

MINIMUM FAVORABLE CONDITIONS FOR HYDROGEN-DIESEL COMBUSTION

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Minimum Favorable Conditions for Hydrogen-Diesel Combustion

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ABSTRACT

A test apparatus was designed and fabricated that allowed very small amounts of diesel fuel to be injected into a hydrogen-air mixture. This apparatus was designed to be able to operate near the limits of diesel fuel injectors. The purpose of this apparatus is to find out if the injectors in diesel engines are capable of igniting a hydrogen-air mixture when operated at their limits and to explore past their limits for further advancement in the field of dual-fuel hydrogen-diesel combustion. The minimum flow rate of diesel fuel the apparatus could produce was $120.46 \frac{\text{cm}^3}{\text{min}}$ and the fastest response time that could be achieved was 1 ms . Both of these parameters at least met the limits of the current diesel injection setups. The smallest mass of diesel fuel that could be injected was 15.7 mg . This mass produced combustion in the hydrogen-air mixture for all hydrogen concentrations and temperatures tested.

TABLE OF CONTENTS

ABSTRACT	iii
LIST OF TABLES	vi
LIST OF FIGURES.....	vii
LIST OF ABBREVIATIONS.....	viii
LIST OF APPENDIX FIGURES	x
CHAPTER 1. INTRODUCTION	1
1.1. World Petroleum Overview	1
1.2. Global Warming.....	3
1.3. Emission Regulations.....	5
1.4. How Hydrogen Fuel Can be the Solution.....	7
CHAPTER 2. LITERATURE REVIEW	12
2.1. Problem Statement and Objectives	12
2.1.1. Theoretical Minimum Diesel Quantity	12
2.1.2. Theoretical Air/Fuel Ratio to Reach Hydrogen Autoignition Temperature.....	13
2.2. Dual Fuel Engine Research	15
2.2.1. Compressed Natural Gas.....	16
2.2.2. Adding Small Amounts of Hydrogen	17
2.2.3. Adding Large Amounts of Hydrogen	19
2.3. Experimental Work Done at NDSU to Maximize Hydrogen Energy Input	21
2.4. Injection Parameters of Industrial Injectors.....	23
CHAPTER 3. RESEARCH APPROACH.....	24
3.1. Experimental Setup.....	24
3.2. Experimental Design	32
3.3. Experimental Procedure.....	33
CHAPTER 4. RESULTS	35
4.1. Mass Equation Validation.....	35
4.2. Mass Injected	36

CHAPTER 5. CONCLUSION	38
5.1. Conclusions and Impacts	38
5.2. Summary	39
5.3. Future Work.....	40
REFERENCES.....	42
APPENDIX. TEST APPARATUS PICTURES.....	47

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Hydrogen and Diesel Physical Property Comparison [32][33].....	10
2. Enthalpy of Formation for Combustion Elements	13
3. Combustion Testing Results	36

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Long-term non-OPEC Crude and Natural Gas Liquid Supply (millions of barrels/day) [7].....	2
2. Global Petroleum Products Demand (millions of barrels per day) [7].....	3
3. United States GHG Emissions by Sector [22].....	7
4. Test Schematic	24
5. Injection Setup	27
6. Steady State Spray [in.]	28
7. 1 ms Injection Spray Profile [in.]	28
8. Dead Weight Pressure Calibration Tester	30
9. 1 ms Pressure Curve.....	35

LIST OF ABBREVIATIONS

a	Speed of Sound
A	Injector Orifice Cross-Sectional Area
ACERT	Advanced Combustion Emission Reduction Technology
BTE	Brake Thermal Efficiency
C_d	Discharge Coefficient
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CH_4	Methane
d_{nh}	Nozzle Orifice Diameter
ΔP	Pressure Difference Across Injector
ECM	Electronic Control Module
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FCV	Fuel Cell Vehicles
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
Hp	Horsepower
IC	Internal Combustion
LHV	Lower Heating Value
\dot{m}	Mass Flow Rate
N_2	Nitrogen
NDSU	North Dakota State University
NHTSA	National Highway Traffic Safety Administration
NO_x	Nitrous Oxides
O_2	Oxygen
OPEC	Organization of the Petroleum Exporting Countries

PM.....Particulate Matter
 P_{bits}Pressure in Units Bits
 P_{inj}Injector Pressure
 P_{psi}Pressure in Units Psi
 P_vVapor Pressure
 r_{nh}Nozzle Fillet Radius
 ρFuel Density
SCR.....Selective Catalytic Reduction
SEC.....Specific Energy Consumption
 SO_2Sulfur Dioxide
TDC.....Top Dead Center

LIST OF APPENDIX FIGURES

<u>Figure</u>	<u>Page</u>
1. Motor and Gear Coupled.....	47
2. Motor Controller	47
3. Injection Setup	48
4. Combustion Chamber Inlets.....	48
5. Combustion Chamber	49
6. Sapphire Window	50
7. Sapphire Window Close Up	51
8. Hydrogen Inlet Setup	51
9. Air Inlet Setup.....	52

CHAPTER 1. INTRODUCTION

Never before, in human history, has the need for “clean” renewable fuels and energy sources been greater than today. While the nonrenewable fossil fuel supply is ever depleting, the demand for fossil fuels is at an all-time high and increasing. The human population is continually growing, increasing the power demand, and thus, the demand for more energy production and energy sources. The excessive burning of these fossil fuels is causing an increase in global temperatures due to the greenhouse gas (GHG) emissions produced during their combustion [1]. Because of this, more destructive weather has occurred in recent years, as well as a rise in the number of endangered and extinct animal and plant species [2]. The effects of the GHGs in the atmosphere are essentially irreversible and, if no changes are made, will continue to get worse [3]. In addition to the GHGs produced, the burning of fossil fuels can produce emissions that create acid rain and smog, both of which have negative health effects in humans, animals and plants [4]. The problem now, however, is almost universally recognized and governments are releasing more stringent regulations that limit emissions and are providing incentives towards the study and development of new, “clean,” renewable energy production. The research in this paper looks to help solve these problems by contributing to the knowledge of using hydrogen as a “clean” energy source.

1.1. World Petroleum Overview

Petroleum, also referred to as crude oil, is formed when organic materials, typically algae and other plants, are buried beneath the earth and undergo millions of years of high pressure and temperature conditions. Coal and natural gas are also formed in a similar way. Fuels such as gasoline, diesel, butane, kerosene, and jet fuel are all products of petroleum [5]. The immense time it takes for petroleum to be created classifies it as a non-renewable resource. This limited resource has been extensively extracted from the earth for many years but will soon run out [6]. In fact, the “peak oil,” or the time when oil production is at its highest, is expected to come within the next 30 years [7]. Once this occurs, oil production will begin declining and continue until the oil is gone or too costly to acquire. The world will then be forced to use other forms of power.

The latest World Petroleum Outlook report published by the Organization of the Petroleum Exporting Countries (OPEC) shows the projections of petroleum supply to reach its peak, for most countries, around the year 2025. Figure 1 shows the current and projected oil supply for various regions and countries. While the supplies in Russia and Eurasia are projected to still be increasing at the end of the projections (2040), all other regions and countries will have begun to see a decrease in petroleum supply [7]. While these are only projections, the consensus among industry leaders and experts is that the peak oil production will occur before the year 2030, and possibly even before 2020 [8]. It is important to remember, however, that oil production does not stop when peak oil occurs, but only begins to decline. The years and decades following the peak oil year will still produce petroleum. However, the rate of production will continue to decrease, which is likely to raise the prices of petroleum and therefore the products of petroleum. This will lead to an economic demand for other energy sources.

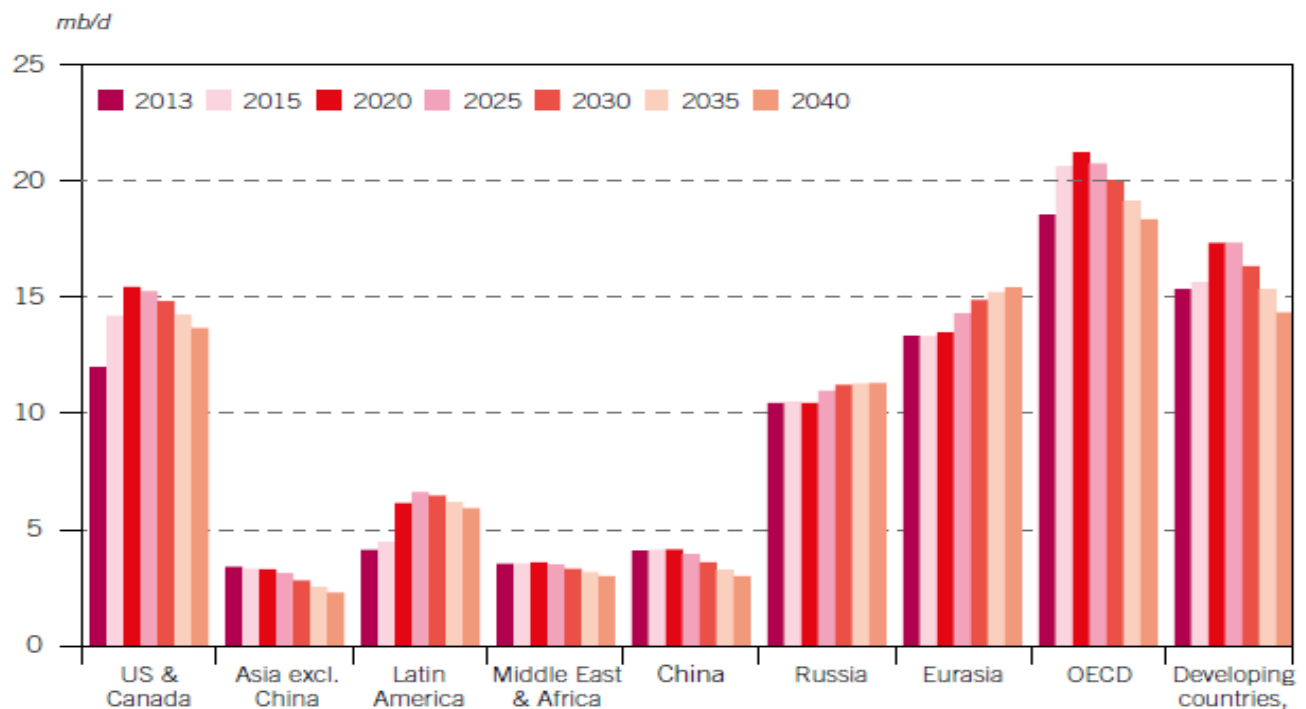


Figure 1. Long-term non-OPEC Crude and Natural Gas Liquid Supply (millions of barrels/day) [7]

While the supply is expected to begin decreasing within the next few decades, the demand for petroleum is supposed to continue to increase. Just as the global population is increasing, and is projected to continue increasing, the demand for energy, and thus petroleum will continue to rise [9]. The projected demand for the various petroleum products is shown below in Figure 2. The most noticeable

increase is in the demand for diesel fuel (up nearly 25%); however, the demand for nearly all petroleum products is expected to increase [7].

Figure 2 shows that the majority of the petroleum is used to produce gasoline and diesel fuel. Gasoline is almost solely used for transportation purposes, while approximately 60% of all diesel use is in transportation [7]. Furthermore, 79% of all petroleum consumption in transportation is by vehicles with internal combustion (IC) engines. While the percentage of gasoline usage in IC engines is projected to decrease, diesel usage is projected to increase [10]. Not only is the demand of fuel for IC engine use great, but it is also one area that can be significantly improved upon, as IC engine vehicles have efficiencies in the range of 25 – 50% (depending on the type of engine).

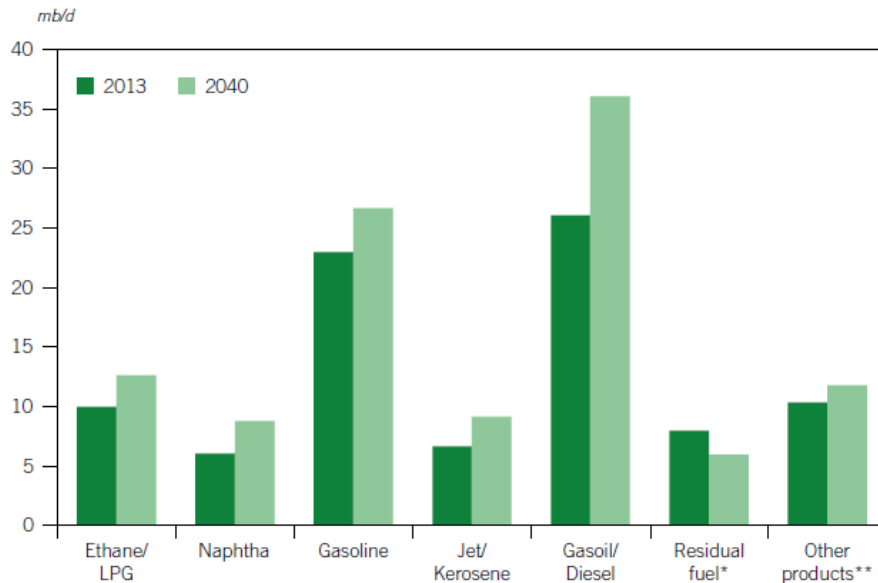


Figure 2. Global Petroleum Products Demand (millions of barrels per day) [7]

1.2. Global Warming

Global warming is quite possibly the greatest single threat to planet Earth. Global warming is the unnatural heating of the Earth's average surface temperature [11]. While it has been proven that the Earth does experience a natural cycle of warming and cooling, 97% of climate scientists agree that the global warming that has been observed over the last century is being caused by humans. Global warming is caused by an enhanced greenhouse effect. The increased amount of GHGs being released into the atmosphere, primarily due to the burning of fossil fuels, is the cause of this enhanced greenhouse

effect [12]. The effects of global warming are already being seen in the form of extreme weather and the extinction and endangerment of animal and plant species [13].

The greenhouse effect is a naturally occurring phenomenon in the Earth's atmosphere. In fact, the greenhouse effect is one of the reasons that Earth is able to sustain life. During the day, GHGs in the atmosphere absorb infrared radiation from the sun directly and from the Earth's surface reflecting back the sun's energy. During the night, the energy is emitted from the GHGs as heat, keeping the Earth at livable temperatures. It was not until the 1950s that the greenhouse effect began to be viewed as a problem. It was at this time that increasing global temperatures and climate change was attributed to an enhanced greenhouse effect [14]. The GHGs released into the atmosphere from the burning of fossil fuels caused more infrared radiation to be absorbed into the atmosphere and thus caused global temperatures to increase.

The largest greenhouse gas contributors include water vapor, carbon dioxide (CO_2) and methane (CH_4). Water vapor is the biggest contributor toward the greenhouse effect. It has the largest capacity to retain the heat from the sun; however, the residence time of water in the atmosphere is only about nine days. The amount of water vapor in the atmosphere is not significantly affected by human activity. Since the residence time is so short, water vapor only acts as an amplifier of the effects of the other greenhouse gases. CO_2 and CH_4 are both introduced into the atmosphere through human devices. Of these, CO_2 is the largest contributor to the enhanced greenhouse effect. While the atmosphere does not contain as much CO_2 as it does water vapor, CO_2 has a residence time of over a century and some stays in the atmosphere for thousands of years. Thus, CO_2 has a much more significant effect on the temperature of the Earth [15]. CH_4 is found in the atmosphere in fairly low quantities; however, due to the larger amount of atomic bonds it has, it can retain more infrared radiation than the other GHGs. Though it has a relatively moderate residence time of approximately 12 years in the atmosphere, in those 12 years methane has 72 times the radiative effect of the Earth than CO_2 does per unit mass. While CO_2 is currently the greatest GHG concern, both CO_2 and CH_4 need to be regulated in the near future to reduce the effects of global warming [15].

While some are still skeptical of global warming, evidence of the effects of global warming have been especially noticeable in recent years. The most direct evidence of global warming is the fact that 9

of the 10 warmest years ever recorded have occurred in the last 15 years. While this in itself is rather physically mild, much more severe weather phenomena have also been observed recently. 2012 saw the worst drought in 50 years in the Midwest region of the United States. The United States also experienced the loss of 9.2 million acres of land ravaged by wildfires. Conversely, in the same year, the U.S. also saw widespread flooding due to the record breaking storm surge caused by hurricane Sandy [16]. On a more global scale, the melting of ice caps and glaciers are resulting in rising seas. Storms are becoming more powerful and droughts more severe. Animal and plant life are also being affected. Due to the melting ice caps, polar bears and other animals must survive on a shortened hunting season. Warming of the world's seas is causing massive losses in coral life and plankton. Plankton loss is resulting in the deaths of many animals, as plankton is a primary food source for many animals [13]. Almost all ecosystems are feeling the effects of global warming. To prevent further damage, action must be taken.

1.3. Emission Regulations

Due to the global issues caused by fossil fuel emissions, world governments have begun to notice and take action. The United States, specifically, is taking significant steps to improve vehicle emissions and fuel economy. This, however, is not a new endeavor in America. In the 1970s and '80s acid rain, caused by sulfur dioxide (SO_2) and nitrous oxides (NO_x) emissions, had become a significant environmental issue [17]. Regulations on both the contributing emissions were accepted and enforced. Today acid rain has decreased by almost 60%, and the environment damaged by acid rain has even begun to recover in some locations [18]. More recently, strict regulations on NO_x and particulate matter (PM) emissions were put into effect. The 2007 Environmental Protection Agency (EPA) regulations called for a 90% reduction in NO_x and PM, which have been put into full effect in 2015 [19].

The newer emission regulations that the United State are putting into full effect in 2025 are focused on GHGs, primarily CO_2 . The emission restrictions are based on the size of the vehicle, which will mean that larger vehicles will be allowed to produce more CO_2 than smaller vehicles. The amount of CO_2 emissions produced must be decreased by 32 – 37% depending on the size of the vehicle. The CO_2 emission reduction for all vehicles will average out to be about 35% [20].

These reduction are not on the same scale as the NO_x and PM regulations. The reasoning behind this is because with petroleum based fuels (gasoline and diesel), there is a maximum amount of

CO_2 reduction available. The atomic structure of both gasoline and diesel is made up of hydrogen and carbon atoms. While the hydrogen atoms produce only water emissions, the carbon atoms produce CO_2 emissions. So as long as gasoline or diesel is the fuel, there is a set minimum of CO_2 that must be produced during the combustion process [21].

In coordination with the EPA, the National Highway Traffic Safety Administration (NHTSA) has produced additional standards regulating vehicle fuel economy. These standards require a fleet-wide average of approximately a 50% increase in fuel economy (of diesel or gasoline fuel). Quite simply, their reasoning is if less gasoline or diesel is used to produce an equivalent amount of power, less CO_2 will be produced. Additionally, better fuel economy will result in less fuel consumption and therefore monetary savings. In fact, these regulations are projected to reduce daily petroleum consumption by 2 million barrels per day, nationally, which will aid in the previously discussed problems of fuel supply and demand [20].

Harmful emissions are obviously not solely caused by vehicles. Transportation produces only about 27% of the total U.S. emissions [22]. While on-road vehicles do consist of 79% of the energy consumed in the transportation sector, they are but one of many areas that need to be improved upon in the future [10]. Figure 3 shows the division of GHG emissions produced in the United States by sector [22]. While each sector has its own regulations and restrictions, transportation has been the recent focus of the government, as well as the media.

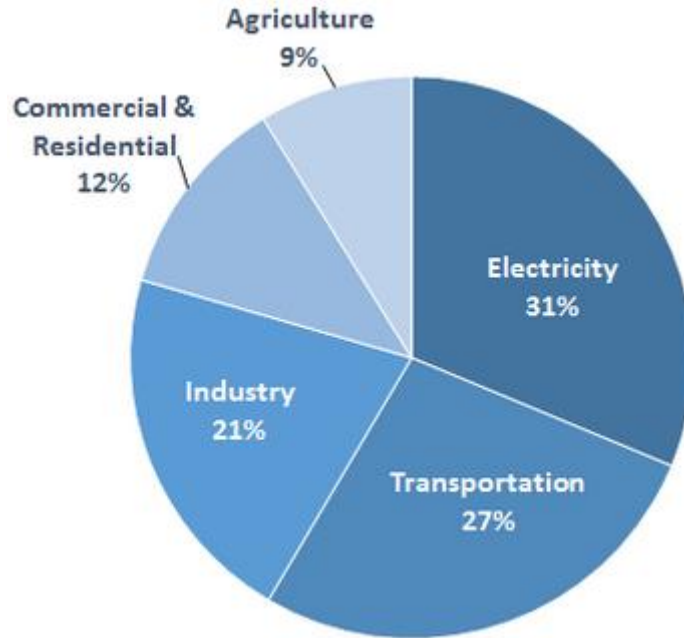


Figure 3. United States GHG Emissions by Sector [22]

The magnitude of the changes required for these regulations may force automakers to invest in research with alternative power sources. Hydrogen is one of the top candidates for effective alternative power. Hydrogen does not produce any CO_2 , as it does not have carbon atoms in its structure. Additionally, it has significantly reduced PM and hydrocarbon emissions. The main hydrocarbon emission is methane, which as discussed previously is a GHG. While it does produce NO_x , like other fuels, NO_x emissions can be controlled through methods such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). The only emission that properly controlled hydrogen combustion produces is water, which has virtually no negative impacts on the environment [23].

1.4. How Hydrogen Fuel Can be the Solution

Hydrogen is the most abundant element in the universe, accounting for an estimated 75% of all mass. While the majority of this mass is located in stars and gaseous planets, on Earth, hydrogen is the third most abundant element in the Earth's crust with respect to mass. On Earth, elemental hydrogen almost exclusively exists as a diatomic molecular gas; however, hydrogen gas is very uncommon in Earth's atmosphere (only one part per million). Hydrogen is most commonly found in compound molecules, primarily in water and organic material such as plants, petroleum, coal and natural gas.

Hydrogen is the lightest of all elements, containing only one proton and neutron per atom; thus, if found in Earth's atmosphere in its diatomic state, it will often escape from the atmosphere into space [24].

Hydrogen, herein synonymous with gaseous diatomic hydrogen, is one of the best candidates for solving the previously discussed issues of the future shortage of petroleum, global warming and vehicular emission regulations. Hydrogen, whether used to generate electricity from fuel cells or burned to produce mechanical energy, creates no carbon dioxide emissions. In fact, almost the only emission produced is water. Water, is also the primary carrier of hydrogen atoms on Earth. If hydrogen fuel were produced from water, it could be considered a renewable resource since water is the primary product of hydrogen energy consumption [24].

Hydrogen (H_2) contains no carbon atoms in its atomic structure, unlike all petroleum based fuels, and therefore is incapable of producing CO_2 emissions. The lack of GHG emissions makes hydrogen one of the most beneficial fuels available. In addition, since there are no carbon atoms, hydrocarbons and smoke cannot be produced either [24]. If the hydrogen is of high purity, other harmful emissions, such as sulfur oxides and lead can also be eliminated. Hydrogen combustion is capable of producing NO_x emissions, however. NO_x is formed at high temperatures, especially in oxygen rich environments, from the nitrogen in the air. The heat of combustion breaks the nitrogen bonds, which will then quickly combine with free oxygen atoms [25]. There are multiple ways to eliminate or reduce NO_x emissions in combustion processes. EGR introduces engine exhaust gas into the engines inlet air. This serves to decrease the combustion temperature reached in the cylinder by allowing more nonreactive molecules (nitrogen and CO_2) into the cylinder during combustion. The non-reactants absorb the heat of combustion but do not add to it, reducing the maximum temperature, thus decreasing the NO_x produced [26]. SCR is another method to reduce NO_x emissions. SCR involves the injection of a liquid-reduction agent (generally urea based) through a catalyst into the combustion exhaust. A chemical reaction occurs and the NO_x is broken up into diatomic nitrogen, water, and a small quantity of CO_2 . In addition to NO_x , SCR also reduces hydrocarbon and particulate matter emissions [27]. So, if properly managed, hydrogen combustion can be achieved with no harmful emissions, only producing water.

In vehicular applications, there are two primary method to using hydrogen as power. The first way is using fuel cells. Fuel cells force hydrogen and oxygen into a chemical reaction that, with the help

of an appropriate catalyst, produces electricity and water. The electricity is then used to power electric motors [28]. Fuel cells can achieve efficiencies up to 80%, depending on the catalysts, and combined with electric motors (which generally have greater than 90% efficiency), fuel cell vehicles (FCV) are a very efficient means of transport [29]. However, even though the cost of fuel cells has dropped by over 75% (per unit power), they still cost 85% more than traditional gasoline engines (per unit power) [28][29][30][31]. While significant progress is being made to get FCVs cost effective, it will still be many years until they are able to economically compete with traditional internal combustion engines.

The second method of using hydrogen as power, in vehicles, is with IC engines. While there are very few engines designed specifically for hydrogen combustion in vehicular applications, many IC engines are capable of undergoing hydrogen combustion. Current on-road IC engine vehicles can be retrofit, potentially relatively cheaply, to be able to use hydrogen either in dual-fuel mode with petroleum or as the sole fuel. Hydrogen, as it is a gas, can either flow into the cylinder with the inlet air or be injected with an injector. The hydrogen is either ignited by a spark plug for a gasoline engine or with injected diesel in a compression ignition engine. Diesel engines run on a constant pressure energy addition cycle. Conversely, gasoline engines run on a constant volume energy addition cycle, which is less efficient at extracting energy from the injected fuel. For this reason hydrogen combustion in diesel engines has a greater potential for high efficiencies than in gasoline engines. The method hydrogen powering IC engines is extremely attractive because all of the emission benefits of hydrogen can be seen without the high costs of fuel cells. Additionally, the established IC engine technology has been thoroughly tested and is more reliable and has a longer lifespan than fuel cell technology [31].

In addition to the superior emissions involved in hydrogen combustion, hydrogen has many other favorable qualities. The most notable physical attribute of hydrogen is its lower heating value (LHV). Hydrogen has a LHV of $52,217 \text{ Btu/lb}$, which is approaching 3 times the amount as diesel fuel. LHV is a measure of energy per unit mass, meaning hydrogen contains a potentially large amount of energy depending on the density it is contained at. Hydrogen also has a very large flammability range of 4 – 74% in air. This allows an engine to run hydrogen lean or rich depending on the amount of power needed. Finally hydrogen has a very low ignition energy of only $.017 \text{ mJ}$, meaning it is very easy to ignite. To better illustrate the scale of hydrogens various properties, Table 1 compares various physical property

values of hydrogen with diesel fuel [32][33]. The autoignition temperature of hydrogen is relatively high. This poses some problems, especially with compression ignition engines. Szwaja and Grab-Rogalinski numerically found that the minimum compression ratio that will ignite hydrogen is 17. While this is a realistic value for many compression ignition engines, in practice they could not produce reliable combustion at this compression ratio [34]. In practical applications it is fairly difficult to achieve consistent, evenly distributed autoignition of hydrogen through just compression. As mentioned previously, the hydrogen may be ignited with injected diesel, as the autoignition temperature of diesel is much lower than that of hydrogen. The diesel fuel will be ignited because of its autoignition temperature and, due to the low ignition energy of hydrogen, once the diesel is ignited, the hydrogen will also ignite.

Table 1. Hydrogen and Diesel Physical Property Comparison [32][33]

	Hydrogen	Diesel
Chemical Composition	H_2	$C_{12}H_{26}$
LHV (<i>BTU/lb</i>)	52,217	18,394
Flammability Range ($H_2/(H_2 + \text{Air})$) (% volume)	4.1-74.0	1.0-6.0
Energy Density (<i>BTU/ft³</i>)	184,100 (3000 psi, 60°F)	843,700
Autoignition Temperature (°C)	500	315
Minimum Ignition Energy (<i>mJ</i>)	.017	.23
Flame Speed (<i>ft/s</i>)	14.4	.98
Cetane Number	-	40-55
Octane Number	130	30
Stoichiometric Air/Fuel Ratio	34.3	14.7

Hydrogen is primarily produced through gasification and electrolysis. Gasification involves heating some hydrocarbon energy source and steam to very high temperatures to break up the molecules in the hydrocarbon and the water vapor. This is done in a very oxygen lean environment so that combustion does not occur. The products produced using this process are mainly hydrogen and carbon dioxide. While the amounts of CO_2 produced are significantly less than with IC engines (per unit energy), they still work to negate the greatest benefit of the hydrogen energy source, the lack of CO_2 emissions. However, gasification can be an appealing process because it can be used to produce electricity with the hot gases in addition to producing hydrogen, giving the process a fuel efficiency as high as 70%. Though it takes energy to heat the gases to temperatures high enough to break apart the molecules, gasification

still is able to achieve relatively high thermal efficiencies, as well as the high fuel efficiencies, when compared to typical IC engines [35].

Electrolysis is the breaking up of water molecules (H_2O) into its individual components of hydrogen and oxygen (O_2). Providing current to two electrodes, of the appropriate material, placed in water will break apart the water molecules into hydrogen and oxygen. Both the hydrogen and the oxygen are easily collected as the hydrogen will be positively charged and the oxygen will be negatively charged after breaking up. The charge of the products will draw them to the cathode (hydrogen) or the anode (oxygen) that are providing the current to the water, effectively separating the components. The efficiencies of this process can be as high as 90%; however, greater efficiencies require more expensive materials. This method for hydrogen production is very appealing, as no negative emissions are directly produced during the process. However, they may be produced indirectly if the electricity was generated with the use of fossil fuels. To ensure that the process is completely “clean;” often electrolysis systems use wind or solar power sources. Economically, it is usually more beneficial to integrate the electricity generated by these renewable sources to the electrical grid. During off-peak hours, however, the electricity can be, and often is, more economically used to produce hydrogen with electrolysis [36].

Hydrogen is one of the most promising fuels for the near future. However, the United States lacks the proper infrastructure for hydrogen vehicles. As of 2013, only 10 hydrogen fill up stations were available to the public, 8 of which were in California. The number of hydrogen fuel stations, however, will increase with the new California bill calling for \$46.6 million to be invested in 28 additional fill stations. With California at the helm, hydrogen fuel is slowly becoming more readily available. And while fuel cells are currently not economical for the consumer, retrofit IC vehicles may be used as a driving force in creating a hydrogen fuel infrastructure on a national scale until fuel cells are as cost-effective as IC engine vehicles [37]. A preexistent infrastructure will reduce the economic problems that the FCV industry faces, trying to create economically viable fuel cell vehicles.

CHAPTER 2. LITERATURE REVIEW

2.1. Problem Statement and Objectives

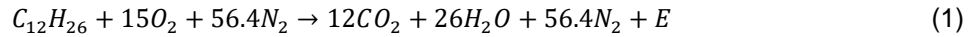
The objective of the research in this paper is to find out if current diesel injectors are capable of igniting a hydrogen-air mixture when operated at their limits. Additionally, this paper will begin to look into the minimum quantity of diesel that will ignite any hydrogen-air mixture, exceeding the limits of the diesel injector setups found in the automotive industry. The results will be a quantity of diesel that will act as an ideal minimum quantity of diesel for compression ignition engines that run on hydrogen and will contribute to the sum of knowledge in the dual-fuel hydrogen-air combustion field and to the development of injectors for the purpose of dual-fuel hydrogen-air combustion operations. Studies have been done in this field by various universities such as North Dakota State University (NDSU), as well as in the private industrial sector. Results and background information found in these studies will be presented in this chapter.

The overall goal of hydrogen combustion research in diesel engines is to get the engine to perform at or above their designed performance level while using hydrogen as the power source and the diesel injected only as the ignition source. Hydrogen autoignites at very high temperatures, and thus needs an ignition source, usually in the form of a spark or a fuel with a lower autoignition temperature, such as diesel fuel. It is very difficult to get an engine to autoignite hydrogen without an external ignition source. Using high concentrations of hydrogen can help to solve the previously mentioned issues of global petroleum supply and demand, global warming and emission regulations.

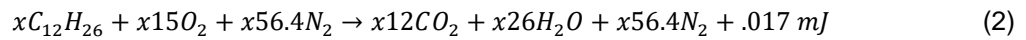
2.1.1. Theoretical Minimum Diesel Quantity

The theoretical minimum amount of diesel needed to ignite a hydrogen-air mixture was found using minimum ignition energy of hydrogen. The minimum ignition energy is the smallest amount of energy provided to a fuel that will ignite the fuel. The minimum ignition energy of hydrogen is $.017 \text{ mJ}$, which is very small compared to most fuels. For example, the minimum ignition energy of diesel is $.23 \text{ mJ}$, which is 13.5 times as much energy [32][33]. As mentioned previously, however, the diesel fuel will autoignite at a much lower temperature than hydrogen, and therein lies the need for the diesel. The theoretical minimum quantity of diesel that will ignite hydrogen will be the minimum quantity of diesel that

will produce .017 mJ of energy. The most energy produced in combustion occurs during stoichiometric combustion, and thus, the minimum quantity of diesel that produces combustion will combust under stoichiometric conditions. The combustion equation for stoichiometric combustion of diesel in air is



In this case E is equal to the minimum ignition energy of hydrogen (.017 mJ). The quantities of each product and reactant shown above are not the exact amount, but just the proportions of each product or reactant. To find the minimum diesel quantity all that needs to be done is to multiply each product and reactant by an arbitrary factor:



The energy produced in combustion is equal to the enthalpy of formation of the reactants minus the enthalpy of formation of the products. The enthalpy of formation of the elements involved are shown below in Table 2.

Table 2. Enthalpy of Formation for Combustion Elements

Element	Enthalpy of Formation [$\frac{J}{mole}$]
$C_{12}H_{26}$	-7,559,396
O_2	0
N_2	0
CO_2	-393,520
H_2O (gas)	-241,820

Using the enthalpies of formation and the appropriate quantity proportions the equation to find the minimum quantity of diesel becomes:

$$.017 \text{ mJ} = x * -7,559,396 \frac{J}{mole} - x * 12 * (-393,520 \frac{J}{mole}) - x * 26 * (-241,820 \frac{J}{mole}) \quad (3)$$

Solving for x , the minimum amount of diesel is $4.9273(10^{-12})$ moles or $8.3764(10^{-7})$ mg [32][33].

2.1.2. Theoretical Air/Fuel Ratio to Reach Hydrogen Autoignition Temperature

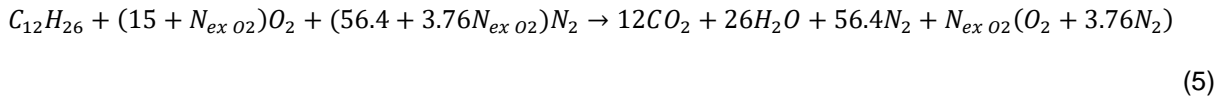
The theoretical maximum air/fuel ratio of air to diesel was found with the autoignition temperature of hydrogen. The theoretical maximum air/fuel ratio is important because if any more air is introduced to the combustion process, the combustion will not create enough heat to ignite the hydrogen. The same

ideal assumptions were applied to this calculation as was applied for the calculations to find the minimum quantity of diesel. The chemistry equation used to find the air/fuel ratio of diesel fuel was

$$\sum h_{fr} = \sum h_{fp} + \Delta T_p \sum N_p C_p \quad (4)$$

where h_{fr} and h_{fp} are the enthalpies of formation for the reactants and products of combustion, respectively. N_p is the number of moles of a given product and C_p is the heat capacity of a given product. ΔT_p is the temperature difference of the adiabatic flame temperature and the atmospheric temperature. Equation 1 calculates the change in temperature from the change in enthalpy of a combustion process. The enthalpy of formation terms include all phase changes and molecular changes. In this case, the calculation is done under constant volume conditions.

To find the air/fuel ratio an “excess oxygen” variable $N_{ex\ O_2}$ is added to the summation of the moles of the reactants time the heat capacities. This variable is the number of moles of oxygen that did not react with any diesel fuel. This variable is multiplied by the heat capacity of oxygen and by 3.76 times the heat capacity of nitrogen as seen in the combustion balance equation below.



From this combustion, equation 1 can then be written as seen below

$$\sum h_{fr} = \sum h_{fp} + \Delta T_p * (N_{N_2}C_{pN_2} + N_{NH_2O}C_{pH_2O} + N_{NCO_2}C_{pNCO_2} + N_{ex\ O_2} * (C_{pO_2} + 3.76C_{pN_2})) \quad (6)$$

To find the maximum air/fuel ratio that will reach a temperature high enough to autoignite hydrogen the adiabatic flame temperature needs to be equal the autoignition temperature of hydrogen (500°C). The only remaining unknown variable, $N_{ex\ O_2}$, is solved for. The number of moles of excess oxygen was calculated to be 30.9569 moles. The total moles of oxygen is then added to excess moles of oxygen to get 45.9539 moles. The total nitrogen was then added to the total oxygen and that sum was divided by the total diesel to get a final maximum air/fuel ratio of 218.7547.

It is important to reiterate that these previous two calculated values, the minimum diesel quantity and maximum air/fuel ratio, are ideal limits. Ideally, the minimum quantity of diesel and the maximum air/fuel ratio of diesel that can ignite hydrogen are the extreme limits that can be used. In practice, however, at these values, combustion of hydrogen will, most likely, still not occur. Non-ideal condition, experienced in actually testing and application, will prevent these values from being practically accurate.

2.2. Dual Fuel Engine Research

The primary purpose of dual-fuel hydrogen-diesel combustion is to reduce the CO_2 emissions. As stated previously, hydrogen produces no CO_2 when combusted. Therefore, as the hydrogen percentage is increased, the amount of CO_2 produced will decrease. Due to the greater LHV, and also the higher flame temperature, hydrogen also has the potential to increase the efficiency of the engine [32][33]. Though a higher flame temperature can result in more NO_x produced, these emissions can be controlled through various previously mentioned processes [38].

There are three primary methods to retrofit diesel engines to be able to operate under dual-fuel mode: manifold injection, port injection and direct injection. Manifold injection involves introducing continuously flowing hydrogen into the intake manifold of the engine. It is usually introduced as far downstream as possible that still allows for even distribution among the cylinders. This method allows the hydrogen to mix with the air before it is introduced into the cylinders, essentially creating a homogeneous mixture of hydrogen and air that promotes thorough combustion [39]. There is some air displacement, by the injected hydrogen, that decreases the volumetric efficiency of the engine; however, if the hydrogen is introduced after the turbo this effect is minimized, though this is not always possible [40]. The main benefits of the manifold injection method are that it is simple and easy to implement and is fairly cheap. For these reasons manifold injection is the most common method to introduce hydrogen [41].

Port injection introduces the hydrogen very near to the intake valve. This method requires as many port injectors as there are cylinders in the engine. Injections are intermittent, corresponding with the engine's combustion cycle, which allows for greater control; however, the installation and part costs are more than with manifold injection. Additionally, this method still experiences similar air displacement as the manifold injection does [39]. Finally, Saravanan and Nagarajan found that the difference in performance of manifold and port injection methods to be negligible for hydrogen-diesel dual-fuel combustion [40].

With direct injection, hydrogen is injected directly into the cylinder after the intake valve closes. This eliminates the air displacement issue of the previous two injection methods and still allows the hydrogen to mix with the air before the diesel fuel is injected. However, it requires either expensive specialized fuel injectors that are able to inject hydrogen and diesel at different times in the engine cycle

or two separate injectors that perform that same function independently [39]. Direct injection is the least common method to inject hydrogen, as it is the most costly and does not provide cost effective efficiency increases. However, it does produce the best results in terms of efficiency and emissions.

Additionally, attempts have been made, with some degrees of success, using only hydrogen in diesel engines. Antunes et al. were able to achieve this by increasing the inlet air temperature in a diesel engine with already high compression ratios. They were able to improve brake efficiency and power when using 100% hydrogen as well as 80% hydrogen when using hot inlet air. This method is not commonly used, as it requires heating of inlet gases, increasing the costs with more hardware and equipment. Though this method and research area is fairly new, the success seen by Antunes et al. may lead to further testing and possible implementation of this method [42].

2.2.1. Compressed Natural Gas

Much more commonly used than hydrogen in dual-fuel combustion, is compressed natural gas (CNG). CNG has a few similarities to hydrogen, most significantly being that it is also a gas. Like with hydrogen dual-fuel operation, manifold injection is most commonly used to introduce the CNG. Many of the same manifold injection kits available for CNG can be used for hydrogen injection. CNG also has an autoignition temperature near that of hydrogen [32]. So as with hydrogen, diesel fuel must be injected into a compression ignition engine to act as the ignition source.

Like hydrogen, CNG's primary benefit is in CO_2 emission reduction. While CNG does have carbon atoms, and thus produces CO_2 , it does not produce as much as diesel or gasoline. Unlike hydrogen (in certain instances), however, CNG produces fewer NO_x emissions. Though, as is the common tradeoff, CNG produces more unburnt hydrocarbon emissions. CNG-diesel dual-fuel combustion has also been more successful at using lower percentages of diesel without efficiency and power losses [43]. CNG has a LHV similar to diesel, which means that it can be said that CNG is essentially energy equivalent to diesel [44].

Natural gas is fairly available, especially in the United States, accounting for 27% of all energy consumed, second only to petroleum products [10]. The availability of natural gas is the primary reason that it is more commonly used than hydrogen, though the lack of CO_2 emissions, in hydrogen, and its greater energy density (per unit mass) make it a more desirable fuel [24][32][33]. Another reasons that

natural gas is more common is that hydrogen is much more volatile due to its high flame speed and low ignition energy, while CNG has a more stable flame speed and ignition energy similar to gasoline or diesel, making it easier to work with. These problems lead to difficulties storing and transporting hydrogen that are less prevalent in the storage and transportation of CNG [32].

2.2.2. Adding Small Amounts of Hydrogen

While operating with large percentages of hydrogen is the primary goal of dual-fuel hydrogen-diesel combustion, small percentages of hydrogen can be used to positive effect without the negative issues that can be seen with large amounts of hydrogen, which will be discussed later. On the topic of hydrogen-diesel dual-fuel combustion small amounts of hydrogen are generally defined as less than or equal to 30% hydrogen (per unit energy). 30% refers to the point when hydrogen addition, with minimum changes to the engine, will produce undesirable engine function. This threshold has been found and validated by multiple sources; however, when changes are made to the engine, higher thresholds can be achieved [45][46][47]. Generally the undesirable engine function observed at higher quantities of hydrogen is in the form of knock.

There are two types of knock: end gas knock and diesel knock. End gas knock occurs when the end gas, or gas opposite of the flame front, is autoignited due to the pressure rise in the cylinder caused by the high temperatures of the burning/burnt fuel gas. This undesirable autoignition causes a high energy release rate, producing abnormally high temperatures, and thus pressures, and creates a pressure wave that travels through the cylinder. This pressure wave can be detrimental to the function of the engine. Diesel knock is defined as the rate of cylinder pressure rise, at a time shortly after the start of combustion, which is too high. This will result in higher than desirable pressures before the piston reaches top dead center (TDC), which translates to power that is working against the normal engine operation. Diesel knock occurs when the premixed charge of fuel is too large, which causes faster overall burning. The almost homogeneous hydrogen-air mixture injected in dual-fuel combustion can be treated as a premixed charge, and thus with increasing amounts of hydrogen, diesel knock occurrence increases. Diesel knock can also occur when the fuel is autoignited too early in the engine cycle, resulting in high pressures before the piston reaches TDC. Kubesh and Brehob have found that, though diesel knock is

the predominate knock mechanism detrimental to engine operation with hydrogen-diesel dual-fuel combustion, both knock mechanisms are present [48].

Shirk et al. introduced 0, 5 and 10% hydrogen (per unit energy) into two diesel engines. One engine was dyno mounted and the other was in a 2005 Chevrolet Equinox. Both engines were retrofit with manifold hydrogen injection systems. Under a variety of speed/load steady state conditions, the dyno mounted engine produced slightly fewer NO_x emissions with hydrogen additions when compared to just diesel operation with statistically insignificant losses in efficiency. The Equinox engine was put through an EPA simulated city driven test. With the hydrogen, again, the engine showed improvements in NO_x emissions and an insignificant loss in efficiency. It should be noted that CO_2 emissions were not measured, but assumed to have improved as less diesel fuel was consumed because of the hydrogen introduced [49]. Results similar to these were also observed by Lilik et al. [45]

Saravanan and Nagarajan, however, were able to produce much more positive results using lower levels of hydrogen. In a single cylinder direct injection diesel engine, hydrogen was introduced at six different flow rates using a modified manifold injection system. This method means that, with the constant flow rates of hydrogen, at increased loads, more diesel fuel must be injected and thus the energy percentage of hydrogen decreases with the load. For example at the median hydrogen flow rate, for 100% load, the hydrogen energy percentage is 6.27%, while at no load the hydrogen energy percentage is 24.21%. In general, Saravanan and Nagarajan's testing produced fewer emissions while increasing performance with increasing hydrogen flow rates. Efficiency and specific energy consumption (SEC) both improved with hydrogen addition, as well as smoke, carbon monoxide and CO_2 emissions. The efficiency improved by as much as 4% and SEC improved by as much as 7%. There was, however, an increase in hydrocarbon emission as the hydrogen flow rates were increased. This was attributed to the high burning velocity of hydrogen, which produces a flame quenching effect. The NO_x emission results varied with the loads. At lower loads hydrogen improved the NO_x emissions, while at larger loads plain diesel produced the best results [50]. This study is a good example of how not only hydrogen quantity, but also load, can affect the emissions produced.

One of the most significant changes that adding hydrogen does in an engine, is altering the ignition delay. Lata and Misra studied the ignition delay in dual-fuel hydrogen-diesel combustion. Their

results show that the primary parameters that affect ignition delay are temperature, pressure, and oxygen concentration. Changes in the physicochemical properties and pre-ignition reactions make dual-fuel ignition delays different from pure diesel. Their results show that an increase in ignition delay occurs at lower hydrogen concentrations, up to 30% hydrogen, and then decreases as concentrations increase up to 50% hydrogen. This decrease in ignition delay at higher hydrogen concentrations is one of the contributing factors limiting the amount of hydrogen that is able to be used, as discussed later. They also found that, at all hydrogen concentrations, as the load increases the ignition delay decreases. This is most likely due to the greater residual temperatures observed with larger loads [51].

Additionally, Miyamoto et al. found a relationship between hydrogen percentage and ideal diesel injection timing. Using hydrogen concentrations from 0 – 17% (per unit volume) it was observed that as more hydrogen is introduced the ideal diesel fuel injection timing should be retarded [52]. While this seems contradictory to what Lata and Misra found (that hydrogen less than 30% increases ignition delay), it actually confirms the relationship they found between temperature and ignition delay [51]. The closer to top dead center the injection is, the hotter the in-cylinder temperature will be, and thus the ignition delay will decrease. This result does not disprove the relationship Lata and Misra found as they only used one injection time.

2.2.3. Adding Large Amounts of Hydrogen

While there are measurable benefits of adding small amounts of hydrogen, as stated previously, the ultimate goal of dual-fuel hydrogen-diesel combustion is to use very large percentages of hydrogen. To get proper engine function at hydrogen quantities greater than 30%, engine operation must be manipulated. Common adjustments made include retarding diesel injection timing, decreasing the amount of diesel fuel proportionally to the hydrogen added, changing compression ratios, increasing inlet pressure or temperature and using different hydrogen injection methods. Even with appropriate engine changes, however, most engines reach a “knock limit”. In the area of hydrogen-diesel dual-fuel engine operation, the “knock limit” refers to the largest percentage of hydrogen that can be used before knock, detrimental to engine performance, occurs.

Deb et al. performed hydrogen-diesel dual-fuel combustion operation at hydrogen percentages up to 46% (per unit energy) with a four stroke, single cylinder diesel engine. This larger amount of hydrogen

was able to be used by retarding the diesel injection timing and by using the direct hydrogen injection method. Their results showed that with increased hydrogen percentages, brake thermal efficiency (BTE) and SEC were both improved; though, at the highest hydrogen percentage knock began to occur which led to nearly the same efficiency as the next lower hydrogen content. Additionally, CO_2 , CO , and smoke were all reduced as more hydrogen was added. However, NO_x was found to increase with greater hydrogen content. Unburnt hydrocarbons were found to increase with lower levels of hydrogen addition, but began to decrease with larger amounts of hydrogen, which leads to the assumption that more complete burning occurs with large hydrogen content [53]. Using only port hydrogen injection Sandalci and Karagoz saw similar emission results; though they reported decreased efficiencies with increasing hydrogen content [54].

Using a naturally aspirated inline 4 cylinder diesel engine, Zhou et al. performed tests with hydrogen contents up to 40% (per unit energy), while varying the engine's load. For all hydrogen percentages, it was found that as the load increases, the BTE increases. Lower hydrogen percentages saw greater BTEs than the higher hydrogen percentages, though all cases were better than the baseline diesel case. CO_2 , CO , and smoke improved both as the hydrogen content increased and as the load increased. NO_x emissions were poor at low loads and high loads, but were better at the middle loads, though the NO_x emissions were still best when no hydrogen was added [55].

The previous two studies observed "knock limits" at around 40% hydrogen. As stated previously, it gets more difficult to operate hydrogen-diesel dual-fuel combustion at hydrogen contents greater than 30% (per unit energy). The larger amount of premixed hydrogen-air charge leads to diesel knock and engine performance begins to deteriorate. The diesel gets autoignited in the cylinder and due to the very fast flame speed of hydrogen (approximately 16 times faster than diesel), very fast combustion occurs, too fast for normal engine operation.

As mentioned previously, load has significant influence on the emissions and performance of hydrogen-diesel dual-fuel combustion, but the "knock limit" is also dependent upon the loads. Saravanan and Nagarajan investigated the "knock limit" in a single cylinder, four stroke, diesel engine, with an assortment of loads. Using manifold injection and advanced diesel injection timing, hydrogen was introduced at up to 90% hydrogen (by unit volume). They were able to run without any detrimental knock

at up to 50% hydrogen for all loads. At 70% and 90% hydrogen, the “knock limit” occurred at loads greater than 80% and 70%, respectively. These results are very promising, as they show that the engines can be run with very high amounts of hydrogen at lower to middle loads. In addition to these results, Saravanan and Nagarajan saw improvements in BTE, SEC, smoke, particulate matter, and even NO_x emissions (except for with 10% and 20% hydrogen) as hydrogen content was increased [46]. It must be noted, however, that these hydrogen contents were calculated on a per unit volume basis, while the majority of the previous cases mentioned were calculated on a per unit energy basis. Volume percentage is not equivalent to energy percentage, therefore, for example, 50% hydrogen by unit volume is equal to less than 50% hydrogen by unit energy, and the results between cases cannot be compared using just the hydrogen percentage given.

Roy et al., in an effort to reduce the NO_x emissions associated with dual-fuel hydrogen-diesel combustion, performed experiments using nitrogen (N_2) dilution to reduce NO_x emissions. N_2 dilution involves introducing nitrogen, an inert gas, into the inlet air (along with hydrogen in this case) to limit the combustion temperature. This occurs because N_2 has a heat capacity that allows it to retain heat; however, unlike hydrogen and diesel it does not produce any heat through the combustion process. At the lower temperatures achieved, less NO_x emissions are produced. This method can be successful because of the large flammability range of hydrogen. Hydrogen is able to ignite in very lean mixtures. In addition to the lower temperatures, N_2 controls the rate of pressure rise, which, as stated previously, is a contributing factor to knock. Thus, Roy et al. were able to achieve dual-fuel hydrogen-diesel engine operation using as high as 90% hydrogen (per unit energy) without any knock and as high as 100% NO_x reduction. BTE was able to be kept consistent, using N_2 dilution, with the large amount of hydrogen and, as expected, CO and hydrocarbon emissions were very low. The main disadvantage of this method is in the need for a means to introduce nitrogen into the engine; however, this method shows great promise in hydrogen-diesel dual-fuel combustion [56].

2.3. Experimental Work Done at NDSU to Maximize Hydrogen Energy Input

Past work done at NDSU primarily looked into maximizing the “knock limit” using varying levels of technology. Hydrogen-diesel dual-fuel combustion studies were started in 2005 by graduate student

Stousland [57]. Stousland used a retrofit 4 cylinder CAT engine with a mechanically controlled diesel injection system with fixed timing for his testing. To add hydrogen into the system, hydrogen was introduced into the intake manifold after the turbo to promote extra mixing and keep costs low. The engine was operational with these changes made and a maximum “knock limit” of 50% hydrogen (per unit energy) was reached. The emission results were promising, with an improvement in CO_2 emissions while NO_x emissions remained unchanged when compared to the baseline diesel operation. The efficiency also remained unchanged until near the “knock limit,” at which time knock began to decrease the efficiency. As this was the initial dual-fuel program at NDSU, Stousland recognized the limitations of a mechanically controlled system and recommended the system be electronically controlled [57].

As recommended by Stousland, Bottelberghe’s testing made use of an electronic control system [41]. A 6 cylinder CAT C6.6 engine was equipped with an Advanced Combustion Emission Reduction Technology (ACERT) Electronic Control Module (ECM). The ECM, designed to meet the EPA’s Tier 3 emissions standards, was able to control injection timing and boost pressure among other operation parameters. Bottelberghe was able to increase the “knock limit” to 60% hydrogen (per unit energy) with the electronic controls. The emission results observed by Bottelberghe were very similar to Stousland; however, Bottelberghe observed a slight decrease in efficiency at lower hydrogen levels before a slight increase at higher levels. It was theorized that this was due to the diesel fuel injection systems. Bottelberghe used a common rail system with solenoid injectors that resulted in superior atomization and combustion, while Stousland used a mechanically controlled injection system. The hydrogen introduced into the manifold resulted in improved mixing and thus improved combustion for Stousland, while Bottelberghe’s superior electronic system had a high level of mixing with or without hydrogen added [41]

Kersting, again, used the 6 cylinder CAT C6.6 engine equipped with the ACERT ECM. While Stousland and Bottelberghe both used control technology new to the program, they looked into only a small range of operation points. Kersting’s contribution to the hydrogen-diesel dual-fuel combustion program at NDSU involved a wide array of operation points, including four different engine speeds and five different loadings at each speed. Kersting observed that as the rpms increased, the thermal efficiency and maximum hydrogen concentration increased. As the load increased, however, the thermal efficiency and maximum hydrogen concentration decreased. The thermal efficiency with hydrogen was

greater than the diesel baseline in all cases, however. The maximum hydrogen concentration achieved was 74% (per unit energy), with a maximum decrease in CO_2 of approximately 47%. The NO_x , however, increased by as much as 224%. The recommendation was made for more control in future work in this area, specifically in the injection timing, but also control of other parameters including rail pressure, boost pressure, injection strategy, injected quantity, etc. [41]. The specific area of injected quantity is where the research done for this paper is focused.

2.4. Injection Parameters of Industrial Injectors

It is important to this research that the test apparatus be capable of at least meeting the capabilities of current diesel injectors in the automobile industry. Quantity of fuel injected is not a common way of measuring the performance of injectors. The two most common ways to express the capabilities of injectors are by volumetric flow rate and by response time. Thus; the results of this research will be compared to the diesel injectors in the automobile industry by the terms of volumetric flow rate and response time.

In general, the injectors found automobile industry need to be able to inject enough fuel for the engine to run and power a vehicle. In standard engine operation, the methods for injecting the correct amount of fuel include either one injection of the appropriate amount of fuel or multiple injections of small amounts of fuel that add up to the appropriate total amount. Higher flow rates and lower response times are the goal for most injectors because better atomization occurs at higher flow rates and lower response times allow for more control.

The lowest flow rates are generally found in injectors that do not use a high pressure common rail fuel system. The lower pressures found in these injectors correspond to lower flow rates. Flow rates for injectors without common rails are can vary anywhere from $133 - 250 \frac{cm^3}{min}$. The fastest response times come from solenoid injectors. The fast response times allow for superior control in the quantity and the timing of the fuel injected. Solenoid injector response times vary anywhere from $1 - 20 ms$. Solenoid injectors almost universally use common rail systems and generally have high flow rates. It is the goal of this research to at least meet both of the lower thresholds expressed in this section [58].

CHAPTER 3. RESEARCH APPROACH

3.1. Experimental Setup

A combustion chamber was designed and built to find the minimum amount of diesel fuel necessary to cause combustion in a hydrogen-air environment. A preheated hydrogen-air mixture was pumped with constant flow rates through the heated combustion chamber to create the hydrogen-air environment. Diesel was injected into the chamber to ignite the mixture. The quantity of diesel was able to be altered between each test run, thus the minimum amount required for combustion could be found through multiple test runs. Combustion was detected with a photodiode through a sapphire window in the combustion chamber. Figure 4 is the schematic of the entire test apparatus.

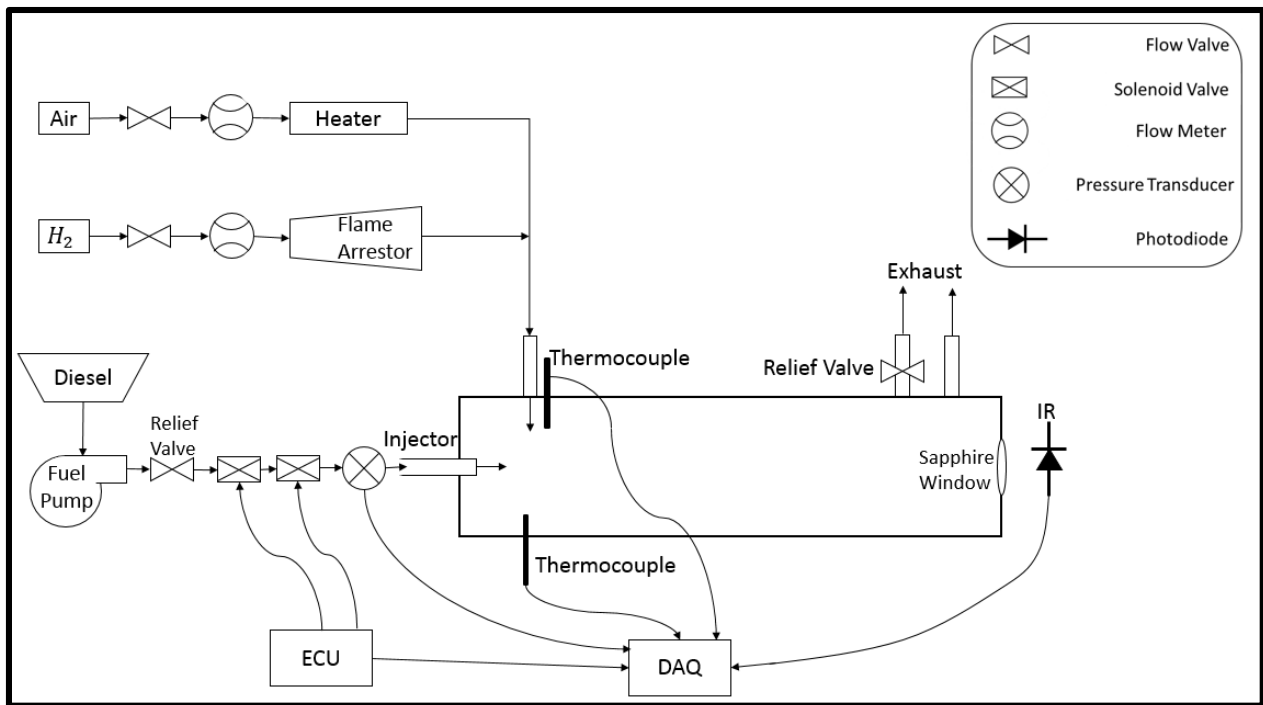


Figure 4. Test Schematic

The main chamber was made from $1/4$ inch seamless black steel pipe, designed for an operation pressure of 300 *psi*. The diameter and the length of the chamber were dependent upon the spray angle and the penetration length of the diesel injector. Preliminary injection testing was done to observe the spray angle and the penetration length for regular engine operation. This was done by unscrewing the injector from the engine cylinder and spraying diesel fuel over a grid while using the same

fuel pump that comes with the engine. No modifications were made to the injector or any engine system for this preliminary injector testing. The spray formation was captured with a high speed camera. The spray angle was measured as approximately 7.5° and the penetration length was approximately 13.5 inches . The fuel should not hit the walls of the chamber for regular operation, so the chamber was made to be 14.5 inches long and have an inner diameter of 3 inches to give enough wall clearance so that the diesel injected did not get sprayed on the chamber walls. The volume of the chamber, therefore, was $.0593\text{ ft}^3$.

The test apparatus was a constant volume combustion chamber, meaning it was designed to have constant gas flow through it. This means that during combustion, flames would propagate through the entire combustion chamber, the inlet piping and exhaust piping. The flow of the air and hydrogen into the combustion chamber was controlled by flow valves and Key Instruments' $.5\text{-}5\frac{\text{ft}^3}{\text{min}}$ Flow Meters. As there would be combustible hydrogen in the inlet piping during combustion, a SuperFlash model DGN flame arrestor compatible with hydrogen combustion was installed to prevent flames from reaching the hydrogen source. Flame arrestors prevent flames from propagating past them. This was just a precaution, as the lines delivering the air and hydrogen contained either pure hydrogen or air, not a mixture of the two. Hydrogen cannot combust without oxygen; and thus, flame could not propagate up the hydrogen inlet lines, without some extenuating circumstances. Refer to Figure 4 to see how the inlet gas lines are situated.

An In-line Omega T-type Air Process Heater was installed to heat the air to the appropriate temperatures for the test. Resistive heating tape was used to heat the combustion chamber in addition to the preheated air. The temperatures in the chamber must be above the autoignition temperature of diesel for ignition to occur. The entire chamber was insulated with Thermafiber mineral wool insulation to reduce heat loss to the environment. Two K-type thermocouple probes were installed near the injector to ensure that injection occurred at the correct temperature. One was located near the hydrogen-air inlet and one was located opposite to the inlet, as depicted in Figure 4. The thermocouples were flame resistant and could measure up to 538°C (1000°F). The air, but not the hydrogen, was heated because the flame arrestor cannot function at higher steady state temperatures, and thus hot air cannot flow through the arrestor's inlet. Additionally, the in-line air heater's heating coils reached temperatures

greater than the autoignition temperature of hydrogen, so a hydrogen-air mixture could not flow through the in-line heater without autoigniting. In addition to the hydrogen not being able to flow through the heater, the heater had to be far enough upstream from the hydrogen inlet that eddy currents of hydrogen did not reach the heating coils of the in-line air heater. The hydrogen was introduced downstream from the in-line air heater approximately 6 inches. Heat transfer and mixing were assumed to have happened in the inlet piping and the combustion chamber before combustion, resulting in a near homogeneous mixture of hydrogen and air.

A mechanical injector from a Yanmar TNM series, three cylinder, .9 liter engine was used to inject the No. 2 diesel fuel. A Dynamic .61 cubic inch Gear Pump was used to pressurize and pump diesel fuel from a tank to the injector. A Leeson 2 hp induction motor was used to power the gear pump. Two in-line Coast Pneumatics HP3000-24VDC series high speed solenoid valves were installed in between the gear pump and the injector to control the amount of diesel injected. For fuel flow to occur both solenoids must be open. One solenoid was opened to initiate the flow and the second solenoid, which was open prior to the first one opening, was closed to end the flow to achieve very short flow times. Solenoid valves are limited by their response time; thus, by using two valves the time between opening and closing can be reduced further and controlled better. Injection could be limited to only one millisecond with this setup. The amount of time the valves are opened directly correlates with the mass injected into the chamber. Figure 5 shows the injection setup just described.

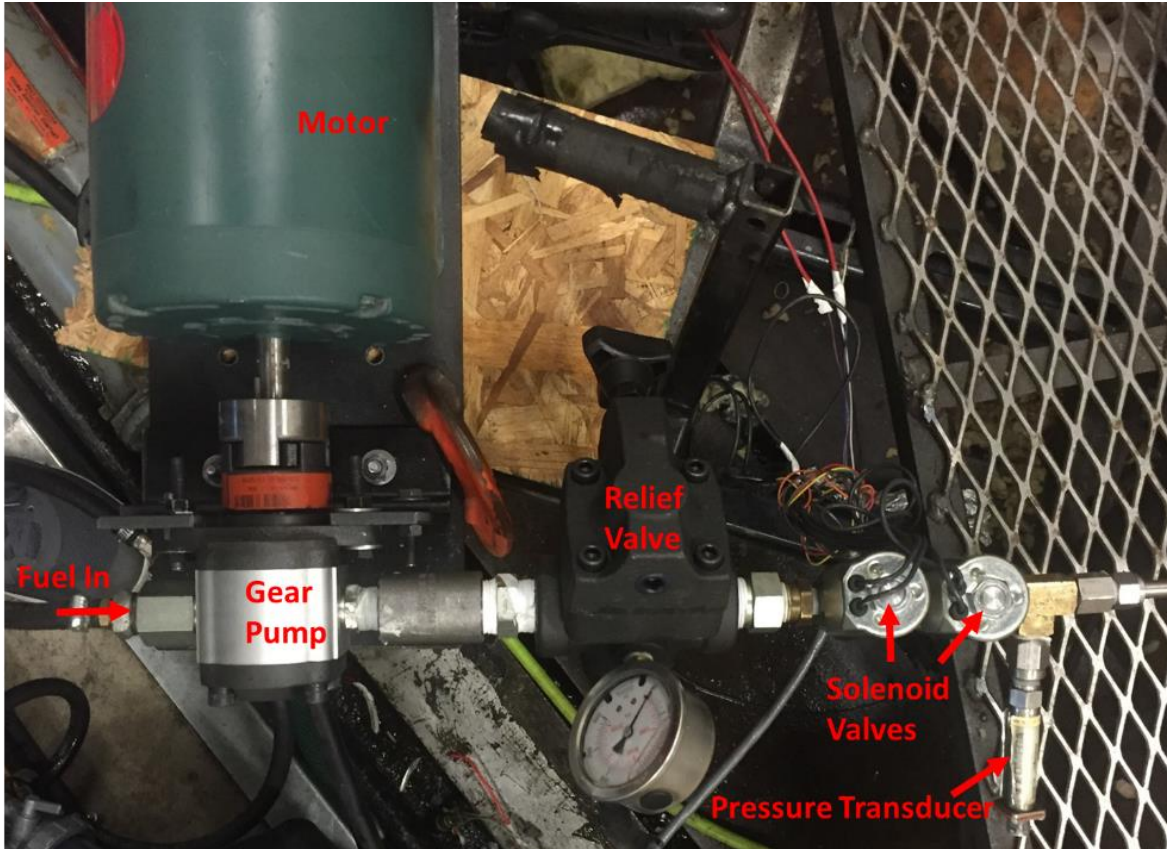


Figure 5. Injection Setup

An Arduino Mega 2560 microprocessor board was used to send signals to the solenoid valves and receive and record signals from the various sensors. It was a 16 MHz processor with both digital and analog inputs and outputs. The response times of all of the various sensors were at least three orders of magnitude slower than the processor; thus the processor speed did not limit any of the signaling or data acquisition. The reason the Arduino Mega 2560 processor was chosen for this application was the low cost and the high speed capability, along with the significant online documentation.

Using the previously described injection setup, along with the Arduino microprocessor, significant injection control was able to be achieved. The injection setup could inject large quantities of diesel, as well as very small amounts of diesel. Figures 6 and 7 show the diesel spray pattern produced by the test apparatus during steady state injection and during a 1 ms injection, respectively. In the steady state injection image shown in Figure 6 the spray angle is seen to be approximately 7°, additionally the spray length (commonly referred to as penetration length) reaches approximately 22 inches. Additionally, the gear pump could provide larger pressures than the pressure used in Figure 6; thus increasing flow rate and spray length. This was not shown, as the goals for this research involve very small injection quantities. Note that the test apparatus produces a greater spray length than what was produced in the preliminary testing. Figure 7 depicts the injected droplets dispersion pattern for a 1 ms injection. No available camera was able to capture the image of the spray pattern for the 1 ms injection. Therefore,



Figure 6. Steady State Spray [in.]

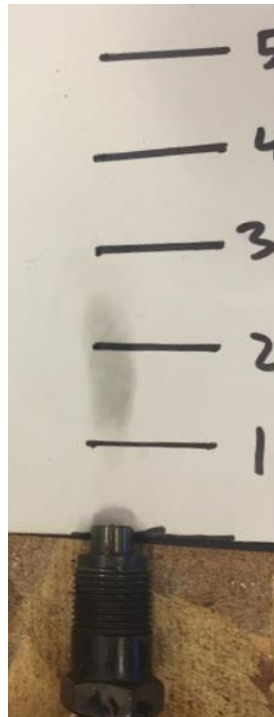


Figure 7. 1 ms Injection Spray Profile [in.]

Figure 7 acts only to portray the small scale of the 1 ms injection, not accurately depict the spray pattern. To get the pattern to show on the paper, multiple 1 ms injection had to be performed and allowed to accumulate on the paper. The spray length was approximately 2.5".

Two equations were used initially to calculate the mass flow through the injector based on the fuel pressure. The first flow rate equation calculated the mass flow rate from the pressure difference across the injector using equation (4).

$$\dot{m} = C_d A \sqrt{2\rho\Delta P} \quad (7)$$

\dot{m} is the mass flow rate of the fuel, A is the cross sectional area of the injector orifice, ρ is the fuel density, ΔP is the pressure difference across the injector and C_d is the nozzle discharge coefficient, which was estimated from equation (5).

$$C_d = \sqrt{\frac{\left(\frac{P_{inj}-P_v}{\Delta P}\right)}{2.6874-11.4\frac{r_{nh}}{d_{nh}}}} \quad (8)$$

P_{inj} is the pressure of the fuel injected and P_v is the vapor pressure of the fuel, but since $P_{inj} \gg P_v$, the vapor pressure term can be neglected. r_{nh} is the nozzle filet radius and d_{nh} is the nozzle orifice diameter. Since the nozzle filet radius is approximately zero the discharge coefficient can be expressed as in equation (6)

$$C_d = \sqrt{\frac{\left(\frac{P_{inj}}{\Delta P}\right)}{2.6874}} \quad (9)$$

where the injection pressure and the pressure difference terms will change with time [59]. Finally the mass injection will be calculated by numerically integrating equation (4) resulting in equation (7).

$$m = \int_{t_0}^{t_1} C_d A \sqrt{2\rho\Delta P} dt \quad (10)$$

The second equation was a simpler equation that calculated mass flow rate as in equation (8)

$$\dot{m}(t) = \frac{A\Delta P(t)}{a} \quad (11)$$

where a is the speed of sound in the injected fluid [60]. The mass was found by numerically integrating the mass flow rate, similar to the method used for the first equation. Armas et al. validated this equation for the use in calculating mass injected from measured pressure [60]. The validation process performed in the research for this paper, for these equations, will be mentioned later in this report.

Due to the short injection times, the pressure increase and decrease times had to be accounted for in the mass calculations. As a solenoid valve opens, the pressure will start low on the downstream side and increase to the pressure from the upstream side of the solenoid. As pressure changes with

time, the mass flow rate, then, changes with time. Using an Omega 3000 psi model px 613 pressure transducer, shown in Figure 5, a pressure-time curve was recorded as the solenoid injector was opened and closed. The pressure in between the pressure increasing and decreasing curves was steady and equal to the pressure from the fuel pump. The steady state pressure from the fuel pump was controlled by a Northman Fluid Power In-Line Hydraulic pressure relief valve. This allowed the pressure, and thus the flow, to be reduced. Flow through the injector only occurred for pressures greater than 950 *psi* which corresponds to the force it takes to counteract the spring and lift the pintle of the injector, thus allowing flow to begin. The reason a flow meter was not used to directly measure flow, is that funding was very limited and pressure transducers were on hand.

The Omega pressure transducer was calibrated using a deadweight tester similar to the one shown below in Figure 8. The deadweight pressure calibration tester works by applying known pressures, produced with various weights sitting on a piston, to the pressure transducer. The calibration curve found was a linear equation that is expressed as follows:

$$P_{psi} = 6.2507P_{bits} - 1270.2 \quad (12)$$

where P_{psi} is the pressure in the units of psi and P_{bits} is the pressure in the units of bits (what the DAQ measure it in). Three readings were taken for each pressure and the R^2 value was a perfect 1.

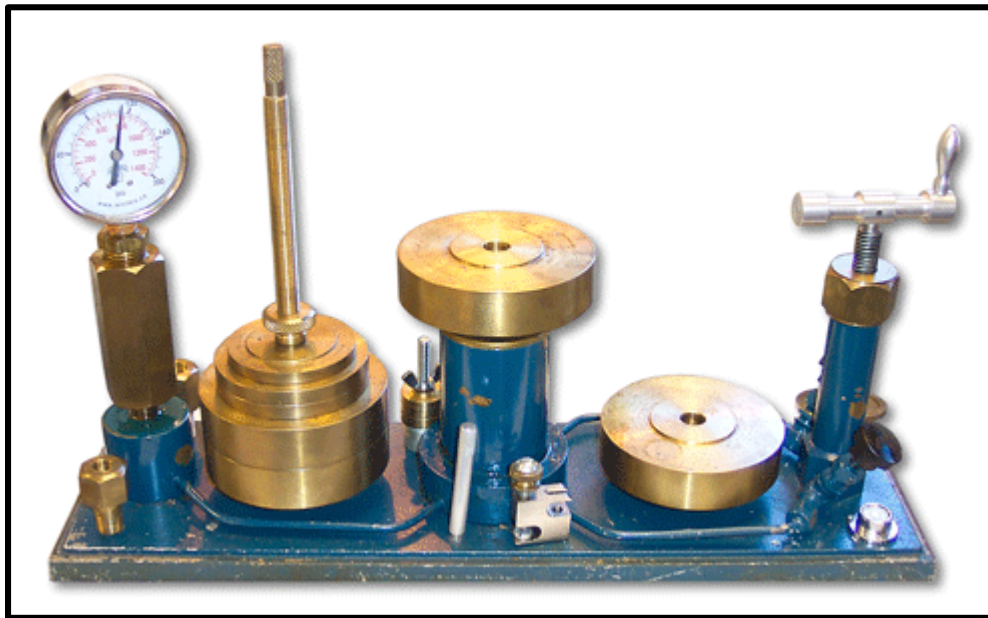


Figure 8. Dead Weight Pressure Calibration Tester

A sapphire window was installed in the combustion chamber opposite to the injector to detect combustion. The sapphire window will allow infrared, ultraviolet and visible light through and can withstand combustion pressures. An infrared photodiode was placed on the outside of the sapphire window. Photodiodes allow current to flow through them when a certain wavelength of light is detected. The infrared photodiode was added to detect the diesel combustion, as diesel combustion emits radiation on both the visual and infrared wavelengths. In the case of this research, the photodiode is activated when combustion occurs and the voltage caused by the current flowing through the photodiode therefore signals combustion. Hydrogen emits on the ultraviolet wavelength, but due to the availability and success of the infrared photodiodes and the price, ultraviolet photodiodes were not used. However, in future research in detecting hydrogen combustion in constant volume chambers, ultraviolet photodiodes should be looked into further. The thermocouple was deemed not reliable to detect combustion because the flame speed of hydrogen is very high. The response time of the thermocouple may not have been fast enough to detect the hydrogen combustion.

As a safety measure, there were two exhaust pipes. One pipe was always open to the exhaust ventilation system. The second pipe was installed with a pressure relief valve set to 250 psi. This ensured that the pressure of the combustion did not exceed the rated pressure of the combustion chamber. Additionally, the exhaust pipes were twice the diameter of the inlet pipe to account for even more pressure during combustion. Both exhaust ports came out of the bottom of the combustion chamber. This was to allow any unburnt liquid diesel to flow out of the chamber and be caught in the bottom of the exhaust pipes. Since the testing facility lacked a forced air exhaust system, one was fashioned to ensure that the exhaust gases were pumped to the atmosphere after combustion so that the hydrogen did not accumulate in the testing lab.

Safety was of the utmost concern during the design and testing of the combustion chamber. All parts were designed to operate at the high temperatures and pressures involved in the combustion and fuel pressurization processes. During testing operators or technicians were controlling the process from outside of the engine dyno, safely behind a concrete wall. The ceiling exhaust fan ran constantly throughout the testing to ensure that there was no hydrogen buildup in the enclosed space. Additionally, to ensure that no hydrogen was allowed to build up in the room, a hydrogen detector was installed in the

engine dyno. Hydrogen combustion can occur at concentrations as low as 4% in air (per unit volume) so the hydrogen detector was set to give a warning at 1% hydrogen and an alarm at 2% hydrogen [32][33][57].

3.2. Experimental Design

Testing was done under steady state conditions at two different temperatures and two different hydrogen concentrations. The two temperatures used for the experiment were 315°C (599°F) and 345°C (653°F). The temperature of 315°C was chosen because it is near the autoignition temperature of diesel (300°C); and thus near the lowest temperature that should produce combustion. This low temperature should be near the minimum threshold where combustion would occur. The temperature of 345°C was chosen because it was the hottest temperature that the combustion chamber could get to while still being able to hold the temperature steady. The temperatures could not be greater than the autoignition temperature of hydrogen (500°C), as the hydrogen could ignite with or without the diesel; thus making the testing irrelevant. The two hydrogen concentrations used were 59% and 43% (per unit volume). These hydrogen concentrations were chosen because of the limits of the test equipment. Two hydrogen concentrations and two temperatures were used to see the relation, if any, between temperature and hydrogen concentration on the results. With the end goal of very low amounts of diesel fuel and high amounts of hydrogen being used in hydrogen-diesel dual-fuel combustion in diesel engines, low concentrations of hydrogen become irrelevant because low concentrations do not produce enough power for IC engines in vehicles. For this reason, testing was not done near the lower end of the flammability range of hydrogen. Due to the limitations of the equipment used, each temperature was allowed to have a tolerance of $\pm 3^\circ\text{C}$ and each hydrogen concentration a tolerance of $\pm 3\%$.

To validate the safety and functionality of the test apparatus, preliminary test runs were performed. The preliminary testing was done at the two operating temperatures using no hydrogen. This was done to confirm that the diesel does ignite with the test setup at the appropriate temperatures, and that no damage has occurs and the test apparatus is safe. Additionally, preliminary testing was done with hydrogen to confirm that the IR sensor could detect combustion of the hydrogen-diesel mixture.

At each operation point, each test was repeated five times to ensure that the quantities of diesel found were statistically significant. The solenoid valve setup allowed for a minimum difference of 1 *ms*

between injection test runs. The quantities injected that are much greater than the final minimum amount found needed only to be ran one time because they were irrelevant to the final minimum quantity and thus a statistically significant amount of data was not needed.

3.3. Experimental Procedure

Before any test runs were performed, the chamber and the inlet air were heated until the appropriate steady state temperature was reached. This allowed for all of the components to reach a temperature that was consistent between all test runs of a particular temperature. To conserve hydrogen, initially only air was pumped through the apparatus to preheat it. Once the test apparatus was heated to the appropriate temperature, hydrogen was introduced and the temperature was increased to compensate for the temperature decrease caused by the hydrogen addition. The diesel fuel was injected once an equilibrium state was reached. Equilibrium was assumed to have been achieved when the temperature ceased to change with time. The data recorded by the microprocessor would then be saved to a file after each test run. The amount of diesel injected was controlled by how long the solenoid valves remain open. If the quantity of diesel injected needs to be changed for the next test, the code was adjusted to change how long the solenoid valves stay open for.

The hydrogen-air mixture was allowed to flow through the test apparatus without diesel injection for at least 11 seconds between each run. This allows the products of the previous combustion to flow out of the combustion chamber so that each test is consistent in lack of water, soot, smoke, NO_x and carbon dioxide. As a general rule, the chamber must have 10 times its volume of fluid flow through it for it to be considered clear of combustion contaminants. The volume of the chamber was $.0593 \text{ ft}^3$; therefore $.593 \text{ ft}^3$ of the hydrogen-air mixture must flow through the chamber after injection before the following injection can occur. For the test runs with hydrogen concentrations of 59% and the air concentration of 31%, the hydrogen and air flow rates needed to be $1.92 \frac{\text{ft}^3}{\text{min}}$ and $1.3 \frac{\text{ft}^3}{\text{min}}$, respectively. For the test runs with hydrogen concentrations of 43% and the air concentration of 57%, the hydrogen and air flow rates needed to be $1.92 \frac{\text{ft}^3}{\text{min}}$ and $2.5 \frac{\text{ft}^3}{\text{min}}$, respectively. These flow rates correlate to .18 minutes (10.8 s) between injections for the 59% hydrogen concentration and .13 minutes (7.8 s) between injections for the 43% hydrogen concentration.

The chamber temperature was confirmed to be correct before injection occurred. The test temperature and hydrogen-air concentrations were kept constant until the quantity of diesel was found. Once the quantity of diesel was found for a set of test parameters, the temperature and hydrogen concentration were adjusted to find the minimum diesel quantity for another set of test parameters.

CHAPTER 4. RESULTS

4.1. Mass Equation Validation

To validate the two previously mentioned equations, the estimated mass corresponding to the pressure curve were compared to the measured fuel injected. During this injection, the pressure of the fuel was measured using the previously mentioned pressure transducer. Figure 9, depicts a typical pressure curve for 1 ms of injection.

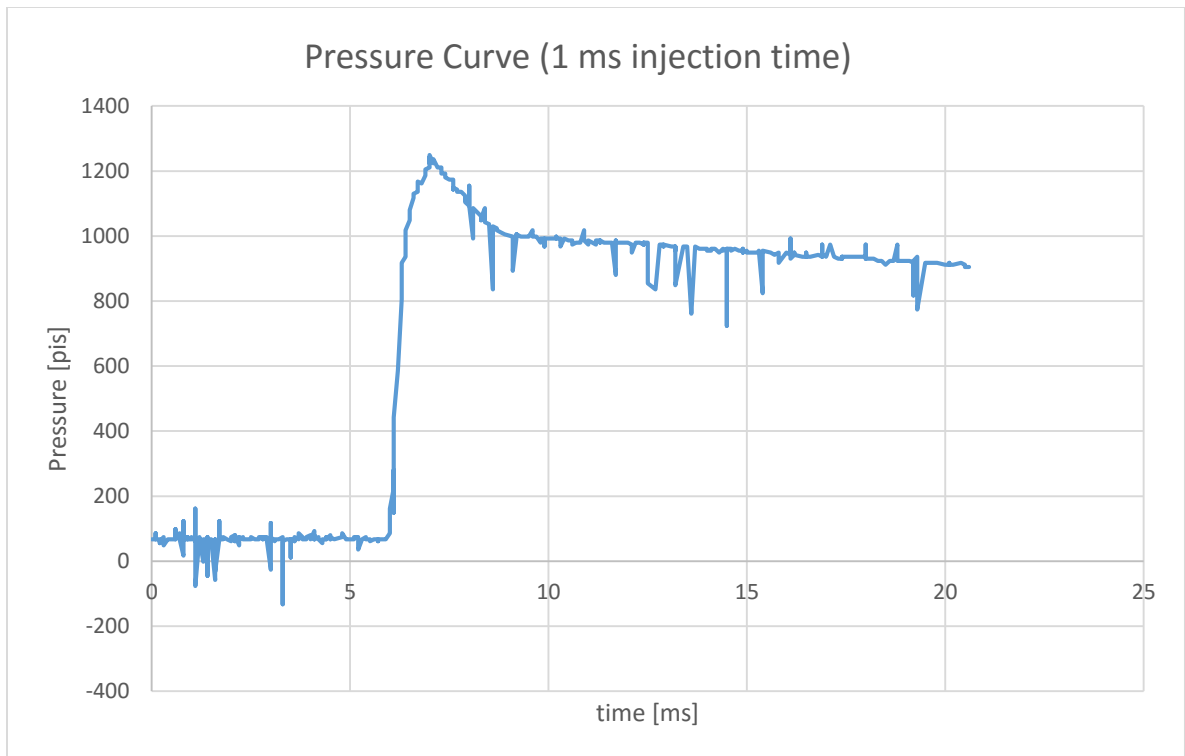


Figure 9. 1 ms Pressure Curve

Before doing any calculations the noise, seen above in Figure 9, was filtered out. The results using both of the previously mentioned equations to calculate mass injected for this case are 19.2683 and 15.4 mg for the first and second equations, respectively. The actual quantity injected was collected using a latex rubber balloon around the injector. The latex balloon was weighed before and after injection. The difference between the weights before and after injection was approximately 15.7 mg. This was done a statistically significant number of times to ensure a valid result. There is an error of approximately 19% when using equation (10). This was attributed equation (10) being derived from a steady state equation. Since the pressure reading was transient the equation did not work successfully. Equation (11) was

based on an equation with a transient pressure input. Thus equation (11) resulted in less than a 1% error in calculating mass injected.

4.2. Mass Injected

The primary goal of this research was to find a very small quantity of fuel that would still result in combustion of the hydrogen-air mixtures. As stated previously, this was done by controlling the time fuel flow was allowed through the injector using solenoid valves. This research found that at both temperatures (315 °C and 345°C) and at both hydrogen concentrations (59% and 43%) the hydrogen-air mixture would ignite with an injection time of 1 *ms* for all combinations. Table 3 shows that combustion testing results. Each box marked with a green check mark indicates that combustion occurred and thus the diesel injected ignited the hydrogen. A dash in a box means that testing was not done at that point. Only the minimums were important for this testing, therefore it wasn't necessary to inject for the all of the longer times. The minimum injection time that the test apparatus for this research was capable of doing was 1 *ms*.

Table 3. Combustion Testing Results

	$T = 315^{\circ}\text{C}$ $H_2 = 59\%$	$T = 345^{\circ}\text{C}$ $H_2 = 59\%$	$T = 315^{\circ}\text{C}$ $H_2 = 43\%$	$T = 345^{\circ}\text{C}$ $H_2 = 59\%$
10 <i>ms</i>	✓	✓	✓	✓
7 <i>ms</i>	✓	✓	-	-
6 <i>ms</i>	✓	✓	-	-
5 <i>ms</i>	✓	✓	-	-
4 <i>ms</i>	✓	✓	✓	✓
3 <i>ms</i>	✓	✓	✓	✓
2 <i>ms</i>	✓	✓	✓	✓
1 <i>ms</i>	✓	✓	✓	✓

The average mass of diesel fuel injected for 1 *ms* was found to be 17.4 *mg* with a minimum of 15.7 *mg*. The average flow rate of diesel was calculated out to be $133.5 \frac{\text{cm}^3}{\text{min}}$, and a minimum flow rate of

diesel of $120.46 \frac{cm^3}{min}$. The average flow rate is almost exactly the same as the minimum rate found in diesel injection systems and the response time for test setup was $1 ms$, exactly the same as the best performing diesel injectors in the automobile industry. The test setup in this research was successfully able to reach both minimum injection parameters found in the diesel engine vehicles, expressed earlier. The results show that even at industry minimums the diesel injected will result in hydrogen combustion, and thus, all current engines should be able to function operating using dual-fuel hydrogen-diesel combustion using their individual minimum possible injected quantity. It is quite possible that the injection profile for the $1 ms$ injection shown in Figure 9 is the smaller than any that can be produced by any vehicular diesel injection setup.

CHAPTER 5. CONCLUSION

5.1. Conclusions and Impacts

From the results presented in Chapter 4, it can be concluded that diesel fuel will ignite a hydrogen-air mixture when injected using flow rates and response times comparable to that of the diesel automobile industry's lowest flow and highest speed injectors. From this conclusion it can then be said that all current automobiles have the potential, with appropriate modifications, to be powered by hydrogen that is ignited by the minimum quantity of diesel that is possible for a vehicles injection system to produce. In other words, all current vehicles can be retrofit to be able to run primarily on hydrogen combustion; furthermore, the hydrogen-air mixture in the cylinders of the engines will be able to ignite when the minimum amount of fuel, that an injection system can produce, is injected. In addition, new vehicles, with current injection capabilities can be initially designed for hydrogen-diesel dual-fuel combustion, forgoing the retrofitting process altogether.

Further developments should be made in the field of diesel injectors. Injecting extremely minimal amounts of diesel is generally not the objective of current injectors, however, with the objective of diesel being only the ignition source, not the power source, new injection systems need to be developed. Furthermore, studies need to be done to find the absolute minimum amount of diesel that will ignite a hydrogen-air mixture. From the analysis done in Chapter two of this paper, the quantity of diesel should be multiple orders of magnitude less than the quantity found in this research. The injection systems developed will need to be able to inject significantly less than the amount capable in current diesel vehicle injection systems.

The knowledge that all current vehicles can be powered by hydrogen using a minimum amount of diesel fuel should promote the expansion of the hydrogen powered vehicle industry. The expansion of the hydrogen vehicle industry will lead to more studies being done to increase efficiencies and reduce emissions, particularly NO_x . Additionally, the issues involved in hydrogen/hydrogen-diesel combustion such as knock and injection timing will also be addressed.

The increase in the hydrogen substitution of diesel will work to reduce the demand for petroleum products. This decreased demand should reduce the costs of petroleum products, as well as reduce consumption. Reducing consumption should allow petroleum products to be used for a longer period of

time because the supply of petroleum will not diminish as quickly. Additionally, reducing petroleum consumption in vehicles will allow it to be consumed in other sectors where the alternative power sources, such as hydrogen, are not as viable as in the automobile industry, particularly power sectors that operate with much high efficiencies than seen in vehicles.

In addition to the economic benefits, increasing hydrogen power; and thus decrease petroleum consumption, will work to stop global warming. As explained in Chapter 1, petroleum combustion produces GHGs, which work to retain heat in the atmosphere, raising the global average temperatures. Hydrogen combustion produces no significant GHGs and thus does not contribute to global warming. This will allow vehicle manufacturers to comply with new and future emission laws, specifically in the area of GHG emissions.

With more hydrogen consumption, however, the demand for hydrogen will naturally increase. This will lead to hydrogen production by means of both electrolysis and gasification. While gasification does produce GHGs, gasification has higher efficiencies than IC engines, and thus less GHGs will be produced on a per unit power basis. Perhaps the greatest benefit of an increased demand for hydrogen, however, is the development of hydrogen infrastructure. Of course, a hydrogen based infrastructure is vital for vehicles to be powered by hydrogen. With a hydrogen infrastructure, additionally, FCVs become more viable. With greater efficiencies than IC engines powered by both petroleum and/or hydrogen, FCVs, when they become economically viable, will be the future of vehicular power. Thus, hydrogen-diesel dual-fuel vehicles are a means to be able to create an environment where FCVs are viable.

5.2. Summary

This research looks into seeing if diesel injectors in the automobile industry are capable of igniting a hydrogen-air mixture when operated at their limits. The goal of this research was to design and fabricate a test apparatus that can produce, detect and contain combustion while operating at the limits of current engine injectors. The test apparatus was able to achieve a minimum flow rate of $120.46 \frac{cm^3}{min}$ and had a response time of $1 ms$, both these parameters are equivalent to, or better than the injection setups found in diesel vehicles. With these minimums, an average minimum quantity of $17.4 mg$ of diesel fuel was injected into a hydrogen-air mixture. Successful combustion occurred and was detected with this

quantity of diesel, thus proving that all diesel injectors and injection setups in the automobile industry can operate using dual-fuel hydrogen-diesel combustion.

5.3. Future Work

There are several areas that this research can transition to. The first area that should be looked into is in finding even lower quantities of diesel that can ignite hydrogen-air mixtures, and ideally find the minimum quantities injected for a range of temperatures and hydrogen concentrations. The quantity found in this research is not the absolute minimum amount of diesel that can ignite hydrogen. The quantity found in this research proves that all diesel injectors used in the automobile industry are capable of igniting hydrogen when operated at their limits. The quantity in this research additionally began to look past the limits of the capabilities found in vehicular injection systems. The absolute minimum quantity should be found and used to help guide the development of new injectors and injector systems that are designed to inject extremely small amounts of diesel for the purpose of using high quantities of hydrogen and the minimum quantity of diesel possible. This quantity should approach the minimum amount calculated in the preliminary analysis of this paper, though the amount calculated in this paper would not be enough diesel to ignite a hydrogen-air mixture due to the ideal conditions and assumptions used in the analysis.

The second area that will need to be looked into is the timing of injection in the engine cycle. The small flow rates used in this research may produce inferior atomization of the fuel. This inferior atomization will cause the time from injection to ignition to increase; and thus combustion may not occur at the correct crank angle in practical applications and may not be as consistently produced. Additionally, decreasing the amount of fuel injected will reduce the number of reactions in the diesel fuel and may also cause delays in ignition or result in not enough energy to ignite the hydrogen.

Finally once these issues are solved, the many issues attributed to hydrogen combustion, in general, mentioned in the literature review section of this paper, will have to be solved. The most prevalent of these issues is knock. If the timing issues are solved, however, knock may also be able to be controlled or eliminated. Further studies will need to be done on the emissions. The CO_2 and hydrocarbon emissions should not be a problem, and be practically non-existent, however, the NO_x

emissions may become a problem. But, as mentioned previously in this paper, various methods of reducing or elimination NO_x are common in industry.

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APPENDIX. TEST APPARATUS PICTURES

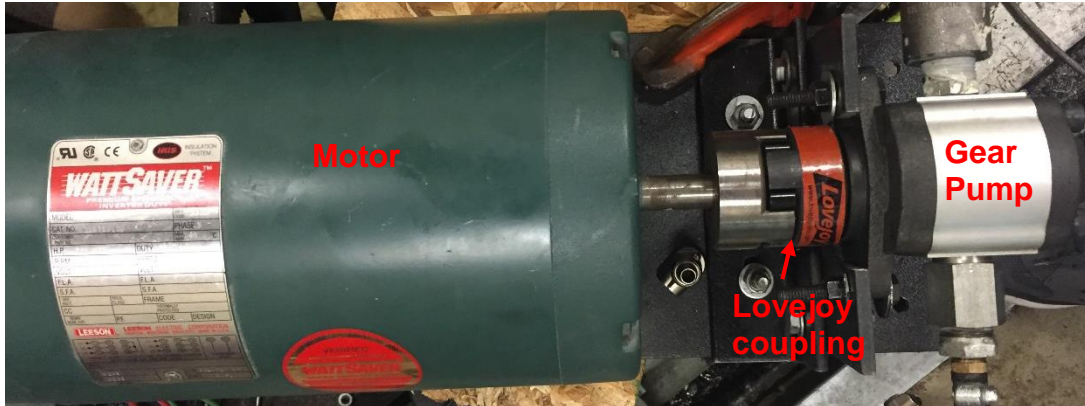


Figure A 1. Motor and Gear Coupled



Figure A 2. Motor Controller

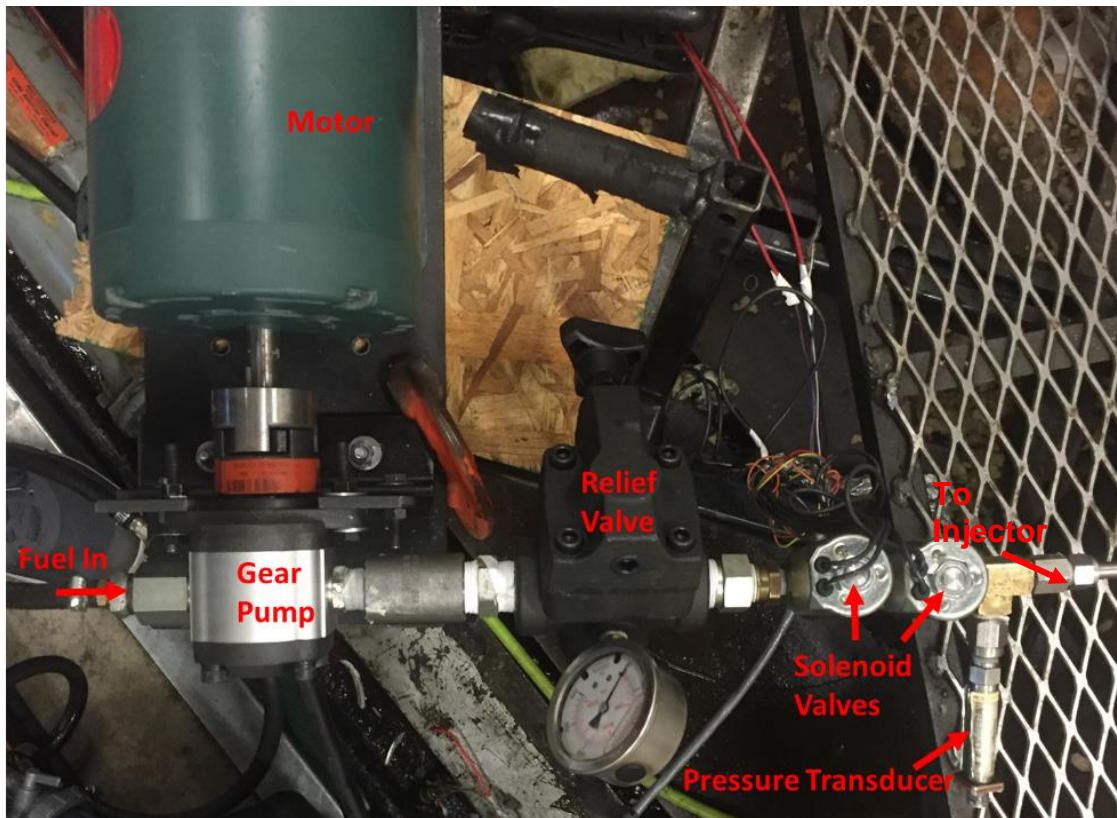


Figure A 3. Injection Setup

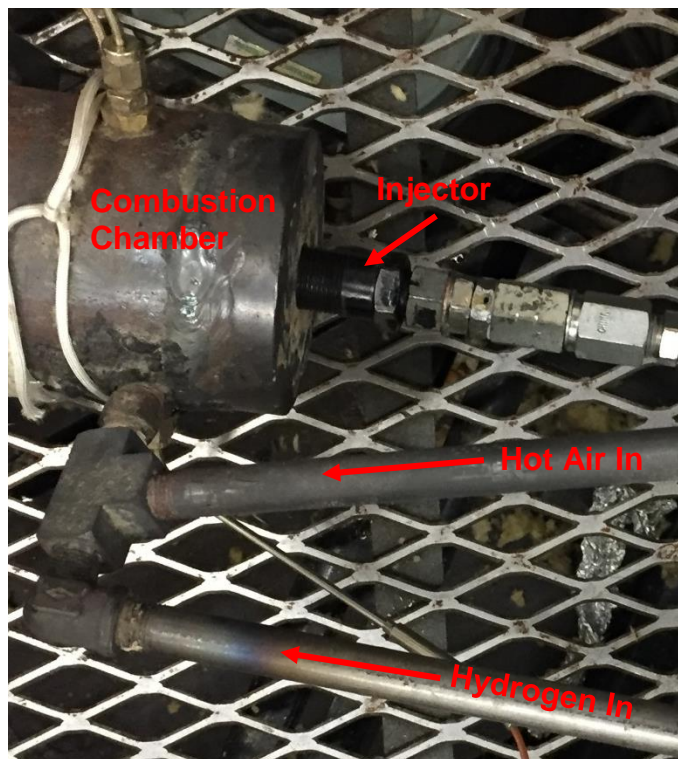


Figure A 4. Combustion Chamber Inlets

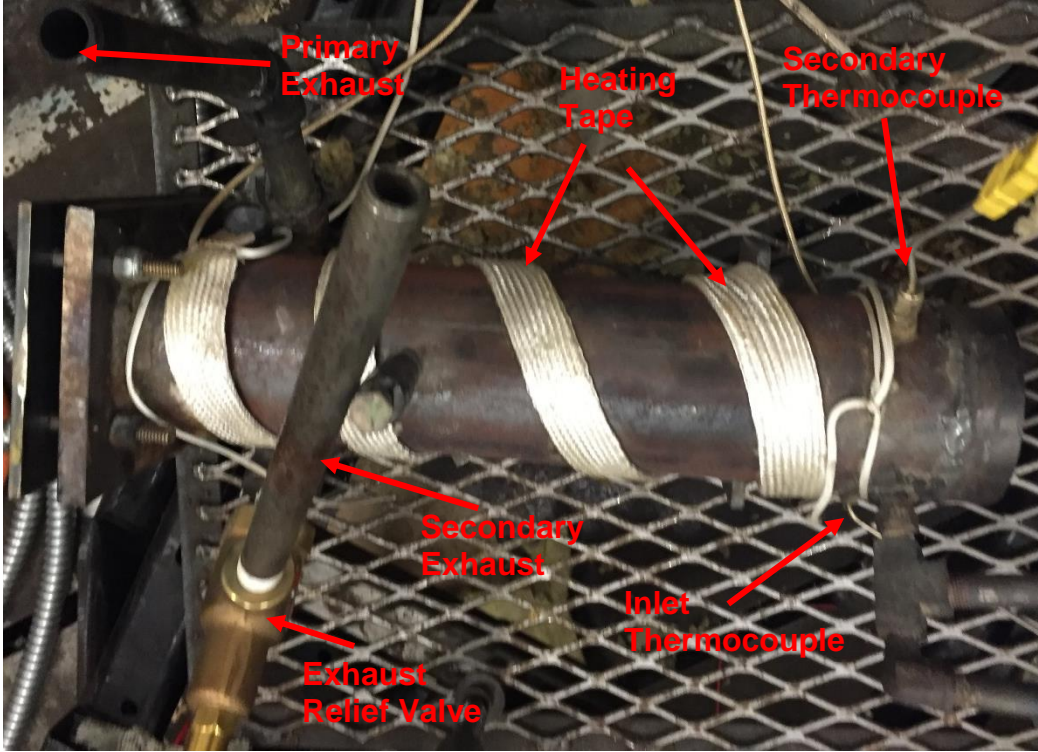


Figure A 5. Combustion Chamber

Note that the main combustion chamber was insulated during testing.

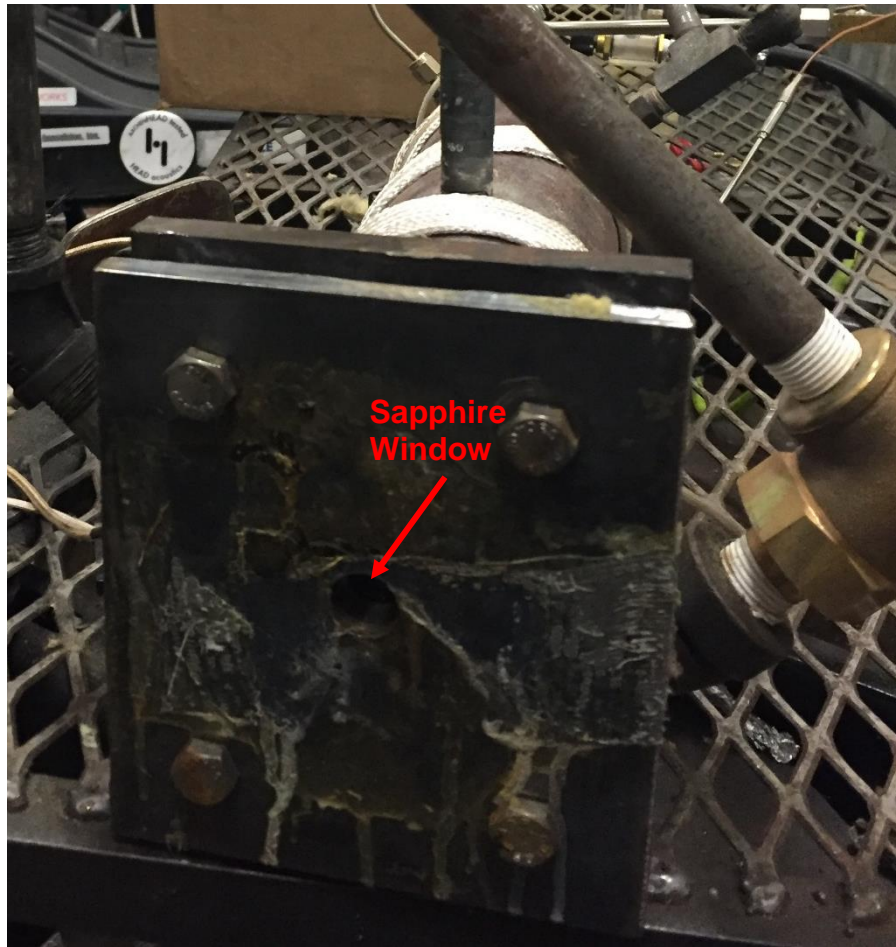


Figure A 6. Sapphire Window



Figure A 7. Sapphire Window Close Up

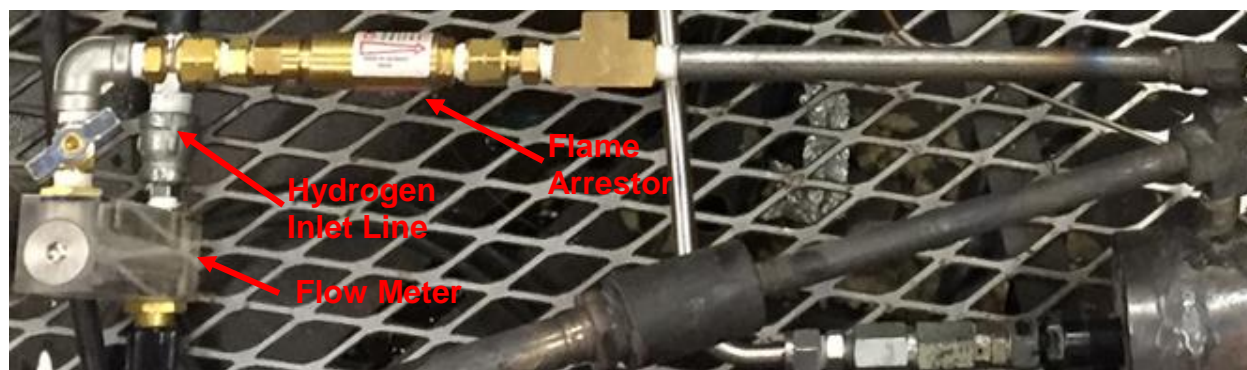


Figure A 8. Hydrogen Inlet Setup

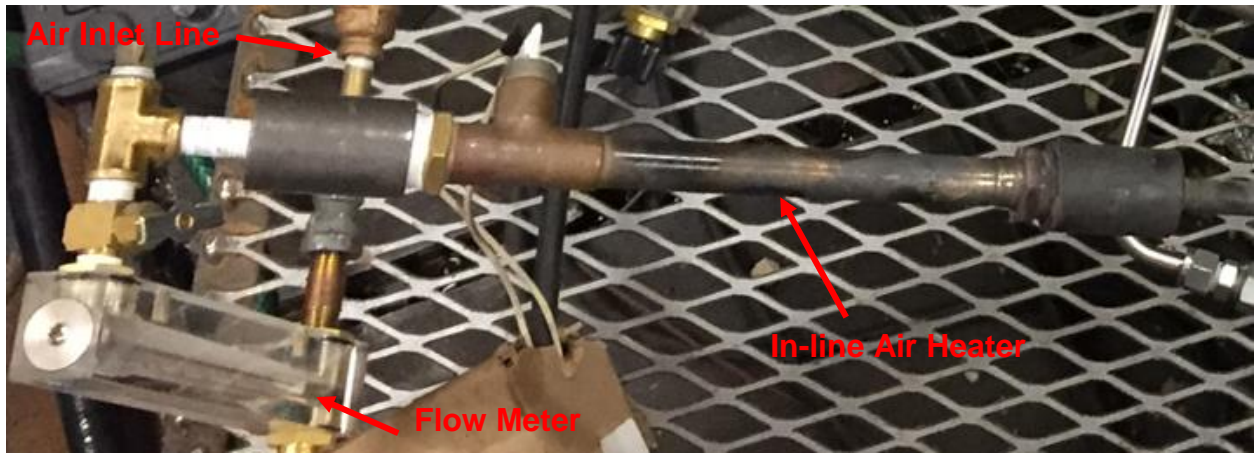


Figure A 9. Air Inlet Setup