Ammonia Powered Engine

A Major Qualifying Project

Submitted to the faculty of

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In

Mechanical Engineering

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Abstract

Cars are a significant source of carbon emissions into the atmosphere and with a growing number of cars on the road, this is negatively affecting the atmosphere. The carbon emissions cars emit comes from the gasoline being burned in the engine. While battery/electrics provide one solution, energy density and speed of refueling are favorable with internal combustion engines. A potential candidate for replacing hydrocarbons as the fuel for combustion engines is ammonia. A molecule of ammonia is composed of one nitrogen atom and three hydrogen atoms producing nitrogen gas and water upon combustion. Neither product of combustion is harmful to our environment and the ammonia itself can be produced through “green” renewable energy processes. Using a small engine from a snow blower, we aimed to modify the engine to run off of ammonia as the fuel source. As a gaseous fuel, ammonia presents an additional challenge metering the air fuel mixture. Our team designed and began manufacturing a dual housing roots type positive displacement pump as a solution to the challenges we faced when using ammonia as a fuel. The roots type blower is controlled by the crankshaft which consistently rotates the lobes of the supercharger for both the air and ammonia at the same speed. We ran structural, mass flow, chemical equilibrium, and power output calculations and computer simulations for our engine. We created the entire supercharger and all of its components in Solidworks and 3D printed the model to visualize it at a smaller scale. Then, we wrote the code in esprit for the parts and began manufacturing them on the minimill and the wire EDM machine. Due to Covid-19 complications our team was not able to finish manufacturing the super charger and run physical tests planned for D term. Our design, and ammonia powered internal combustion engines as a collective, shows promise for future work and we have left off this project at a place we are confident will be easily picked up and carried through to fruition.

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1. Introduction

With current fuel sources, cars are burning gasoline which emits carbon emissions into the atmosphere. As more carbon goes into the atmosphere, it pollutes the air and negatively affects the ozone layer. Gasoline is the main source of fuel for engines today and has always dominated the market. However, research is now being done to find alternative fuel sources.

The number of cars on the road increases every year, so carbon emissions continue to be a growing problem. In 2018, 276.1 million cars were registered it is projected to increase to 281.3 million in 2019 (Hedges Company, n.d.). Assuming the average gasoline vehicle on the road today has a fuel economy of about 22.0 miles per gallon and drives around 11,500 miles per year, 4.6 metric tons of carbon dioxide are emitted from each vehicle per year (EPA, n.d.). That equates to about 404 grams of carbon dioxide per mile. Carbon emissions also vary between gasoline and diesel. A gasoline (C8H18) powered engine emits 8,887 grams of CO2 per gallon whereas a diesel (C12H24) engine emits 10,180 grams of CO2 per gallon (EPA, n.d.).

Research is being done to determine an alternative fuel. When considering fuel sources, they all have benefits and drawbacks. According to NH3 Fuel Association, the ideal fuel is environmentally friendly, cost effective and produced from a primary energy source. Taking into account other qualities, ammonia comes out on top against other sources such as natural gas and biofuels. Researchers at the International Research Organization for Advanced Science and Technology at Kumamoto University in Japan have also taken note as to ammonia being a potential new alternative fuel because it has a high H_2 density, it is easily liquefied, and can be produced on a large scale (Kumamoto University, 2018). Ammonia provides lost cost and safe storage and transportation of hydrogen, which has one of the highest energy densities and it only needs a small amount of energy to ignite. (Fung, 2005). Hydrogen combines with other elements easily, but it can be separated by renewable sources for the creation of ammonia. Using hydrogen fuel would also improve air quality. However, the production of hydrogen is more costly than using fossil fuels (Fung, 2005).

Currently, the market for ammonia is centralized around farming and used for pesticides and cleaning supplies. The average price of ammonia in 2018 is $1.89 per gallon (Widmar, 2019). Although at first glance ammonia is less expensive than gasoline and diesel, the energy density is less than both gasoline and diesel, so it requires more mass of fuel to do the same work. Comparatively, Gas cost an average of $2.72 per gallon in 2018 (Wagner, 2020) and Diesel cost an average $3.18 per gallon in 2018 (Transport Topics, 2018). This is true assuming for a 300 mile trip and a 30 mpg gasoline equivalent, it would require 27.4 gallons of ammonia, 10 gallons of gasoline, and 8.8 gallons of diesel (NH3 Fuel Association, n.d.). A typical gasoline engine operates around 25%-30% efficiency, whereas a typical diesel engine operates around 30%-35% efficiency (Thermal Efficiency, n.d.). Theoretically, ammonia could have an efficiency between 11%-19% (Brown, 2017).

Ammonia is stored in pressurized tanks typically composed of carbon steel because it is resistant to low temperatures and will not react with ammonia (Anhydrous, 2005). Ammonia storage tanks should be able to withstand a minimum internal pressure of 250 psi. Inside the tank, ammonia is cooled to -28 degrees Fahrenheit (BEPeterson, 2017). There is already an infrastructure to safely transport ammonia by pipeline, truck, barge, or train. Trains are the primary method of transportation of ammonia. Via pipeline in the United States, 2.9 millions tons of ammonia per year can be transported (Hattenbach, n.d.). There are approximately 6,000 train cars in service and 31 U.S. barges in service with a 2,500 ton capacity. In 2018, trains carried 2.4 million carloads of plastics, fertilizer and other chemicals (Freight, n.d.). One rail car carries about as much as four truck loads to put it in perspective.

Ammonia is a colorless, highly irritating gas with a suffocating odor. It is toxic when it comes in contact with skin or if it is inhaled in high amounts which causes burning and cellular destruction (Department of Health n.d). During fuel combustion of NH_3 and H_2O, N_2 and NO_x and produced. NO_x can be toxic when inhaled which poses another problem for the combustion of ammonia. Fortunately, research is being done to eliminate the NO_x within the reaction. Low levels of ammonia are naturally found in the environment. Plants and microorganisms rapidly take up ammonia, however ammonia levels can decrease rapidly because it is naturally recycled (Toxic, 2004). In the case of an ammonia spill. Ammonia is less dense than air so it will decompose on its own and not cause any harm. Ammonia has a higher-octane rating than gasoline, >111 as opposed to 87 (Cornelius, 1984). This means it is more resistant to knocking and allows a higher compression ratio. The higher the compression results in a higher internal temperature within the chamber which results in a greater thermal efficiency and more power produced (Difference, 2012).

The impact of our project would help to reduce carbon emissions and improve the environment in the air from burning gasoline, ammonia could be an alternative. It could start off in small engines and improve to cars and potentially more to generate electricity. Ammonia, a compound without carbon combusts with no CO_2 emissions. Currently, methods to power combustion engines using ammonia are not ready for market, and the energy density is lower than gasoline, there is still the potential for ammonia powered cars.

2. Background

2.1 The Internal Combustion Engine

An engine converts chemical or thermal energy into mechanical energy that is then capable of doing work. In a combustion engine, the initial energy is chemical potential energy that is burned creating heat energy which is captured and converted into mechanical energy. The four-stroke internal combustion engine was first designed in 1861 by Nicolaus Otto (Collins, 2018) The combustion of a fuel (gasoline) with an oxidizer (air) is confined within the engine and translated into usable kinetic energy. The basic principle of the four-stroke engine has been the same since. The cycle, commonly referred to as the Otto cycle, can be separated into four different operations. See Figure 1 and Figure 2 below.

1. Intake Stroke: The piston lowers in the combustion chamber creating a low-pressure zone above the piston crown. The intake valve is then opened. Air is pulled through the carburetor, drawing up the fuel, and the air fuel mixture is pulled into the combustion chamber (Briggs and Stratton, n.d.).
2. Compression Stroke: The intake valve is closed when the piston reaches the bottom of the cylinder (bottom dead center). The momentum of a flywheel on the crankshaft pushes the piston back up the cylinder, compressing the air-fuel mixture in the combustion chamber.
3. Power Stroke: Right before the piston reaches its highest point (top dead center), and the combustion chamber has its smallest volume, a spark is triggered across the ignition coil (spark plug). The spark ignites the air-fuel mixture greatly increasing the pressure within the combustion chamber and forces the piston down the cylinder to bottom dead center.
4. Exhaust Stroke: Once the piston reaches bottom dead center the exhaust valve is opened. As the piston moves up the cylinder the exhaust gasses are expelled until the piston reaches top dead center and the exhaust valve is closed. The 4-stroke cycle is then repeated starting with the intake stroke.

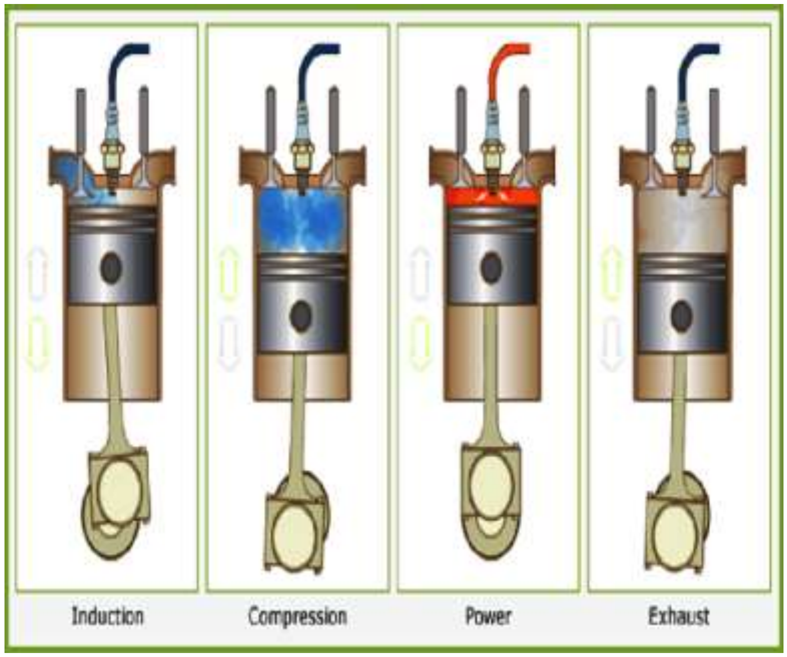

Figure 1. Four Stroke Diagram

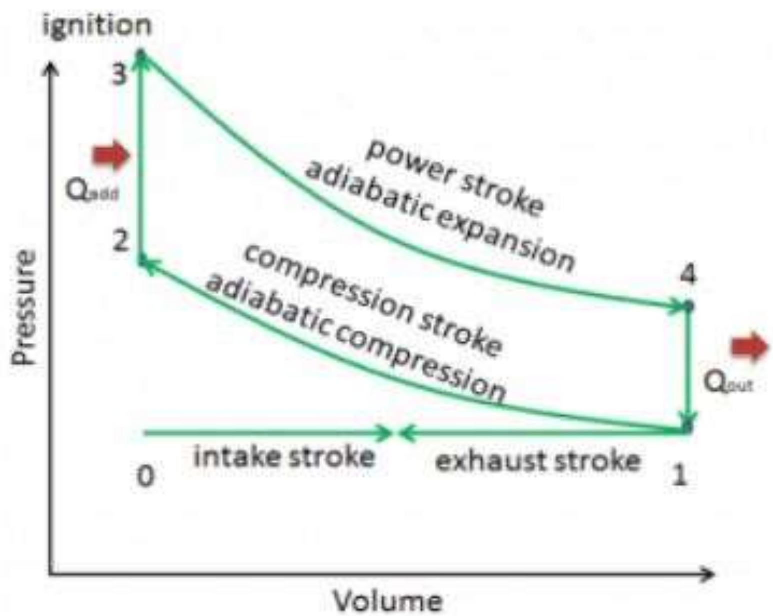

Figure 2. Otto Cycle P-V Graph

2.2 The Carburetor

For spark ignition engines, the carburetor was invented in 1888 by Karl Benz (Woodford, 2009). They are only used in internal combustion engines and were essentially the heart of the automobile. A carburetor serves three major functions: combine air and fuel, regulates the ratio of air and fuel, thereby controlling the engine speed (National Carburetors, n.d.). A carburetor is a fluid mechanical computer for metering fuel to the engine.

The way a carburetor works, is the valve at the top, known as the choke valve, allows air to flow into the tube. This valve regulates how much air can flow in. It is only closed during startup, to produce higher vacuum and draw in fuel. As the air moves down the tube, it passes through a narrowing part called the venturi. This decrease in area causes the velocity to increase, which decreases the pressure. This decrease in pressure in the tube draws in fuel from the fuel pipe. The more the butterfly valve below the venturi opens, called the throttle valve, the more air flows through the carburetor and pulls in more fuel. The more the throttle valve is opened, the more fuel and air will be available to be converted to mechanical work by the engine. When the choke is closed, less air flows in which draws in more fuel, creating a fuel rich mixture into the engine for starting a cold engine.

Looking specifically at the fuel chamber, there is a float and valve that controls the inlet. As the float feed chamber supplies fuel to the carburetor, the fuel level and float drop. Once the float reaches a certain level, it opens a valve allowing fuel from the main chamber to refill the float feed chamber and the fuel feed switches off.

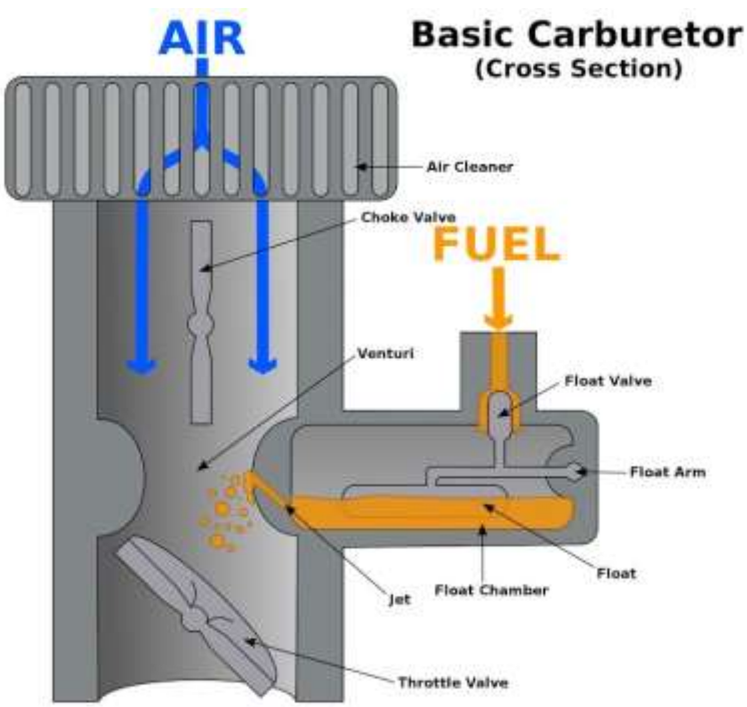

Figure 3. Carburetor Simplified

2.3 Gasoline and Carbon-Based Fuel

Different hydrocarbons have different levels of emissions. When gasoline is burned, it emits 157 pounds of CO2 per million Btus (EIA, n.d.). Petroleum, also known as crude oil, is a fossil fuel composed of a mixture of liquid hydrocarbons extracted from the ground. Hydrocarbons are organic compounds composed of hydrogen and carbon in different lengths. These different hydrocarbons can be turned into a variety of products. Refineries separate these different lengths of hydrocarbons through a process called distillation. The distillation occurs in a distillation column where the temperature is raised causing certain hydrocarbon chains to boil off one at a time. Once they boil, they are separated and condensed. Once gasoline is separated, different ingredients can be mixed with it to achieve specific octane ratings (Wonderopolis, n.d.). The higher the octane number, the higher compression required before the gasoline ignites (Donev, 2020). Octane rating is a measure of a fuel's resistance to knock (Exxon Mobil,* n.d.). An engine knocks when there is an incorrect air-fuel mixture. When this happens, the fuel burns in even pockets and can combust without the spark plug igniting it (Charlet, 2015). This can cause damage to the piston and cylinder wall so it is a major aspect to avoid.

2.4 Ammonia

One molecule of ammonia is made up of three hydrogen atoms and a single nitrogen atom. This molecular structure means ammonia is 17.8% hydrogen by mass. Ammonia has a hydrogen density of 121 kilograms of hydrogen per meter cubed (kg-H2/m^3), making ammonia more hydrogen dense than liquid hydrogen which has a density of 70.8 (kg-H2/m^3) (Kobayashi, 2019). Figure 4 displays the hydrogen densities of various hydrogen carrier molecules. Due to the liquid nature of ammonia, transporting and storing ammonia is far easier than that of liquid hydrogen. Ammonia condenses into a liquid at -10 C, whereas hydrogen condenses at -253 C. The relatively high condensing temperature of ammonia means that less energy would go into converting the gas into a liquid. The energy required to liquefy hydrogen,

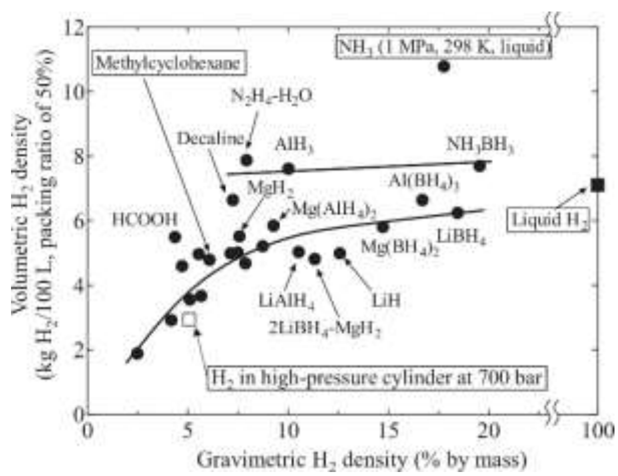

Figure 4. Gravimetric vs Volumetric Hydrogen densities (Kobayashi, H, 2019)

The energy density of ammonia is also significantly higher than alternative fuels, but lower than traditional hydrocarbon sources. NH3 has a heating value of 22.5 MJ/kg. Some common carbon-based fuels such as coal and natural gas have energy densities of 20 MJ/kg and 55 MJ/kg respectively (Valera-Medina, 2018). In terms of volumetric energy density, or "raw energy density," liquid NH3 is 11.5 megajoules per liter (MJ/L). In terms of volumetric energy density, ammonia has a higher value than liquid hydrogen, which has a density of 8.491 MJ/L (Lan, 2014). Figure 5 displays the energy densities of various combustible fuels and batteries.

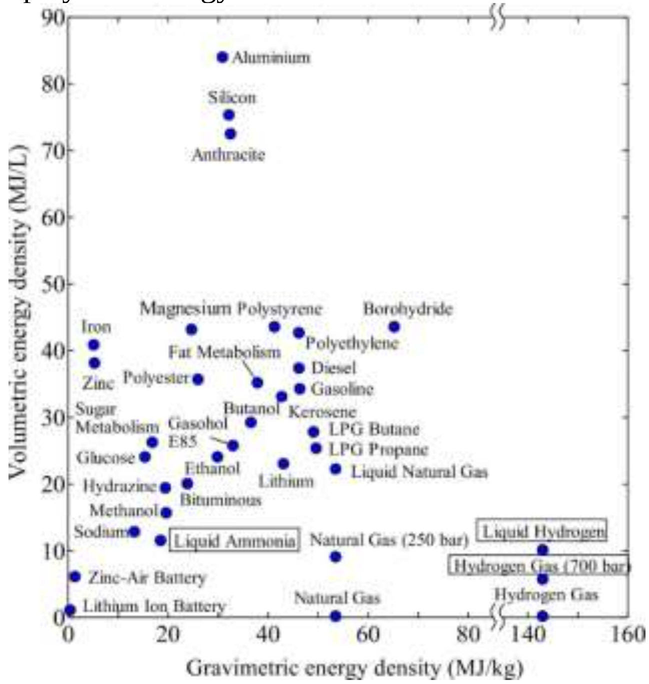

Figure 5. Energy Density Graph (Okafor, n.d.)

The current method of producing ammonia is known as the Haber-Bosch process. Nitrogen is taken from the air and hydrogen is taken from natural gas. High pressure is necessary to break the strong bonds between nitrogen molecules. The nitrogen and hydrogen are forced together using a catalyst, high temperature, and high pressure (Briney, 2019). Research is being done to improve the production method and eliminate carbon emissions from natural gas. Nitrogen and hydrogen production could potentially be driven by renewable energy such as wind and solar instead of natural gas. Utilizing the electricity that renewables generate, current ammonia producing plants are beginning to separate water into oxygen and hydrogen using electrolyzers. There are other methods currently being developed to produce ammonia without the Haber-Bosch process. Utilizing electricity from renewables, reverse fuel cells can create ammonia in a chemical reaction using anodes and cathodes. The drawback to this method is that the production rate is far slower than that of the Haber-Bosch process. In May of 2018 researchers at the University of Central Florida published their findings that the addition of palladium hydride as a catalyst decreases the electrical energy needed to yield the same amount of NH3 (University of Central Florida, 2018). NH3 production rates by the electrochemical method may be increased to be comparable to the natural gas method for NH3 production. The electrochemical method does not require the extreme temperatures and pressures necessary in the Haber-Bosch process and can be carried out at room temperature (University of Central Florida, 2018). This new electrochemical process using fuel cells is far more efficient and produces substantially less carbon emissions.

3. Methodology

3.1 Ideal Otto cycle:

The figure below depicts the ideal Otto cycle on a Pressure vs Volume plot (Figure 6). State 1→ 2 is the compression stroke for which we assumed adiabatic compression for an ideal cycle. State 2→ 3 is the combustion of the air-fuel mixture when the piston is at top dead center. For an ideal Otto cycle, we assume that combustion takes place instantaneously for this reason the Otto cycle is also known as combustion at constant volume. State 3→ 4 is the power stroke for which we also assumed ideal compression. State 4→ 5 is when the exhaust valve opens and the piston is at bottom dead center. In the ideal cycle the gas is exhausted instantaneously, this means the pressure and volume at state 5 is the same as state 1. State 5→ 6 and 6→ 1 is the exhaust and intake strokes respectively.

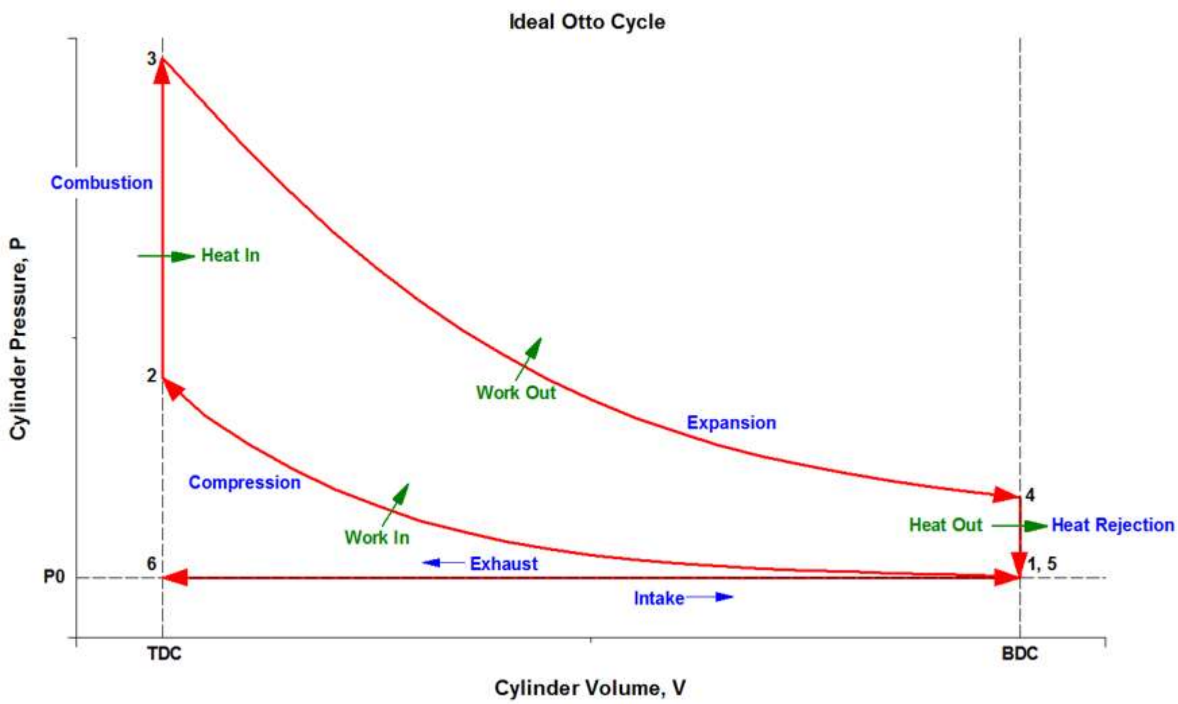

Figure 6. Ideal Otto Cycle

Our first assumption in this process was to assume ideal gas. We also calculated the pressure and temperature of state 1 at atmospheric pressure and room temperature. This is not correct for our final design because the intake pressure is above atmospheric but it is a fair starting assumption for a naturally aspirated engine. We explain this more in section 3.4. We needed to find the pressure and temperature at state 2 in order to use the Chemical Equilibrium with Applications program from NASA to find the exhaust products (NASA, 2001). The volume change from state 1→ 2 would give us the density ratio, and assuming adiabatic we could get the pressure ratio. The theoretical ideal power could be calculated if we had the pressure at state 3 and 4. We could have estimated this by using the heat input from the fuel, but we wanted to finish our prototype to get the actual power first and then compare to get the efficiency of the engine. To calculate the exhaust products, compression ratio, and power of our ammonia fueled engine, we first needed to calculate the properties of state 1, 2, 3, and 4 in the Otto cycle and below are our calculations for states one and two.

State One:

Volume (V1) = *Volume of combustion chamber at bottom dead center*

Pressure (P1) = 101,325 Pa *We assume that the pressure in the cylinder is at atmospheric*

Temperature (T1) = 291.15 K *We assume that the gas is at room temperature with air properties*

State Two:

We know the volume at state 2 after compression is the clearance volume once the piston is at top dead center.

Volume (V2) = *Volume of combustion chamber at top dead center*

We do not know what the pressure or temperature are after compression. These values need to be calculated and assuming adiabatic compression we have the following formulas:

Ideal Gas Law: PV=nRT

γ = CPCV PV=Constant=K W=K(V21-γ-V11-γ)1-γ

Variables

W=Work P=Pressure V=Volume R=Universal Gas Constant T=Temperature n=number of moles Cp=Specific Heat Constant Pressure CV=Specific Heat Constant Volume

From lookup:

CP=29.13kj/kmol*K

CV=20.77kj/kmol*K

γ = CPCV =1.4025

Calculate K:

K=P1V1=0.9257Nm

Find P2 using above formula on state two:

P2=KV2=1,250,479Pa

Find T2 using ideal gas law:

T2 = P2*V2*n*R=598.86K

Calculate the work of this process:

W = K(V21-γ-V11-γ)1-γ=-67.91J

From these calculations we found that the work required during the compression stroke is just less than 68 joules. We can subtract this from the work output during the combustion stroke to find the net work of our engine for each completion of all four strokes. We also found the pressure at state 2 and the temperature which allowed us to use these properties to find the exhaust products.

3.2 Exhaust Products

To calculate the exhaust products of our combustion we used a program developed by NASA called Chemical Equilibrium with Applications (CEA). This program was developed to calculate many thermodynamic properties, including combustion products, of most usable fuels and oxidizers in a combustion reaction (NASA, 2001). From our calculation of state two properties, we could use the pressure and temperature in the CEA program. We assumed a stoichiometric mix of ammonia to air in CEA. The assumption of a known temperature and pressure was not entirely correct. Residual gas in the combustion chamber would add heat to the incoming gas and change the pressure. Also, the temperature of the engine would add heat to the incoming air increasing the temperature of the gas pre combustion. We knew that the combustion process for ammonia would be slow compared to gasoline and that the pressure and temperature would increase throughout the combustion process. For our purposes, we wanted to get an idea of the exhaust products, we decided the level of error that would come with this assumption was acceptable. We found that the most prominent exhaust products are water (H2O) at 22.4% by weight and nitrogen gas (N2) at 76.5% by weight. Trace amounts of argon and CO2 were also displayed but are carried through from the intake air (NASA, 2001). These results were as we expected from simple chemical equilibrium calculations. It makes sense that we would not get more rare products such as nitrogen oxide, as we were worried about, because the pressure and temperature within the combustion chamber are not high enough to form higher energy compounds.

3.3 Acquiring Engines and Motoring Test

The first thing we had to do with the end goal of running an engine with ammonia was to get an engine to be able to run it. To do this, we sent a message to the WPI potpourri asking for engine donations, regardless if they work or not. We picked up eight engines mostly from four stroke lawn mowers and snow blowers. Next, we started going through all the engines, cleaning them and seeing if they work. We decided on using the engine from a snowblower because it is a four stroke and has an electric start. We opened the engine up and cleaned the cylinder and all the housing with degreaser and noticed the gasket was starting to fall apart. To fix this, we opened the other engines and found another gasket that was similar size, so we shaped it to the proper size.

In order to know what RPM and air intake we were working with in the engine, we had to run a motoring test. Knowing this, we would know for a specific RPM, what the air intake is and what the volumetric airflow is. We bought an anemometer and tachometer for this test. An anemometer is a device used to measure wind velocity. A tachometer is a device that measures rotation speed. We attached a PVC pipe to the carburetor, then another one with a larger diameter to that pipe to put the anemometer in and read the air intake speed. For the tachometer, we put a piece of black reflective tape on the flywheel and another on the crankshaft to test it on two different backgrounds. Then as the engine was running, we used a scanner to detect how many times it saw the reflection per unit time.

Volumetric flow rate: Vdot=A*V

A = Cross sectional area of the pipe

V = Velocity of the fluid through the pipe

Mass flow rate: Mdot=AV*ρ

ρ = Density of fluid

Using the ideal gas law, we calculated the density of air

While doing these tests, the flow of air into the engine was too low for us to accurately pick up on the anemometer that we were using and without a load on engine maintaining a constant speed was very difficult. We wanted to use a large enough pipe that the impedance from the anemometer would be negligible. We recommend using a smaller diameter pipe to control the airflow and restrict it to moving through the blade of the anemometer. The graph of incoming air velocity would then have less noise with a long narrow pipe close to the diameter of the anemometer for a clearer reading. We recommend attaching the crankshaft to a centrifugal pump and a tank of water in order to put a load on the engine to reduce vibrations and maintain a steady speed. The water pump will stabilize the engine and we could later use it as a dynamometer to measure the power output of the engine. Using the dynamometer, we can also plot charts for volumetric flow rates at different power outputs of the engine.

3.4 Unique Challenges

Using Ammonia as a fuel presented unique challenges and properties compared to a standard gasoline fuel. The three challenges that were the most important to our project were metering the air fuel ratio, compression, and safety.

A naturally aspirated engine draws air at atmospheric pressure into the combustion chamber during the intake stroke as discussed in section 2.2 The Carburetor. Using a needle valve and pressure regulator on our ammonia tank, we could dial in the air to ammonia ratio to about 22% fuel mole fraction (equivalent to an air fuel ratio of 6.06 by weight). This was our plan when we first started working on our project. We developed early carburetor designs that featured a venturi with an ammonia jet to mix the NH3 and air. Our computer model of this design can be seen below in Figure 7 and Figure 8.

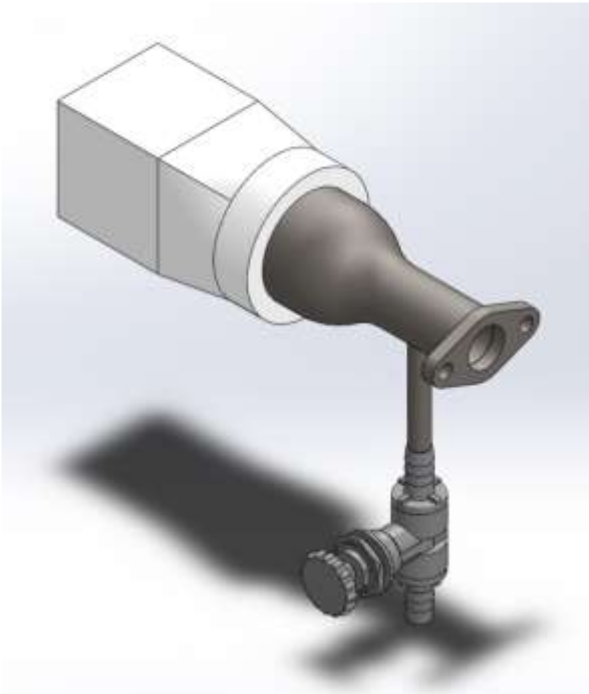

Figure 7. NH3 Carburetor Design

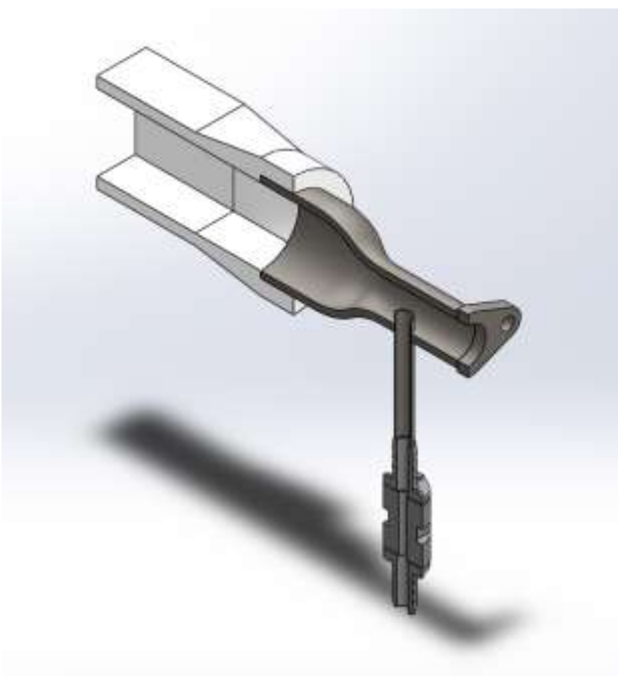

Figure 8. Carburetor section View

As the rpm of the engine increased or decreased we would need to be constantly adjusting the flow of ammonia to get a stoichiometric burn. We needed a device that could have a regulated air to ammonia ratio regardless of the rpm or the load on the engine was.

Ammonia has a high temperature of auto ignition of 930K (657C) and relatively slow reactivity characteristics. The energy it takes to ignite an ammonia mixture is about two orders of magnitude more than most hydrocarbons such as gasoline. This means that in an internal combustion engine, ammonia would need a higher compression ratio than standard gasoline. This is also reflected in ammonia's octane number, which is 120, compared to gasoline's, which can be between 80 and 93 for commercial gasoline and up to 100 for high lead racing and aviation fuels. The octane number refers to the amount of compression a fuel can take before detonating. The higher the octane number the larger the pressure ratio the fuel can take (Hofstrand, 2009). A higher octane number can be a good thing though because it means a higher internal temperature inside the chamber which results in a greater thermal efficiency and more power produced. The burning rate of an ammonia flame propagates four times slower than a methane mixture. This adds to the problem because this means that if the engine is running too fast, it is likely that we will not burn all of the ammonia. This makes our calculations on the Otto cycle (at the start of section 3) less accurate because we assumed an ideal instantaneous combustion from state two to three (Valera-Medina et al., 2018).

When working with a chemical such as ammonia we had to consider the safety precautions not only because of its flammability but because of its toxicity. Ammonia has been classified as a class 3 hazard to health by the National Fire Protection Association (NFPA). On this scale from 1 being "No hazard" to 4 being "Severe hazards" gasoline is a class 1 health hazard for comparison, see Figure 9 below (Valera-Medina et al., 2018).

Substance	Health	Flammability	Reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Gasoline	1	3	0
LPG	1	4	0
Natural Gas	1	4	0
Methanol	1	3	0

0=No hazard, 4=Severe hazards

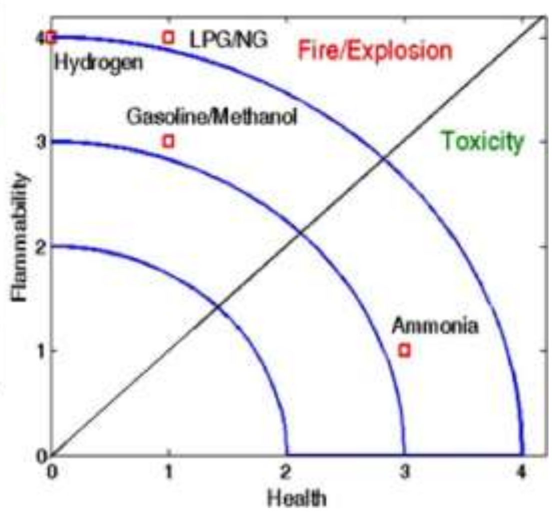

Figure 9. Health/Flammability/Reactivity comparison of various fuels. Received from NH3 fuel association. www.Nh3fuelassociation.org

Ammonia is not a large fire concern because it is lighter than air, so it disperses very quickly, and it does not combust easily. Because of the health risks, we needed to minimize any leaks of NH3 that could occur. The major area of concern for us was not unburned exhaust products, we knew this could be fixed with more refined mixing ratios and burn times. We were concerned with how the ammonia would be mixed with the air before entering the combustion chamber. With our carburetor design in Figure 7 the potential for leaking ammonia was very high. The ammonia would have a steady flow into the carburetor, but it would only be pulled into the engine during every intake stroke. We considered using a one-way valve system to prevent any backflow out of the carburetor. Any system that we would implement would impede the flow of air into the combustion chamber and would need to have fast reaction speed and high cyclic loading lifetime. For example, at an engine speed of 1000rpm there would be 500 intake strokes every minute. This would mean that a one-way valve would need to open and close over eight times every second. At this speed we would have a large air flow impedance if the valve were to be strong enough to function at such high speeds and we would inherently have leakage as the valve closes.

3.5 Supercharger Solution

A positive displacement pump pushes a fixed volume of fluid into a system with every rotation. This provides an interesting opportunity to use such a device to meter fuel. There are many different types of positive displacement pumps, including the roots pump type shown in Figure 10 below.

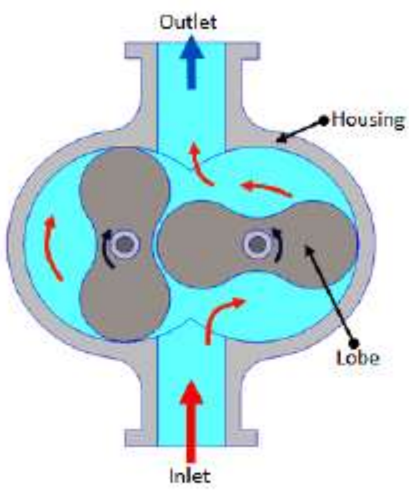

Figure 10. Positive Displacement Pump Diagram (Classification of Hydraulic Pumps. 2017. https://cat-engines.blogspot.com/2017/10/classification-of-hydraulic-pumps.html)

Each lobe is geared together to turn at the same rate forcing a fixed volume of fluid through the outlet. A non-positive displacement pump uses a propeller to push liquid through an outlet. The pressure of the outlet highly impacts the flow rate of the fluid and when these pumps are not running the system is not closed. This means that when the pump is not turning the fluid can still flow through the pump (Classification of Hydraulic Pumps, 2017). We figured we could use a roots pump to regulate the air to fuel ratio and keep the ratio constant across all speeds and loads of the engine. Our idea was to design a dual housing pump that had a separate pump for air and ammonia and mixed the two together in a reservoir after the pump's output. The air pump and the ammonia pump would be geared together so they would always turn at the same speed as each other. We could “trim” the air to fuel ratio using the pressure regulator on the ammonia tank. Increasing the pressure would increase the ratio of fuel to air and vice versa. This was our solution to keeping the fuel to air ratio consistent across all speeds and loads the engine would encounter.

The added pressure produced by the super charger (also called boost) adds more initial energy to the ammonia mixture before it reaches the combustion chamber. This reduces the work that the compression stroke needs to exert on the mixture in order to add enough energy into the mixture to ignite it with a spark. The other benefit of pressurizing the intake mixture is the amount of chemical potential energy in each cycle is higher than if the engine were to be naturally aspirated. We wanted to be able to run the engine at low RPM because of the flame propagation time of ammonia. We know that it would take longer to burn the entire mixture than it takes for a regular hydrocarbon to burn and without using a very large engine that we could run at low rpm and still have a decent power output, using a super charger allows us to get a longer combustion stroke time without having to sacrifice too much power by running the engine slower.

Utilizing a positive displacement pump reduced the chance of leakages and increased the safety of our project. There is no uninhibited path for the ammonia to flow out of the system and leak. In fact, if we were able to machine our parts with exact dimensional accuracy there would be no openings for the ammonia to leak out of. Because we needed to factor in clearances and tolerancing into our design, inevitably there would be opportunities for trace amounts of ammonia to escape. To reduce this risk even further, we decided that because we were using a positive displacement pump and we were pumping a gas and not a liquid, there was no need to have the pressure regulator for the ammonia higher than atmospheric pressure. We designed our lobes so that the intake of the ammonia pump could be regulated at just over 0.6 absolute atmospheric pressure. The roots blower would have to overcome a larger pressure difference to pump in the ammonia but this way ensured that any leakages would first be pulled back to the NH3 pump intake. This makes the design redundantly safe because if the supercharger inherently blocks any flow of ammonia out of the intake but also if any leakages were to occur the ammonia would flow to the zone of the least pressure which would be the intake to the ammonia side of the super charger. Also having a pressure below atmospheric ensures no flow of ammonia out of the pressure regulator until the engine and supercharger are starting to turn over and the pressure can drop.

3.6 Mass Flow Calculations

Before we started to machine anything, we needed to determine the size of the lobes for the roots pump. We already knew the shape of the lobes; this is discussed in the next section Computer Modeling. There were two main size considerations that we had to address. First, the size of the air lobes compared to the ammonia lobes must be able to output an air to fuel ratio of 6.06 while keeping the pressure of the ammonia inlet below atmospheric pressure. Secondly, the combined flow of the super charger must produce a boost higher than atmospheric but not so high that it is dangerous to contain or would cause the engine to knock. The high-octane rating indicates that the ammonia engine would operate better at higher compression ratios than a standard gasoline engine. But, because ammonia is an untested “new” fuel, it cannot be directly mapped with gasoline based on the octane rating to find the maximum compression before the engine would begin knocking. This made the second constraint difficult to quantify because the maximum compression, and therefore the boost from the supercharger, was uncertain. We had no data or studies to reference telling us at which point was too much pressure. We decided that below 15psi was acceptable because the materials we had for plumbing were not rated for pressures above 15psi. We knew future testing may find a more suitable pressure but these were the boundaries that we constrained our design with.

We started by calculating the ideal volumetric flow rate through the engine with every revolution of the crankshaft. We measured the diameter of the cylinder bore of our engine to be 2.785in with the total travel distance of the piston to be 1.94in. The total volume of gas that is sucked into the engine was then a calculation of PI()*(2.785/2)^2)*1.938 which gives 11.08 cubic inches. The engine is a four stroke, so in reality this volume is only being displaced every two rotations of the crankshaft. The ideal volumetric flow rate of the engine is therefore 5.9 cubic inches per revolution.

We designed multiple configurations of the lobes with varying thicknesses and diameters. Using Solidworks we could model the negative space of each lobe, where the fluid would be constrained. From these negative space models, we had the volume of every concave feature of each lobe, Figure 11 below.

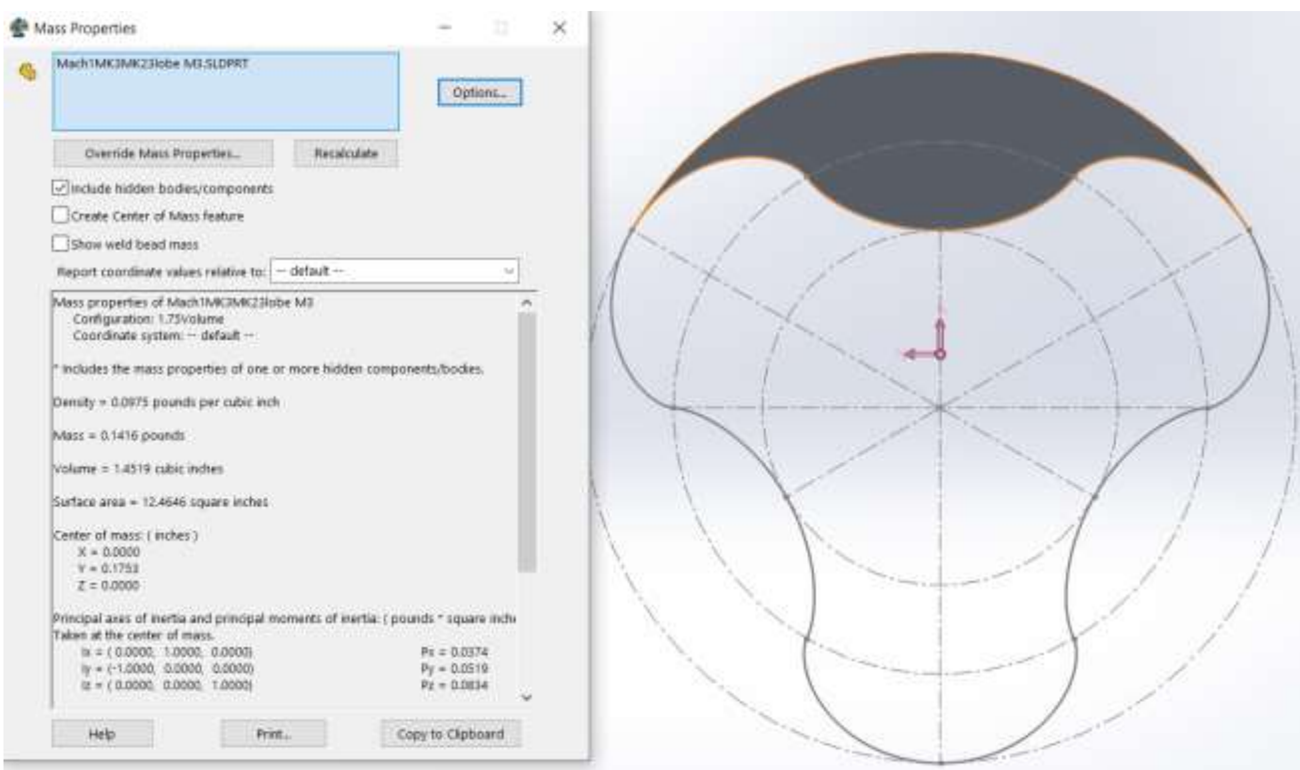

Figure 11. Negative Space Model

For every revolution of the crank shaft each lobe made a full rotation. Each pump has two lobes and each lobe has 3 concave features. We calculated the volumetric flow rates per revolution of each of our designs. Then using the density of air and ammonia at 1atm we calculated the mass flow rates and the air to fuel ratio of each NH3 configuration with each air configuration until we found one slightly above 6%. The design we settled on had a 9.45% NH3 by weight. We knew that if we chose a design that had a high air to fuel ratio then the actual pressure of the ammonia intake would be below atmospheric pressure. We could then calculate the actual pressure of the ammonia intake by setting the mass percent to 6.06. We found the pressure needed for the ammonia intake side to be .62atm absolute (.626bar absolute pressure). Lastly, we needed to check the scale of our model to ensure the boost pressure was in between zero and 15psig. To do this, because all the gas in our calculation is at atmospheric pressure other than the ammonia intake, we could compare their volumetric flow rates and adjust the ammonia pressure to accommodate this. We found that we would ideally have 11.7 pounds per square inch of boost pressure. Our equation is below.

*Boost = ((NH3 Volumetric Flow Rate) * (Pressure of NH3 Intake) + (Air Volumetric Flow Rate)) / (Volumetric Flow Rate of Combustion Chamber)*

Boost = (1.7274*0.618+9.5466)/(5.903)-1=.0798atm

3.7 Computer Modeling

Our team started modeling the lobes of the roots pump first because everything else was dependent on the sizing of the lobes. To make the profile of the lobes we used an equation driven curve. We used an epicycloid function to model the outer curvature of the lobes and a hypocycloid function to model the interior concave curves. The curves are called out in Figure 12 below.

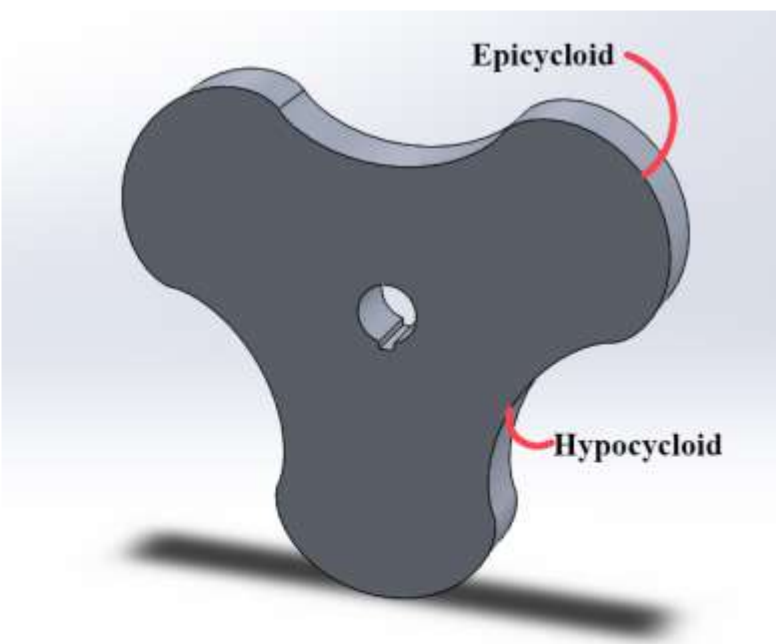

Figure 12. Lobe Function Diagram

When the two lobes spin the profile of the curves must have a hypocycloid curve in contact with the opposing lobes epicycloid curve. Using these functions for the curvature of each opposing curve ensures that there is always one point of contact between the lobes as they rotate. The lobes were finalized to work with pre-made gears. We did not have the resources to make custom gears so we matched our designs with existing products so they would mesh correctly. We chose gears that had a diametral pitch close to the diametral pitch of our lobes and then we changed the size of the lobes to match the gears correctly.

Once the lobes were finalized then we progressed to concurrently design the housing of the supercharger, the air and ammonia pump lids, and the axles. The housing of the super charger could have been done in one of two ways. Our first consideration was to make two completely separate pumps, one for air and one for the ammonia. At first this made sense because we needed the pumps to be separate for the purposes of flow regulation and it would be simpler than trying to design and machine a housing with two separate pumps in it. Our second consideration was to make a single housing that had the air roots pump on one side and the ammonia pump on the other. We decided that our second design consideration (which we refer to as the dual housing design) was our optimal design. Our dual housing had one shared axel between both sides which mechanically was a simple solution to ensure that both pumps rotated at a constant speed to one another. The main body of the dual housing was quick to design because we had all the dimensions from our lobes that we needed to adhere to. We included a clearance of five thousandths of an inch between the radius of the lobes and the inner radius of the housing. The clearance from the face of the housing to the face of the lobes was two thousandths of an inch. We knew that to have small clearances of about two thousandths, we needed to ensure that our parts were machined carefully to keep the faces of the lobes and housings as flat as we could manufacture them to be. This was a manufacturing constraint that we felt like we could achieve. Our dual housing design is shown below in Figure 13 of the ammonia side and Figure 14 of the air side. Figure 15 shows the dual housing with the lobes in place.

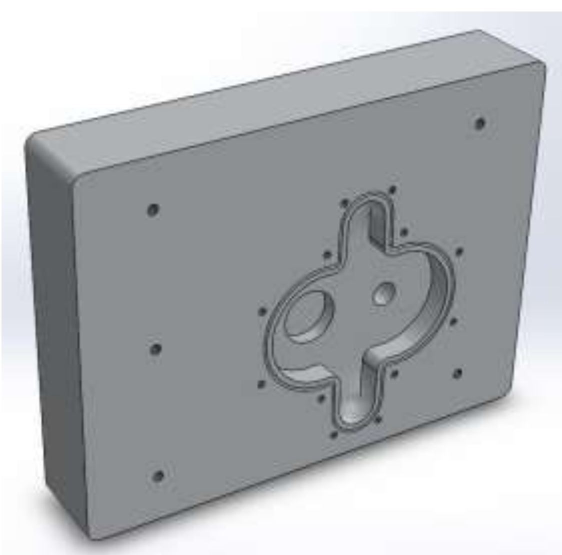

Figure 13. Dual Housing (Ammonia Side)

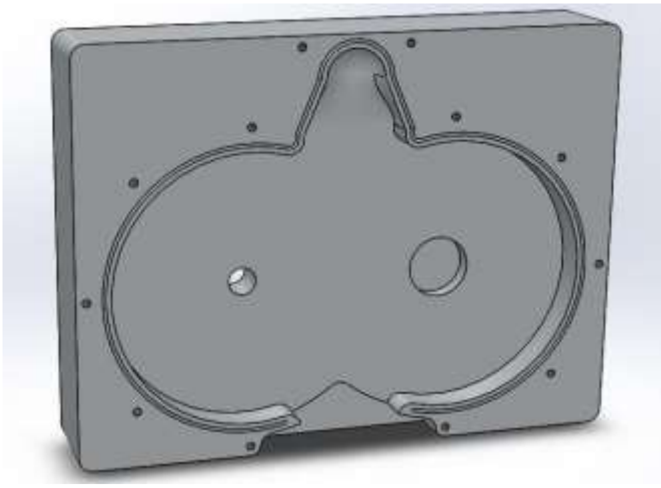

Figure 14. Dual Housing (Air Side)

Figure 15. Dual Housing (Air Side with Lobes)

We originally designed the dual housing with a quarter inch thick outer profile following the contours of the inner pockets. We decided to leave our design with a rectangular profile of the stock to simplify the machining process and to adhere to our tight inner tolerances. With a curved outer profile, we would have needed to make soft jaws in order to hold it in place while machining the inner pockets. This would be more work, and it would not let us grip our stock as well as if we had one flat surface to grip in the vice. We decided it was more important to have the interior operations as precise as possible rather than profiling the outer contours which is why our design is so bulky.

Both of the lids were designed in very much similar ways, to match the contours of the pocket they were encasing. We used number 10 counterbore clearance holes aligned with the tapped holes on the housing to secure the lids in place. A gasket within the groove of the housing, prevented leakage between the lids and the housing. We decided not to use locating pins in our design because it was more important that the lids be aligned with the axles rather than the housing. Each lid has two pocket features to hold the bearings below the inner face of the lid so the bearings do not interfere with the pump's operation. For the ammonia lid, both the input and output ends of the lid have half inch NPT tapped holes to fit half inch PVC pipe connectors for the plumbing system. The air lid has a three-quarter inch NPT tapped hole to fit a respective PVC pipe connector on the outlet. Figure 16 and Figure 17 depict the front view of the ammonia lid and the back view respectively.

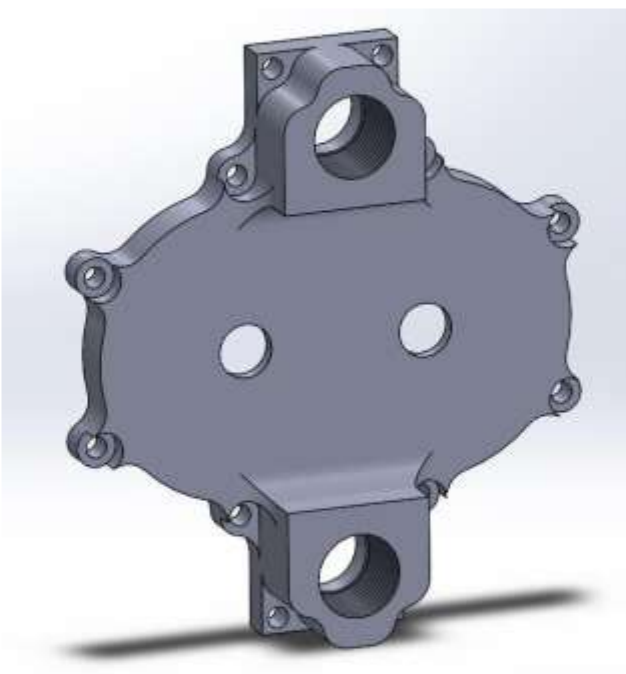

Figure 16. Ammonia Lid (Front)

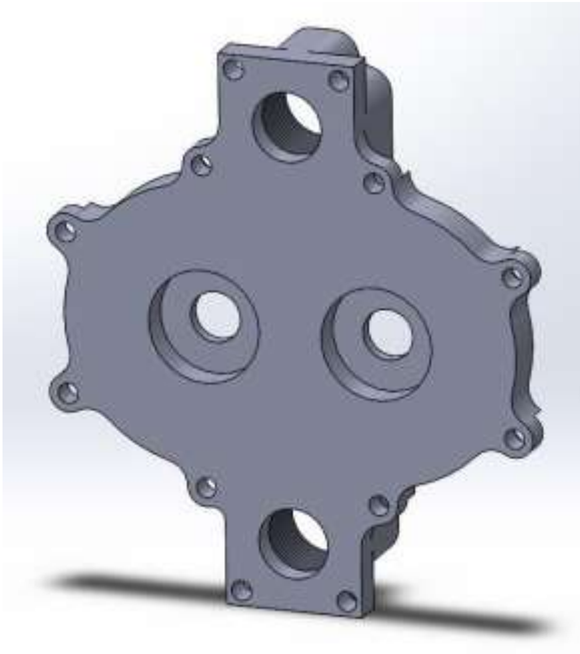

Figure 17. Ammonia Lid (Back)

Lastly, we designed the plumbing system to mix the air and fuel, provide a buffer, and deliver it to the intake of the engine. In our solid model we choose to use a half inch and three quarter inch inner diameter tubing to connect the ammonia and air outputs from the supercharger to the reservoir. The air and ammonia stay separate until they enter the reservoir which is a three-inch inner diameter PVC section of pipe that is eight inches in height. This reservoir allows the super charger to have an enclosed volume to continuously pump in the air fuel mixture. The engine only has one intake stroke for every two rotations of the crankshaft. Without a large reservoir we would have large pressure spikes between each intake stroke. The reservoir acts as a buffer and maintains a boost pressure of just over 11psi.

We used 80/20 aluminum extrusions for the framing of our project to hold the engine and supercharger in place. We used quarter twenty screws with angle brackets to secure the framing. The ammonia side of the dual housing has five tapped quarter twenty holes to fix the charger to the framing. We modeled the entire framing, supercharger, plumbing, and all the fasteners in Solidworks. We used a public model of a similar single cylinder engine in our final assembly, free for public use and modification, as a placeholder for our engine. This model is smaller than our real engine but we included it as a reference for how the real engine would be positioned. Figure 18 below is our final model assembly.

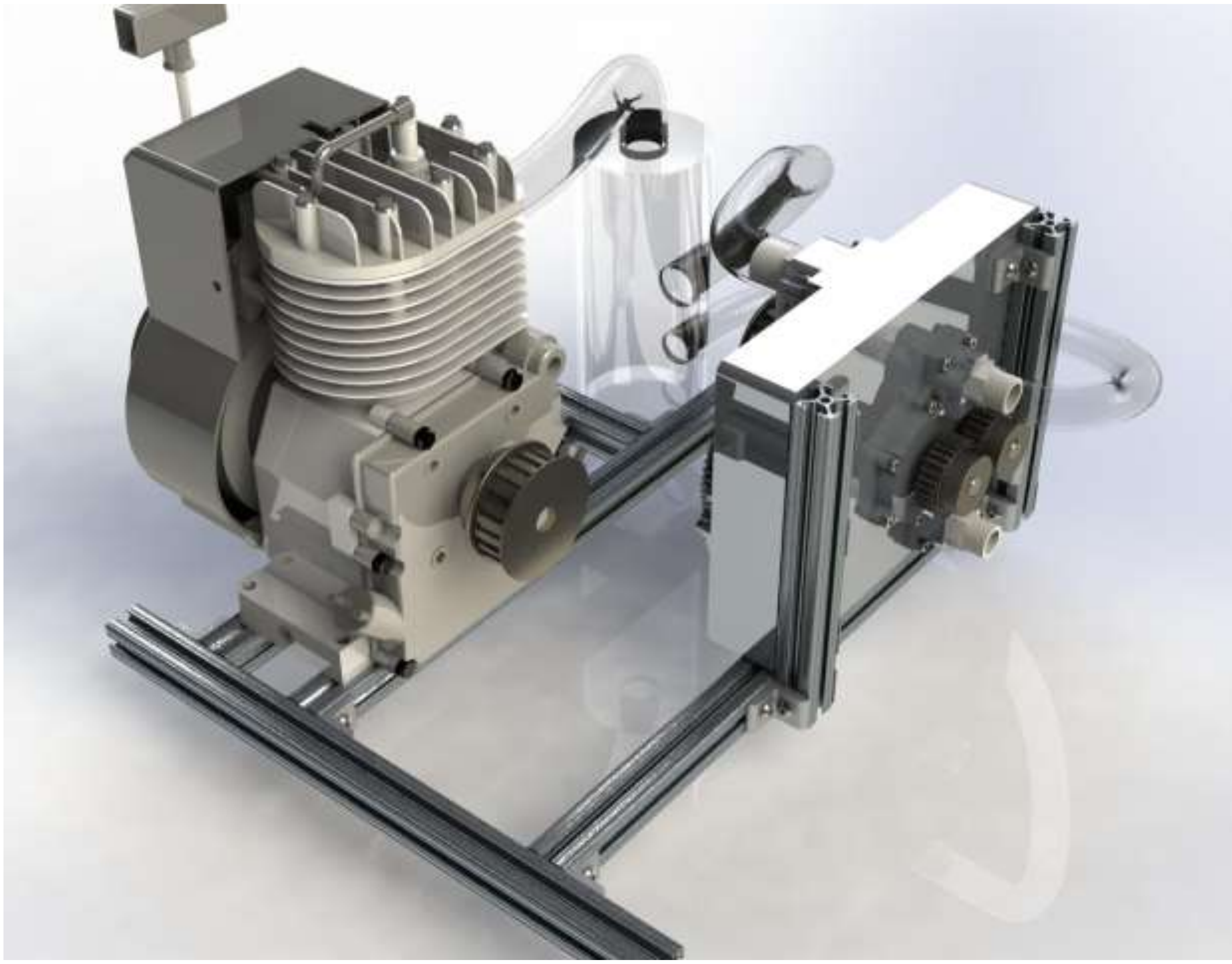

Figure 18. Final Model Assembly

3.8 Write code in esprit

Using the model that we created in SolidWorks we were able to create Computer Aided Manufacturing (CAM) code using the software Esprit. This software allows us to create code that will be uploaded to the Washburn shops CNC mills to machine precise parts. When deciding how to manufacture our supercharger design, we came to the conclusion to mill most of our pieces. For our supercharger housing, we decided to break the design into three separate pieces. The first of these pieces is an inner housing block that will hold two sets of lobes on each side. This would be made from 6061 aluminum bar stock. The operations to manufacture this part would be a facing operation on each side of the stock in order to get a piece to a dimension within the tolerance of our design. This would be done with a rough pass of a 1/2'" end mill followed by a finish pass of a 3" square insert face mill. The next step would be pocketing operations for the housing of each set of lobes, as well as pocketing operations for the gas outlet and bearing housings. These pockets would be made using 3/8" endmills. The next two pieces were the NH3 and air lids. These would be milled down on HAAS minimills as well. The materials to assemble the supercharger housing were to be acquired from Yarde Metals.

3.9 Manufacturing

Before manufacturing the lobes, we searched the scrap pile in Washburn and talked to the lab monitors to see if there was any aluminum that would fit our size requirements in order to save money. We were able to find scrap stock that was big enough, all we had to do was use an endmill to trim the piece to the correct thickness, cut two holes for the wire EDM to go through in each lobe. Lastly, we faced the block to make it smooth. We followed the same procedure for both the air lobes and ammonia lobes within the supercharger.

When deciding the process that we would use to make the lobes we had many options of manufacture to choose from. However, many of these options had limitations in respect to our design. Due to the nature of a roots blower, the supercharger lobes cannot make contact with each other while in use. To ensure that the lobes avoid contact with each other, their alignment was a key factor to take into consideration when deciding the method of manufacture. In order to have proper alignment in the supercharger housing, the lobes would have to be keyed in precise locations. Initially, the leading method of machining the lobes was with a HAAS Minimill in Washburn Shops. However, due to the need for precise keyway locations on the lobes, we would need to be able to machine all features of the lobes in one operation, something that is not possible to do on a HAAS Minimill. Instead, making the lobes for the supercharger was done using wire electrical discharge machining (EDM). Electrical discharge machining uses the discharge between two electrodes to cut into a metal workpiece. In our process of making the lobes for the supercharger, we used the EDM machine located in Washburn shops. Manufacturing the lobes using this process was crucial due to the fact that both internal and external machining operations could be completed without having to reset the stock location in a vice, this allowed for a precise placement of the keyways in the lobes to ensure the lobes can function properly. The air and ammonia lobes can be seen in Figure 19 below.

Figure 19. Manufactured Air (right) and Ammonia (left) Lobes

4. Results

Due to Covid-19 complications our team was not able to finish manufacturing the super charger and run physical tests planned for D term. We printed a full scale model of the dual housing along with both lids to build a physical representation of the final product. Throughout this process from the data we gathered through research and our own calculations and testing, our design and ammonia powered internal combustion engines as a collective, shows promise for future work. We have left off this project at a place we are confident will be easily picked up and complete. The housing and lids need only to be machined to have a viable prototype for testing.

We were disappointed to not be able to carry this project to fruition. In our final term we had planned to: finish machining the dual housing and lids, mount the water pump and supercharger to the frame, test run on propane, and strain measured run on ammonia and gasoline. We planned on using a strain gauge on a torque arm to measure the strain in the shaft or alternatively using a gauge on the engine mount to find the reaction torque and using the strain to find the force on the piston head. The steps below are our equations which we planned to use to find the force on the piston head.

1. Obtain the strain value from strain gauge
2. Calculate the stress from: $\tau=E*\varepsilon$

ε = Strain

τ = Shear Stress

E = Elastic Modulus

3. Calculate the Moment from: $\tau=Tr/J$

T = Moment

r = Radius of crank shaft

J = Polar Moment of Inertia of Area

4. Calculate the Force on the Piston Head: $T= F*D$

F = Force on Piston Head

D = Length of connector rod

(TDC-BDC)/2 = 1.938/2= .969 in = D

At the end of the project, the final test to prove the worth of the engine aside from the zero carbon emissions is that the engine is able to successfully run consistently with ammonia as the fuel source at a comparable power. Not only was it important to have the engine run and maintain stable combustion, the power of our engine needed to be comparable to running on gasoline. If our engine were successful at completing the first requirement of turning over and running consistently, we would attach a strain gauge to the engine mount and calculate the force output on the piston head. We would then reattach the carburetor and run the same test, but using gasoline and compare the forces to the ammonia fuel forces.

4.1 Future Recommendations

Our planned next steps to complete the project in D term include finishing the esprit code for the housing of the super charger and then machining it. Once the whole supercharger is complete, we would connect it to the water pump with a dynamometer attached to it.

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