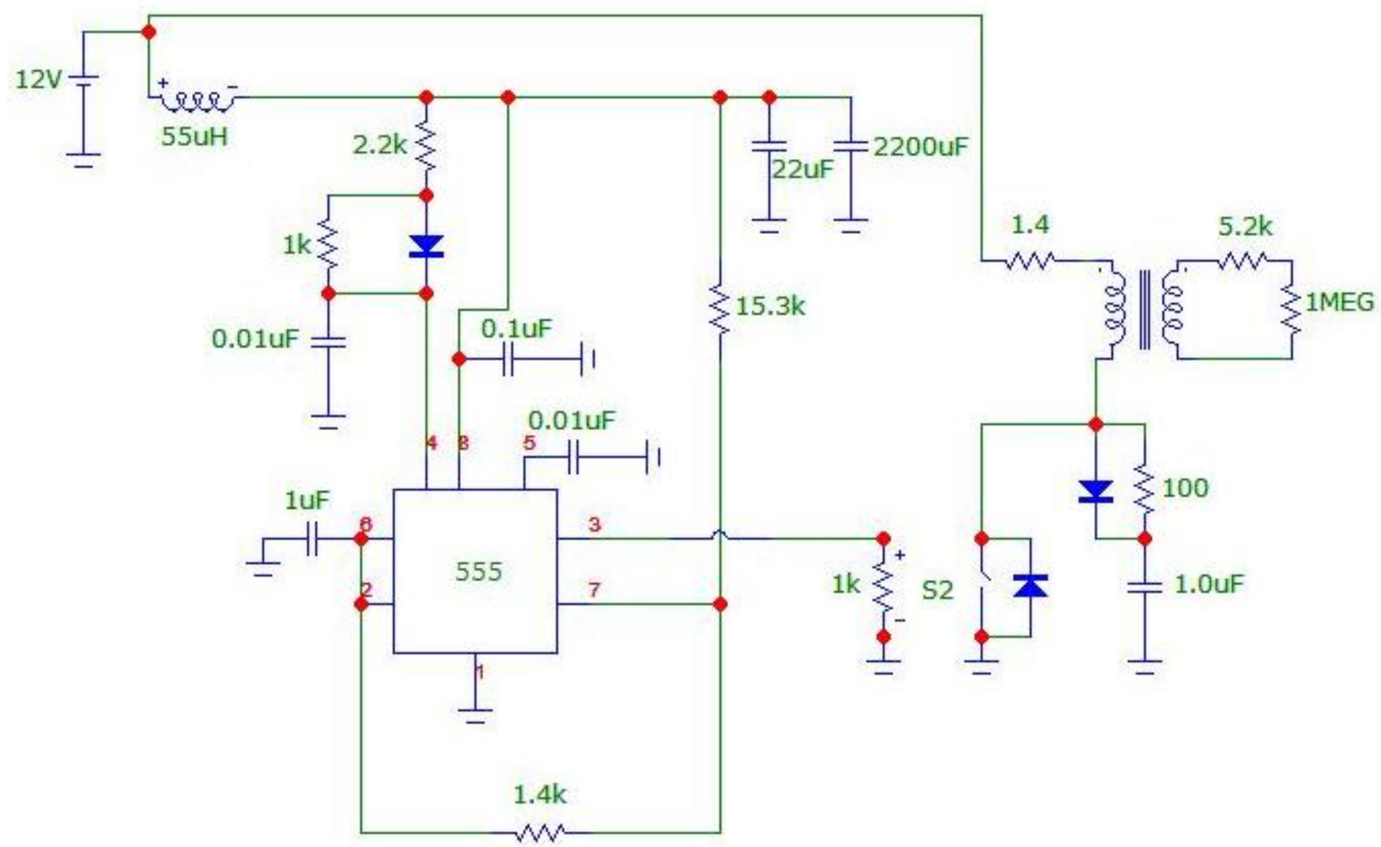

Figure 2 THE IGNITON CIRCUIT DIAGRAM

MODELING

The ignition circuit was modeled using Micro-Cap 11 (Evaluation Version) while the engine dynamics (resonance, pressure, temperature) were modeled using Matlab and ANSYS Computational Fluid Dynamics (CFX) programs.

Figure 3 shows the average power (top) and current (bottom) with respect to time of the 12V battery.

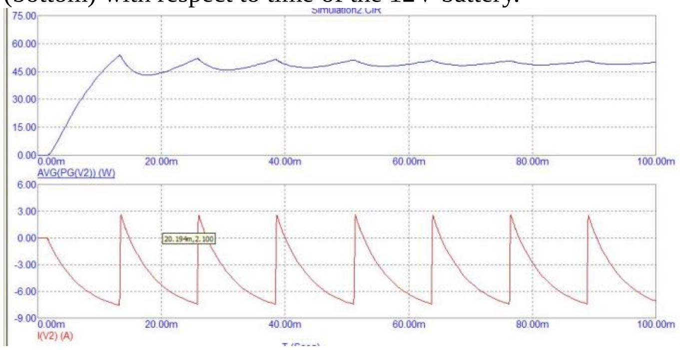

Figure 3 SIMULATION BATTERY MEASUREMENTS

A 1 MΩ resistor was used to model the air gap of the spark plug. The peak voltage was predicted to be between 28 to 29 KV as shown in **Figure 4**.

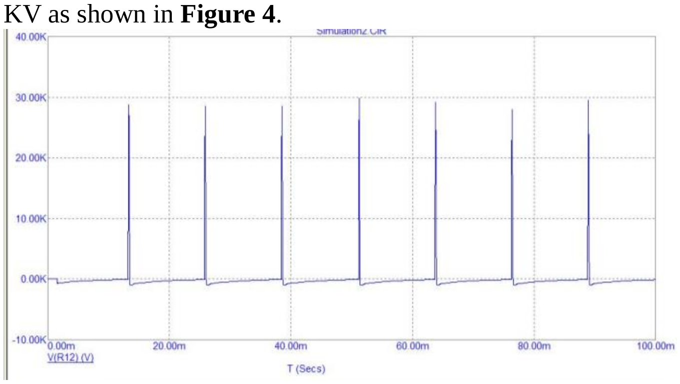

Figure 4: SIMULATION SPARK PLUG VOLTAGE

To obtain an accurate prediction of the resonate frequency of the engine and to make sure the engine would operate, Matlab and CFX were used to simulate the engine running. **Figure 5** is a temperature contour graph that shows both ends of the engine pulsing together; note that the hot exhaust (red) reaches both ends at the same time. This result as a whole means the engine would resonate and proved that the design had the correct dimensions. The output of the engine was modeled inside of a box to make it easier to compute. Matlab was used to simulate the pressure wave. This was accomplished by using the one dimensional wave equation with the engine body as the boundaries, and with energy added at time steps predicted by the Helmholtz resonator frequency.

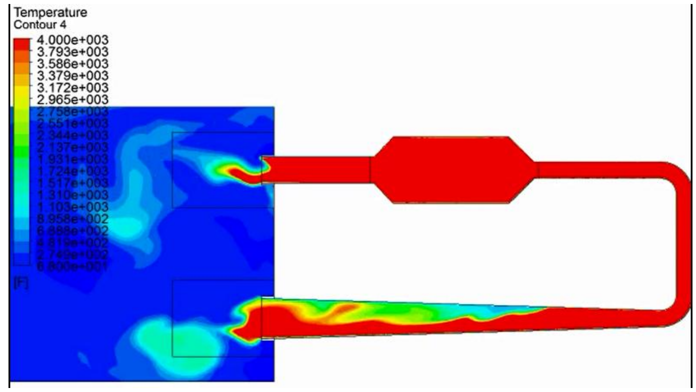

Figure 5 SIMULATION OF ENGINE TEMPERATURE

TESTSTAND AND MANUFACTURING

The engine was constructed in cylindrical and conical sections which were then welded together using TIG techniques and filler-material. The top cone was hydroformred (i.e. was welded together as a flat envelope and then inflated by a pressure washer to the proper shape). Most of the engine was constructed using 16-gauge 316L and 304 stainless steels. The hydroformed cone was connected to the combustion chamber via pre-manufactured pipes and elbows. The combustion chamber and the rest of the engine was rolled then welded. Multiple tapped bosses were welded onto the combustion chamber for the spark plug, the carbon dioxide line, and the fuel line (**Figure 6**).

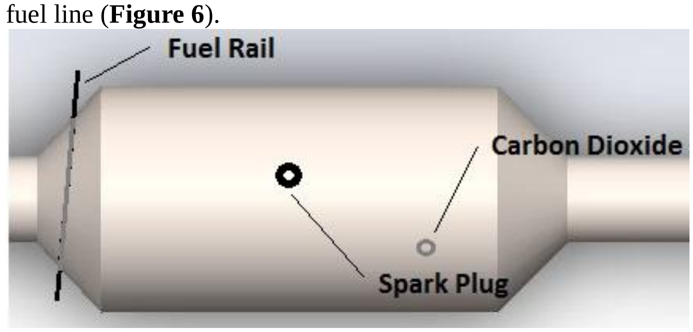

Figure 6: THE ENIGNE BOSSES AND OTHER ORIFICES

The trailer began as a rectangular base with the lights, wheels, tongue and frame (Haul Master 420708) with bed dimensions of 40” by 49” (**Figure 7**). From there an 18” by 49” by 40” rectangular prism was constructed using 1” angle iron and enclosed with metal, melamine or fiberboard. This hollow prism was filled with a propane tank, a 12V lawn and garden battery, an electronic control box and a carbon dioxide bottle for emergencies. It also houses all of the plumbing and wiring to make these items function correctly.

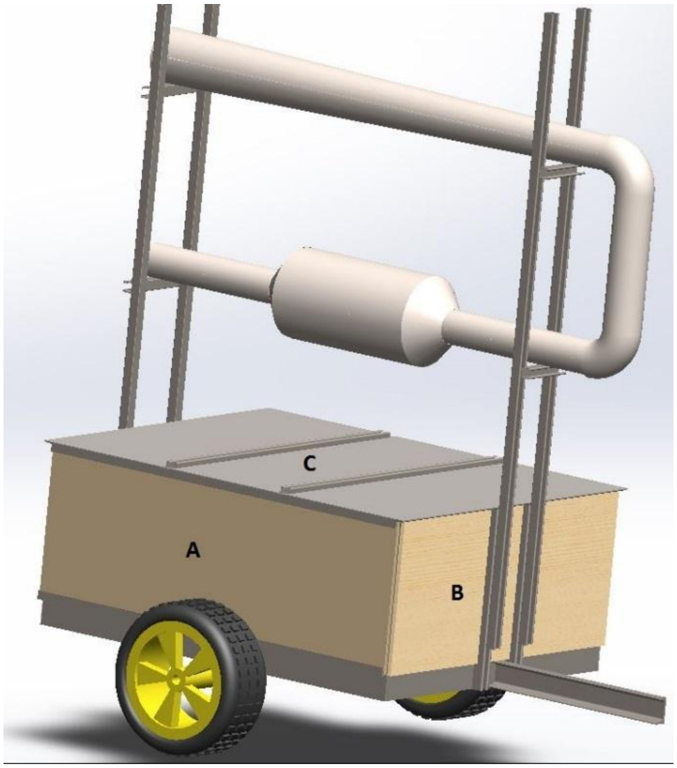

Figure 7: THE TRAILER WITH THE ENGINE

The base of the trailer (opposite from C in figure 7) is covered by 3/4 inch melamine 49" by 40" as is the 18" by 49" sliding panel (opposite from A). The upper deck, also called the heat shield, is 18" above the lower (C) and made of sheet metal. The two short sides (B and opposite from B) on the front and back of the engine are 18" by 39.5" and made of fiberboard. The melamine side opposite of the sliding panel (A) is 18" by 39.5." As shown in **Figure 7**, a 14-gauge Unistrut structure is attached to the trailer to support the engine. The engine inlet frame is 49" by 7." The outlet frame is 63" by 10." The trailer weighs 455lbs without the engine and 530lbs with.

MEASUREMENTS

Table 1 RESULTS

Pulsejet Engine Performance Results		
	On Propane Vapor	On Liquid Propane
Temperature (°F)	~1600°F	~1600°F
Trust (lbs.)	5.8lbs	28lbs
Sound Produced (dB)	135	135
Spark Voltage	22.6KV	22.6KV
Resonate Frequency	52.6	54-56Hz
Average Gas Temperature	~332°F	~332°F

The engine temperature was approximated using the color of steel and a pyrometer [10, 11]. The thrust measurements were lower than expected, possibly due to the lower than expected operating temperature which lowered the frequency and the thrust. Also the force gauge appeared to be too slow for the engine's rapid impulses. The maximum sound was measured from a distance of ~1.5 ft. from the exhaust of the engine. **Figure 8** shows the sound field produced by the engine running on vapor at distances of 25 and 50 ft. measuring from the exhaust [12].

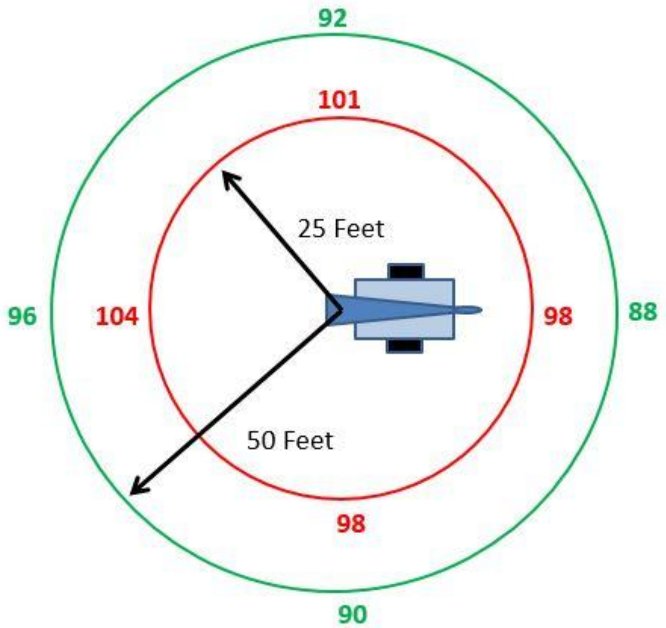

Figure 8: ENGINE SOUND FIELD ON VAPOR

Figure 9 shows the voltage of the spark coil versus time as measured by a high-voltage probe and imaged by an oscilloscope [13]. The peak voltage is 22.6 KV.

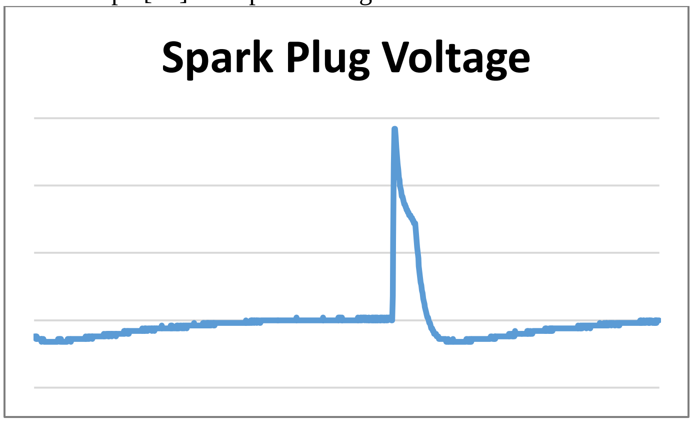

Figure 9: MEASURED SPARK PLUG VOLTAGE

The frequency of the engine is measured by analyzing an audio recording of the engine running on liquid propane analyzed with Audacity 2.0.5. With a low pass filter, everything above 100Hz is attenuated at 48 decibels per octave, and then amplified so that the signal is clear. From these data, the engine frequency was calculated. **Figure 10** displays the sound divided in to right and left earphones (top and bottom). Going from left right the unfiltered sound changes to filtered.

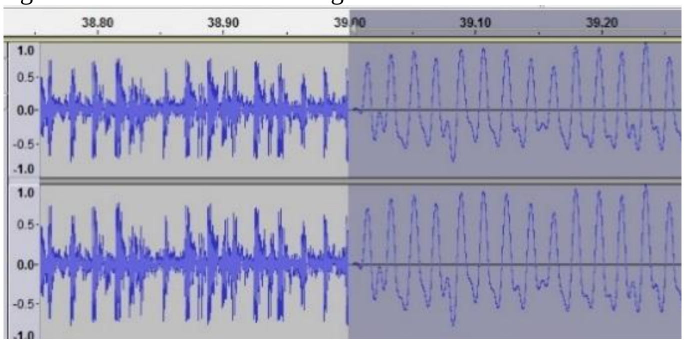

Figure 10: THE SOUND OF THE ENGINE BEFORE AND AFTER FILTERING

The audio filtration software matches the results from a two pole RC filter based on another engine video in which the engine used propane vapor. This produces a fundamental frequency of 52.6Hz on vapor and 54-56Hz on liquid. The discrepancy is most likely due to a small change in the average gas temperature. The average gas temperature was calculated using the equations found in Smith [4] and the frequency of the engine. This relatively low average is likely caused by the mixture of hot gas with the cool outside air.

CONCLUSION

As a whole the engine runs well. It starts quickly when a leaf blower is used to mix the fuel and air in the combustion chamber along with a spark. The engine would not start without a spark, but even a poorly tuned spark frequency would easily start the engine. Pyrometer measurements indicate that the temperature of the combustion chamber running of on propane vapor exceeds 1200°F. While it approaches this value on liquid fuel; it does not reach it. This is likely because the fuel flowed in as a liquid and thus cooled the engine as it boiled before it was combusted.

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[1] This section only was written by Hugh C. Kirbie on account of his knowledge and role as project leader.

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