Title
Evaluation of the Performance of a Variable Geometry Low-Swirl Burner Operated on Simulated Renewable Fuels in a Boiler Environment

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Publication Date
2014

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Evaluation of the Performance of a Variable Geometry Low-Swirl Burner Operated on Simulated Renewable Fuels in a Boiler Environment

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in Mechanical & Aerospace Engineering

by

Nathan James Kirksey

Thesis Committee:
Professor Scott Samuelsen, Chair
Dr. Vincent McDonell
Professor Derek Dunn-Rankin

2014
DEDICATION

To my parents, Judie and David,

Amanda,

And to my friends and family

For their support and encouragement
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ABSTRACT OF THE THESIS

Evaluation of the Performance of a Variable Geometry Low-Swirl Burner
Operated on Simulated Renewable Fuels in a Boiler Environment

By
Nathan James Kirksey
Master of Science in Mechanical and Aerospace Engineering
University of California, Irvine, 2014
Professor Scott Samuelsen, Chair

This thesis evaluates a variable blockage low-swirl injector operated on digester gas in a simulated boiler environment to understand how such a device can impact combustion performance as fuel composition varies. California, like many other states, is requiring a reduction in emissions from primary sources of electricity generation. As emission regulations become stricter, novel strategies for achieving the reductions required are required. The current energy policy in California specifically promotes the use of renewable and carbon neutral fuels such as digester gas. The future generations of burners must be fuel flexible in order to meet these emission laws while providing continual operation. To address this, a variable geometry low-swirl injector was developed and its emissions and stability performance assessed using a variety of diagnostics. It was found that a fiber optic probe, integrated into the injector head, was able to provide a reliable measure of emissions and stability. One key result from the optical probe is that the recorded radiation emitted by the reaction corresponding to the lean blow off limits of any composition of digester gas remains constant, implying it could serve as a robust stability sensor with minimal signal processing. Evaluating the role of the variable geometry found that (1) variable center blockage in a low-swirl injector has no effect on the lean blow off...
limits, (2) as the center blockage becomes less restrictive the NOx emissions will increase, and (3) incorporation of a quarl expansion rather than a sudden expansion increased the lean blow off limits and gave a 50% reduction in NOx emissions. Utilizing a low-swirl injector with high blockage in the central flow, high swirl number, can reduce the NOx emissions across the range of lean operating conditions.
CHAPTER 1: INTRODUCTION

1.1 Overview

The use of combustion across the world is an essential part of almost all daily tasks whether it is for transportation, electricity, resource synthesis, or other processes. In the United States about 67% of the total electricity produced comes from a combustion source whether this is a boiler, gas turbine, or some other generator. Combustion is an integral part of the electric grid but it does not come without its flaws, all combustion sources produce emissions as a byproduct of the necessary heat release process. In recent years, these emissions have been directly tied to being environmental and health risks and as such legislation has come forward to limit the amount of emissions that can be released for a given generator.

Combustion emissions are regulated on many species but the three most common emissions are oxides of nitrogen (NO\textsubscript{x}), carbon dioxide (CO\textsubscript{2}), and carbon monoxide (CO). Each species has certain mechanisms that contribute to its creation; as such avoiding the activation mechanisms can greatly reduce the amount released. Some methods used to avoid the activation of said pollutants are changing the fuel and changing the mixing. An increase in the use of natural gas, largely composed of methane (CH\textsubscript{4}), in recent years is in part due to the environmental impact natural gas plays when burned as opposed to coal. Coal has large carbon chains, as compared to natural gas, that produce a lot of carbon emissions, so by replacing coal with natural gas the amount of carbon emissions can be reduced. As will be discussed, changing the fuel in a combustion system is non-trivial and in some cases cannot be done. The mixing of fuel and air and in what proportion is a large contributor to emissions. Fuels that are premixed with the air generally have lower emissions than fuel injected boilers but this is a tradeoff for stability. In addition, operating with extra air can lower the emissions of NO\textsubscript{x} and CO, but again
the penalty is a narrowing of the reaction’s stable regions. One category of emission reduction that does not fall under one of the aforementioned methods is to use a renewable fuel type. A renewable fuel is one that is produced from a renewable source and is generally considered carbon neutral. One example is biogas or digester gas; this fuel is generally produced in a digester from municipal waste and consists of CO$_2$ and CH$_4$. Biogas is considered carbon neutral because the source of the fuel comes from organic matter; organic matter is composed of carbon chains that come from the synthesis of CO$_2$, and during combustion that same amount of CO$_2$ is released therefore it is neutral in net emission.

The section above refers to the use of alternative fuels, but in reality using a range of such fuels in a combustion system is not straightforward to accomplish. The injectors for a given burner are generally designed to operate on a given fuel in a given range of air mixtures. When operated outside of this range, the injector generally exhibits reduced performance in terms of emissions or stability and may actually no longer be operable. Traditional injectors are beginning to be retrofitted in order to allow combustion systems to meet emission regulations. A common approach, to meet increasingly restrictive emission regulations is to operate the burner very near blow off which helps avoid conditions favorable for NO$_x$ formation. The composition of every fuel varies to some degree and an injector operating near the blow off limit could have operability issues if a fuel fluctuation was to reach the injector without being compensated for beforehand. To complicate matters further, some fuel mixtures behave unexpectedly and traditional knowledge of burner design is inadequate (Lieuwen, et al., 2008). An injector’s lack of fuel flexibility causes problems for some generators that operate on a renewable fuel, which varies day to day, and has a backup fuel such as propane; switching between the two require a special or separate injector. Also, a strategy of co-firing renewable fuels with traditional fuels
may provide an opportunity to reduce carbon intensity. However, the amount of renewable fuel that can be co-fired will depend directly on how fuel flexible the burner is.

This thesis examines a strategy for solving the lack of flexibility of current injectors and the need for low emissions combustion systems that can operate on renewable fuels, specifically biogas. In order to meet both of these criteria a variable geometry low-swirl injector will be used to operate in a boiler running biogas. The blockage in the center of the low-swirl injector will be varied to change the stability regime of the injector depending on what fuel is being burned. A wide range of biogas will be burned in conjunction with more reactive fuels to determine fuel flexibility. The goal is to make a drop in replacement for legacy injectors that will safely operate on a wide range of Wobbe Indexes and with minimal emissions.

1.2 Goal and Objectives

The goal of this project is to use a variable center blockage in a low-swirl injector operated on biogas in a 400,000 BTU/hr (117 kW) boiler environment in order to determine its effect on flame stability. In order to fully simulate the effects that a renewable fuel will play in the injector the fuel composition of the digester gas will range from 100% CH₄/0% CO₂ to 50% CH₄/50% CO₂ by volume. The included range is similar to those found in industry as well as an included control case of pure natural gas. The main goal of this project will be to:

1. Determine the flame stability and emissions of variable geometry low-swirl injector technology in a simulated boiler environment operating on natural and digester gas.

The necessary steps to be taken in order to successfully complete the goals of this project will be:

1. Develop and Execute Test Plan. This will establish guidelines in order to gather the diagnostic data required to obtain knowledge of the entire process.
2. Install a Low-Swirl Burner With Variable Geometry. This will allow testing of the effects of the blockage, independent of other parameters, for stability.

3. Design a Fuel Flow Control Circuit. This circuit will be capable of supplying the necessary range of digester gas while maintaining the input heat rate.

4. Establish Diagnostics. Particle image velocimetry and OH*/CH* imaging will give further data on the changes that occur when the blockage and fuel is changed.

5. Data Analysis and Design Tool Utilization. Once all the data are collected and processed the trends and correlations can be developed for the changes.
CHAPTER 2: BACKGROUND

The following chapter serves as a primer to the reason why this research is so important and how these phenomena act in our lives. The main areas to be covered will be emissions including NO\textsubscript{x}, CO, and CO\textsubscript{2}, injector geometry and performance, and lastly fuels including biogases and their properties. Controlling emissions is of paramount importance, so knowing the catalyst that drives their production is vital in developing a strategy to mitigate them. Knowing how the injectors operate to stabilize and reduce emissions is a priority for developing future fuel flexible injectors. Lastly, fuels are very diverse and can pose a plethora of properties that make using two different fuels in one injector a challenge for performance as well as emissions.

2.1 Oxides of Nitrogen Emissions
2.1.1 Creation of NO\textsubscript{x}

Oxides of nitrogen are commonly known as NO\textsubscript{x} but this category includes the two molecules: nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). In the presence of favorable conditions, to be covered shortly, the NO that is present reacts to form NO\textsubscript{2}; it is common practice to combine the two species into one group and call it NO\textsubscript{x}. A variety of different mechanisms lead to the creation of NO\textsubscript{x} and the environmental cycle that processes NO\textsubscript{x} is very complex, which makes limiting it at the source very important.

NO\textsubscript{x} creation from combustion sources can take place due to four different drivers and depending on the conditions one or two will be more influential than the others. The first driver that will be covered is known as thermal NO. The thermal NO mechanism is catalyzed by high temperatures, the typical trigger point for NO\textsubscript{x} is around 1850 K, in the presence of nitrogen and
oxygen, or atmospheric air. The Zeldovich mechanism describes the process of the oxidization of nitrogen very well (Zeldovich, 1946):

\[
O_2 \rightarrow 2O
\]

\[
N_2 + O = NO + N
\]

\[
N + O_2 = NO + O
\]

\[
N + OH = NO + H
\]

Leonard and Stegmaier conducted a series of tests with multiple injectors and over many test conditions to develop a graph of flame temperature vs. NOx. The graph in Figure 1 shows the data they compiled and it is clear that the NOx emissions are dependent on temperature; as the flame temperature increases the NOx increases (Leonard & Stegmaier, 1994). The NOx axis is on a log scale indicating that the NOx grows exponentially and at temperatures above the 1850 K trigger point the formation of NOx due to the thermal NO mechanism is very influential.

Figure 1: Corrected NOx vs. Flame Temperature of Many Parameters (Beerer, 2013)
The last driver to consider for the amount of thermal NO produced is the residence time. A reaction that is only exposed to the high temperatures for a short period of time has less time to produce the thermal NO, therefore thermal NO is usually sensitive to how long it is held at these high temperatures.

A second method for NO\textsubscript{x} production is known as the nitrous oxide mechanism. This mechanism is similar to the thermal NO mechanism but includes some extra intermediate reactions that can be found in between the Zeldovich mechanism. The N\textsubscript{2}O pathway is mainly found under high pressure applications so near atmospheric applications, such as in boilers, are usually free of this mechanism. The reactions that use nitrous oxide as a catalyst are summarized as (Nicol, et al., 1995):

\[ N_2 + O \rightarrow N_2O \]
\[ N_2O + O \rightarrow NO + NO \]
\[ N_2O + H \rightarrow NO + NH \]
\[ N_2O + CO \rightarrow NO + NCO \]

The production of N\textsubscript{2}O opens a doorway for three different methods of forming NO.

A third mechanism for producing NO\textsubscript{x} is known as the prompt NO\textsubscript{x} method. This occurs rapidly at the beginning of the reaction when many CH radicals are present. The CH radicals are able to split diatomic nitrogen opening two nitrogen atoms for oxidization. Prompt NO\textsubscript{x} production has been found to be directly related to the presence of hydrocarbons (Fenimore, 1971). Hydrocarbons with larger carbon chains such as acetylene increase the amount of prompt
NOₓ because they have more CH radicals present. Adding more air or running leaner increases both the oxidizing potential as well as the amount of nitrogen available.

A last mechanism for NOₓ production is given by fuel bound nitrogen and is known as fuel nitric oxide. This is not much of a concern for natural gas as it generally does not contain nitrogen but coal or some liquid fuels can have significant amounts of nitrogen present. This nitrogen is then present at the core of the reaction to undergo any of the three aforementioned processes.

2.1.2 Health and Environmental Effects of NOₓ

This section will cover the problems and risks associated with emitting NOₓ into the atmosphere. The presence of NOₓ in the environment is commonly referred to as photochemical oxidant, and when Ozone and NOₓ are found together it is referred to as photochemical smog. The smog over major cities is a complex equilibrium equation that depends on concentrations, sunlight, and other factors. The photochemical reactions of NOₓ and ozone (O₃) in the environment occur as follows (Glassman & Yetter, 2008):

\[
\text{NO}_2 + \text{Ultraviolet Light} \rightarrow \text{NO} + \text{O} \\
\text{O} + \text{O}_2 \rightarrow \text{O}_3 \\
\text{O}_3 + \text{NO} \rightarrow \text{O}_2 + \text{NO}_2 \\
\text{Net Reaction: Light} + \text{NO}_2 + \text{O}_2 \leftrightarrow \text{NO} + \text{O}_3
\]

The above reaction represents the transformation of NO into NO₂ and then the subsequent increase in transformation of oxygen into ozone. Certain regions are prone to extremely high levels of these pollutants; one common example is the Los Angeles Basin. This location has
some major disadvantages mainly being it is a basin that is excellent at keeping the pollutants in one area and the heavy population provides a considerable amount of sources for the NO\textsubscript{x} emissions. The temperature inversion at night as well as the surrounding topography in Los Angeles is a main factor in keeping the constituents present to continue the smog cycle.

The health problems associated with smog are generally associated with O\textsubscript{3} because it is more hazardous relative to NO\textsubscript{x}; the problem with NO\textsubscript{x} is it is essential in the production of O\textsubscript{3}. The major effect of NO\textsubscript{2} on health is likely though the formation of ozone and not due to primary pollutant effects. One study continued on to say that there have been some results that point to NO\textsubscript{2} as being an irritant that can aggravate other symptoms but it is negligible in comparison to the effects of ozone (Bernstein, 2004). Ozone is a strong oxidizing agent that can easily react with most organic materials to destroy them. The presence of ozone is irritating to plants and animals; in animals specifically, it attacks the mucus linings in the respiratory tract and can cause serious damage. In addition, to damage it can even be lethal in humans with previous conditions such as asthma (Haagen-Smit, 1952).

2.1.3 NO\textsubscript{x} Mitigation Methods

The consequences of emitting and the mechanisms for producing NO\textsubscript{x} represent a clear need for a strategy to eliminate these emissions. The methods to be covered in this section all reduce emissions but they all come with a sort of catch or tradeoff that must be made. This section will cover the dry low NO\textsubscript{x} or lean premixed method, using water injection, using air separation units, post scrub strategies, and lastly exhaust gas recirculation methods.

Figure 2 represents a typical emission curve; the curve shows the concentrations and temperature on the vertical axis and the equivalence ratio of the flame on the horizontal axis. By
operating at fuel rich Φ>1 the peak flame temperature is avoided which reduces a large amount of NO\textsubscript{x} that would be emitted due to the Zeldovich mechanism; the downside is that this region does not have enough O\textsubscript{2} to fully oxidize the fuel, leaving CO and unburned hydrocarbons (UHC) behind. Another advantage to operating fuel rich is the stability bonus, fuels burned at or slightly above stoichiometric are very stable and are not prone to blow off. Peak temperatures, and subsequently higher NO\textsubscript{x}, are found in the stoichiometric region as indicated by Φ=1; most burners avoid the stoichiometric or rich zones because they release high emissions. The lean region, Φ<1, has excess air that can absorb heat from the surrounding reaction and provide many oxygen molecules for complete oxidation of the fuel. The lean region has generally lower emissions as compared to rich or stoichiometric but at the expense of reaction stability. (Turns, 2012):

Figure 2: Emission Curves versus Equivalence Ratio (McDonell, 2008)
The dry low NO\textsubscript{x} method operates very similarly to the lean burn section of RQL mentioned before. The key in this method is to have a homogeneous mixture of fuel and air; the premixing of the fuel and air allows it to be evenly distributed eliminating any hot spots in the flame. When the reaction occurs a homogeneous mixture will have a good distribution of air around the fuel in order to absorb heat and aid in complete combustion; through this process the fuel is completely oxidized and the NO\textsubscript{x} is kept low by having extra air to dilute the flame. The lean premixed flame is run with excess air which as seen from Figure 2 has a lower flame temperature and thus lower NO\textsubscript{x} emissions. This method of combustion is termed “dry” because no water is added to the combustion chamber, the water injection method is sometimes used in order to lower flame temperatures. The potential problem with premixed combustion is that any perturbations could provide a path for the flame to propagate up into the injector and cause damage; in addition, the flame could have too much oxygen and could blow off (Lefebvre & Ballal, 2010).

The dry low NO\textsubscript{x} approach mentioned above works well but has its problems with stability; another method is running closer to stoichiometric but using water injection in the flame zone. The water can serve two purposes: one is to absorb heat and therefore reduce flame temperatures while the other is to reduce the availability of O radicals. The reaction continues as follows:

\[ \text{H}_2\text{O} + \text{O} \Rightarrow 2\text{OH} \]

The reaction forces an addition of OH radicals to be present which are not readily used in oxidizing N\textsubscript{2} thus reducing NO\textsubscript{x}. The chemical reaction from the water is not as impactful as the quenching effect the water serves in reducing the effects from the Zeldovich mechanism. The
downside to this solution is the requirement of having a supply of water for injection and any possible complications with equipment downstream (Glassman & Yetter, 2008).

The formation of NO\textsubscript{x} emissions is only made possible through the presence of nitrogen so a proposed method is oxy-fuel combustion, combustion with pure oxygen. This process removes all the nitrogen from the air before combustion to prevent any NO\textsubscript{x} from being produced. The complications of this method include high temperature because no diluting gas is present to lower flame temperatures, extra equipment is necessary to separate nitrogen from air, and typically a supply of water. In most oxy-fuel combustion cases the flame temperatures are so hot they would melt all the equipment if water was not injected to cool the flame, however in some cases the water can be condensed out and recycled. One extra advantage besides the low NO\textsubscript{x} emissions is the chance to sequester the CO\textsubscript{2} emissions because of the lack of other exhaust constituents (Amato, et al., 2013).

If the control strategies in the combustor are not implemented, methods to remove or scrub NO\textsubscript{x} from the exhaust gas stream are necessary. Injecting a stream of urea, ammonia, or cyanuric acid into the exhaust can trigger reactions that will synthesize the NO\textsubscript{x} into another molecule. Using ammonia takes some extra care because temperatures outside of 1250 K will either not help or even increase NO\textsubscript{x} emissions. During use the ammonia will break down into an amine radical (NH\textsubscript{2}) which is effective in bonding with NO and thereby reducing the NO\textsubscript{x} emissions. Urea and the acid both absorb NO in a similar manner but with different intermediate steps. The complications with this method, although it is widely implemented in addition to other combustion control strategies, are the need for a scrubbing substance, temperature control of the catalyst bed, and possible problems with releasing ammonia out of the stack (Glassman & Yetter, 2008).
The last method for controlling NO\textsubscript{x} is by recycling exhaust products back into the combustion chamber. The main reason for using exhaust gas recirculation (EGR) is that it consists of inert molecules that will absorb heat from the flame and lower the flame temperature. In addition to reduced flame temperatures there is a possibility that in some cases the NO\textsubscript{x} emissions can be re-burned in order to reduce their overall concentrations. The EGR method is effective and in some cases necessary; although it does mean more hardware is required to utilize it (Amato, et al., 2013).

2.2 Carbon Dioxide Emissions

2.2.1 Creation of Carbon Dioxide

Carbon dioxide (CO\textsubscript{2}) is associated with the combustion of fossil fuels. All fossil fuels are composed of chains of carbon and hydrogen and during the combustion process the carbon is oxidized to form CO\textsubscript{2} among other species. During the oxidization process one oxygen molecule combines with a carbon atom to form carbon dioxide; the hydrogen molecules form with an oxygen atom to form water. The ratio of the carbon to hydrogen in the fuel determines the carbon dioxide emissions in comparison to the heat released. Fuels such as natural gas are better to burn than fuels such as coal because the carbon chains in natural gas are not as complex as that found in coal.

2.2.2 Health and Environmental Effects of CO\textsubscript{2}

Health effects of CO\textsubscript{2} are negligible; the gas is inert and does not react with most things, however, the environmental effects of CO\textsubscript{2} are significant and give rise to global warming. Carbon dioxide has specific absorptivity characteristics which make it influential in altering the environment. CO\textsubscript{2} has four discreet absorption bands, in the infrared region of the spectrum, which can absorb most of the incident radiation in that region. The sun’s radiation peaks at
wavelengths in the visible region allowing it to pass through the atmosphere relatively un-
attenuated. As it hits the ground it is absorbed and heats the ground; upon remission of the
radiation it leaves at a peak in the infrared wavelengths. The radiation emitted in these infrared
wavelengths is absorbed by the CO$\textsubscript{2}$. This leads to a net absorption of radiation transitioning into
a change in the overall temperature of the environment (Howell, et al., 2011). The problem with
this natural phenomenon is that it can lead to unexpected consequences including a change in the
global climate that may not be natural. With increased combustion and CO$\textsubscript{2}$ emissions the
concentrations present in the atmosphere increase and this leads to an even greater impact on the
environment.

2.2.3 CO$\textsubscript{2}$ Mitigation Methods

CO$\textsubscript{2}$ emissions are very stable and do not react well with other species present therefore it
is difficult to remove from the atmosphere. The only true method for removing CO$\textsubscript{2}$ from the
atmosphere in a timely fashion is to let nature do its work. Living things that undergo
photosynthesis absorb the atmospheric CO$\textsubscript{2}$ to help lower the atmospheric concentration;
however the rate at which current combustion emits CO$\textsubscript{2}$ and photosynthesis absorbs it is not
equal, leading to a net increase of CO$\textsubscript{2}$.

One of the only ways to reduce the amount of CO$\textsubscript{2}$ emitted for a given fuel is by
improving the efficiency of the generator in use. As was mentioned earlier the amount of CO$\textsubscript{2}$
emitted per amount of heat is a constant for a given fuel. If a given combustion system can use
more of the heat released than another then it is more efficient and will require less fuel to
produce the same amount of useful product; if less fuel is used then less CO$\textsubscript{2}$ emissions are
released.
Another method to remove CO$_2$ from the environment is with carbon capture and storage (CCS). This method takes a CO$_2$ rich exhaust stream and separates off the other emissions. The excess CO$_2$ is then compressed and stored in salt caverns or other geological formations (Amato, et al., 2013). This solution is not a permanent answer for dealing with CO$_2$ because the inert nature of CO$_2$ means that the captured gas will not ever be removed but instead it will stay in storage forever.

A last method for removing CO$_2$ from the environment or rather to stop its net increase is to burn carbon neutral fuels. Fuels derived from human waste or biomasses are taken from plants that over their lifetime absorbed CO$_2$ in order to grow. Once burned the emission of CO$_2$ is the same as what was initially absorbed so it can put a stop to CO$_2$ emissions. Burning fossil fuels in the ground brings forth a net increase in CO$_2$ because these fuels have not provided CO$_2$ abatement for thousands of years.

2.3 Carbon Monoxide Emissions

2.3.1 Creation of Carbon Monoxide

Carbon monoxide is produced in a reaction for a multitude of reasons and poses a serious health risk. CO is readily created during a rich reaction; the excess fuel is not completely oxidized leaving the carbon as CO instead of CO$_2$. CO in lean conditions is produced because the burning rate is dramatically slowed at lower temperatures leading to yet again insufficient oxidation (Lefebvre & Ballal, 2010).

2.3.2 Health and Environmental Effects of CO

CO is a dangerous gas that can cause serious illness to those that come into contact with it. CO is a tasteless, odorless, non-irritating gas but it is highly toxic because it has a strong affinity to bond to hemoglobin in the blood. The affinity for hemoglobin with CO is 210 times
that for oxygen making it preferentially absorbed and replacing oxygen. CO poisoning causes the vital oxygen molecule to be unavailable for bodily processes which eventually leads to asphyxiation. The steps of CO poisoning include headache, dizziness, irritability, confusion, disorientation, nausea, chest pain, cerebral edema, convulsions, coma, and death (Prockop & Chichkova, 2007).

2.3.3 CO Mitigation Methods

Reducing CO is a manageable practice that has a few key points to achieve in order to reduce or completely mitigate CO emissions. One common starting point in reducing CO emissions is getting a perfectly premixed mixture of fuel and air. If the mixture is not perfectly premixed there will be pockets of rich and lean equivalence ratios. In the reaction zone of a rich pocket a lack of air results in a failure to oxidize the fuel producing CO and if a lean zone pocket is reacted the reaction may not be enough to complete the reaction. If the perfect premixing is achieved the equivalence ratio will be consistently at a value that will reduce CO. Another way to reduce CO is to eliminate the presence of cold regions on the wall that could quench the reaction and freeze the CO in that state (Lefebvre & Ballal, 2010).

2.4 Fuels
2.4.1 Renewable Fuel Legislation

Currently in the state of California multiple pieces of legislation call for a reduction in emissions and an increase in the use of renewable fuels for electricity production. The cause for the legislation is essential in producing a sustainable society and reducing the factors that influence global warming. Assembly Bill 32 calls for a reduction in greenhouse gas emissions, CO$_2$ among others, from current levels to those that were present during the year 1990 by 2020 (Board, 2006). The second piece of legislation is California’s Renewable Portfolio Standard.
This program calls for 33% of the electricity in California to come from a renewable source of energy by 2020 (Commission, 2011). Sources of renewable fuels that come from plant matter are considered carbon neutral because the plants take in the same amount of carbon during their growth as would be expelled during combustion. Using renewable fuels from this source would meet both pieces of legislation allowing a reduction in greenhouse gas emissions and using a source of fuel that can be continually replenished.

2.4.2 Digester Gas

Digester gas is a fuel derived from municipal waste or other similar waste streams. The process for transforming waste into fuel starts in the digester. In the digester the waste is mixed together with bacteria; the bacteria feed on the waste in the absence of oxygen. As the bacteria are feeding they give off the products of methane and carbon dioxide. The waste stream used to capture this fuel would otherwise be wasted and go through natural anaerobic digestion that would give off methane molecules into the environment. The capture of this stream and using it in a digester allows the maximization of useable energy or fuel and the minimization of negative environmental impacts. Upon exit of the digester the gas can range anywhere from 55% methane to 70% methane with the remainder being carbon dioxide (Krich, et al., 2005).

As mentioned before the problem with directly substituting biogas with natural gas or propane is due to the high amounts of CO₂ diluting the fuel stream. Given the same hardware trying to flow biogas into a boiler would produce too much air for the amount of methane being injected and would lead to either a no light scenario or a poorly stabilized flame. In addition, the reaction is much slower due to the increased concentration of diluent present; the laminar flame speed of a 60% methane biogas mix at an equivalence ratio of 1 is about 17 cm/s as compared to pure methane at a speed of 28 cm/s (Hinton & Stone, 2014). The solution in the past has been to
use a parallel burner designed specifically for biogas but this is costly and complicated among other things. The future of injectors calls for fuel flexible injectors such as the low-swirl injector which can operate on a wide range of fuels.

2.4.3 Fuel Interchangeability

When considering the operation of a combustor with a fuel other than what it was designed for some important things must be considered. Mainly a highly reactive fuel such as hydrogen will perform differently than an inert fuel such as digester gas. The main number for comparing fuels is known as the Wobbe Index (WI):

\[
WI = \frac{HHV}{\sqrt{SG}}; \quad HHV = Higher\ Heating\ Value, SG = Specific\ Gravity
\]

When this number is similar between two fuels it suggests that the fuels are interchangeable with the current hardware. The WI takes into account the heat released per cubic foot of the gas and the density of the gas, by relating these it can combine the effects of pressure drop and heat release between different fuels to decide if one injector is compatible. The problem with trying to drop in fuels becomes apparent when you consider the WI of multiple fuels as seen in Table 1:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Natural Gas</th>
<th>Digester Gas</th>
<th>Syngas</th>
<th>Hydrogen</th>
<th>Propane</th>
</tr>
</thead>
<tbody>
<tr>
<td>WI (Btu/scf)</td>
<td>~1360</td>
<td>~600</td>
<td>~300</td>
<td>~1200</td>
<td>~2000</td>
</tr>
</tbody>
</table>

Table 1: Wobbe index of multiple gaseous fuels on HHV basis

Table 1 implies that natural gas and hydrogen would perform similarly through the combustion system however this is not as straightforward as it seems. Hydrogen is a much more reactive flame than natural gas and in a premixed flame the risk of flashback is a dangerous proposition.
Putting hydrogen in a natural gas injector would give similar pressure drop and heat release but the possibility of flashback could easily destroy a burner. Similarly syngas will not supply enough heat without increasing the pressure drop and propane would release too much heat or not give enough pressure drop to hold a flame.

Due to the difficulty most combustors are designed to operate on one fuel and lack fuel flexibility. The call for fuel flexible injectors is a priority more than ever for multiple reasons: they can allow for improved emissions, an inexpensive alternative when other fuel prices increase and they can meet future legislation. Digester gas is one alternative fuel that poses the complication in the aforementioned sentence, it can be challenging as a drop in fuel but it does emit less emissions and is cost effective. Adapting injectors for operation on digester gas can provide many wastewater plants with the access to a relatively free energy source that is a welcome alternative to traditional fossil fuels.

2.5 Injector Geometry and Performance

Improving performance of injectors has led to the wide variety and innovation of injectors. The typical injector is a geometric configuration that injects fuel into the air stream. Older injectors typically consisted of fuel injected burners where the fuel and air would have little to no time to premix before it is burned. This gave rise to high emissions but as a tradeoff the stability of these injectors was relatively high. Newer style burners operate using a premix strategy where the fuel and air are mixed together before they are burned. These injectors have lower emissions but the tradeoff is that the stability region of these injectors is smaller; in order to improve the stability of these injectors many different geometries and styles are used. Modern injectors incorporate swirl in order to improve mixing, ignition stability, and a spot for the flame speed to match with the injection speed.
2.5.1 Variable Geometry Injectors

Current research has shown that variable flow geometries can, in some cases, improve the performance of the burner by enhancing mixing and improving stability. Varying the flow of air and fuel between multiple concentric annuli in a telescopic fashion, as seen in Figure 3, showed a decrease in NO\textsubscript{x} and an increase in efficiency (Gupta, et al., 1991).

![Diagram of telescopic and concentric annuli of a variable geometry swirler](Gupta, et al., 1991)

Another study was established in order to show the effects that a simple variable geometry would have on the performance of a gas turbine injector. The injectors all had cam shafts that would raise and lower a plug in order to adjust the effective area around the injector as seen in Figure 4. The injector used in this study demonstrated a performance increase as seen by the efficiency and an ability to increase operational loading conditions at regulated emission...
levels. The emission levels were unchanged during these conditions but the efficiency of the system was increased (Arellano, et al., 2001).

![Figure 4: Gas Turbine Injector with a Variable Geometry](image)

Variable geometry injectors have shown promise in allowing the operator to optimize the performance of the injector at all times. During any loading condition or equivalence ratio the strategic distribution of air or fuel can have a significant impact on emissions or stability limits.

### 2.5.2 Low-Swirl Injector Geometry

In this study a low-swirl injector was employed with a variable geometry the following section will cover the effects such a device could impose. The low-swirl injector (LSI) is an injector that consists of two concentric cylinders, the outer annulus provides swirl to the flow and the central jet allows relatively undisturbed flow to pass through. A perforated sheet serves as the blockage in the center of the injector and depending on the amount of blockage it controls the flow split between the inner and outer, swirling, region. The low-swirl injector is reliant on three main geometric parameters to determine the level of swirl the ratio of radii of the two cylinders.
R, the angle of the vanes $\alpha$, and the mass flow split $m$. Combining these three parameters into Equation 2 results in (Therkelsen, et al., 2012):

\[
S = \frac{2}{3} \tan \alpha \frac{1 - R^3}{1 - R^2 + \left[ m^2 \left( \frac{1}{R^2} - 1 \right)^2 \right] R^2}
\]

Equation 2

These three parameters combine for a wide variety of testing cases and possible configurations, all of which can change the flow field and play a role in influencing the flame. The key to properly developing a LSI is to keep the swirl number at a low enough level to avoid vortex breakdown. With the advent of premixed burners the need for strong mixing is not as important, the LSI capitalizes on this with a low strain flame that creates a thin flame front and eliminates vortex induced recirculation. Vortex breakdown can lead to recirculation in the center which increases residence time and thus higher emissions; the proper swirl numbers found previously suggest $S$ is between .4 and .55 (Cheng, et al., 2008).

When designing the LSI the constraint for vane angle is to keep it within a region of $30^\circ$ to $42^\circ$; operating outside of this range will cause either too much or not enough swirl. As far as lean blow off or stability the vane angle does not have an effect in changing this. The ratio of radii is suggested to be held in a range of .5 to .8, but this also does not have any positive or negative effects on lean blow off. In all the test cases the flow split was not explicitly tested and only kept to a previous rule of thumb of .7 to .8 (Therkelsen, et al., 2012). Figure 5 includes some of the previous trials done in the study; as can be seen the blockages were not changed systematically so the effect of the blockage could not be discerned individually. Another test was performed on a LSI, with swirl of .54, on natural gas and other hydrocarbon blends, the blockage on the LSI was replaced with one that dropped the swirl to .5 in order to allow the LSI
to operate on hydrogen (Cheng & Littlejohn, 2008). The above data seem to suggest that changing the blockage can allow the LSI greater control on the performance than any of the other parameters.

<table>
<thead>
<tr>
<th>Swirler</th>
<th>Center plate blockage</th>
<th>S</th>
<th>CH₄ φₑ boo @ 16 m/s</th>
<th>Drag coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV-α32-R52</td>
<td>63.8 %</td>
<td>0.48</td>
<td>0.49</td>
<td>1.30</td>
</tr>
<tr>
<td>TV-α37-R52</td>
<td>63.8 %</td>
<td>0.56</td>
<td>0.46</td>
<td>1.12</td>
</tr>
<tr>
<td>TV-α42-R52</td>
<td>63.8 %</td>
<td>0.65</td>
<td>0.45</td>
<td>1.04</td>
</tr>
<tr>
<td>TV-α32-R67</td>
<td>77.2 %</td>
<td>0.53</td>
<td>0.48</td>
<td>2.10</td>
</tr>
<tr>
<td>TV-α37-R67</td>
<td>77.2 %</td>
<td>0.60</td>
<td>0.46</td>
<td>1.93</td>
</tr>
<tr>
<td>TV-α42-R67</td>
<td>77.2 %</td>
<td>0.70</td>
<td>0.45</td>
<td>1.99</td>
</tr>
<tr>
<td>TV-α32-R80</td>
<td>77 %</td>
<td>0.45</td>
<td>0.49</td>
<td>4.59</td>
</tr>
<tr>
<td>TV-α37-R80</td>
<td>77 %</td>
<td>0.54</td>
<td>0.47</td>
<td>4.68</td>
</tr>
<tr>
<td>TV-α42-R80</td>
<td>77 %</td>
<td>0.64</td>
<td>0.46</td>
<td>4.76</td>
</tr>
<tr>
<td>CV-α37-R67</td>
<td>59%</td>
<td>0.53</td>
<td>0.46</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Figure 5: Parameters Changed During Testing in (Therkelsen, et al., 2012)

A wide variety of combustor liner geometries have been checked to determine the effects that the expansion ratio or downstream restrictions play on the flow field. The results show that the effects of the dump plane or enclosure size are small. No changes in flashback or blow off limits have been observed due to the flame enclosures (Yegian & Cheng, 1998). The increasing size on the enclosure does lead to increased recirculation zones near the dump plane exit and some small recirculation zones at the top center of the flame. These zones do not change their structure drastically with changing enclosure size so the performance scales relative to each injector. The best expansion ratio in order to decrease the recirculation zones while also not entraining or restricting the reaction is approximately a 3:1 ratio (Cheng & Littlejohn, 2008).
2.5.3 Low-Swirl Injector Performance

The lean premixed operation of the LSI is one key aspect in reducing emissions. Another key aspect of the LSI is the way in which it stabilizes the flame allowing it to reach lower equivalence ratios than traditional HSI. The LSI operates by using divergence in the flow rather than large recirculation zones which allows it to operate at lower firing temperatures, especially in the central region, while maintaining stability. Unlike the HSI which uses the recirculation zones in the center to bring hot products back as a sort of pilot to maintain the reaction the low-swirl injector uses the divergence region to develop a linearly decaying axial region of flow. As the axial position increases the flow speeds drop linearly which allows the LSI to match injector velocity to flame speeds in a very wide range. This crucial characteristic of the LSI allows it to maintain lower emissions with greater stability and natural fuel flexibility as compared to the HSI (Johnson, et al., 2005).

The unique flow pattern in the central region allows the LSI to anchor many different types of fuels. The fuels range from reactive with high flame speeds like high hydrogen fuels to slow reacting fuels such as digester gases. The blockage used will change the amount of un-swirled air sent to the center which will change the initial velocities out of the injector. If a blockage was chosen to have more restriction it would bring the exit velocities down so that a slower fuel such as digester gas could be burned. On the other hand picking less restriction would allow more reactive fuels with hydrogen to burn more safely. These blockage changes also influence the height of the flame front; more blockages bring the flames closer to the injector. The closer they are the more robust the flow field is and the more protected the flame is from the acoustic oscillations; however the risk comes from possible turbulence or flashback
episodes that are closer to damaging hardware. It is seemingly possible to endlessly improve the fuel flexibility and increase stability if a variable blockage center region was to be implemented.

The initial testing done by others with the LSI involved the use of a sudden expansion nozzle. Some of the findings pointed to problems with the flame stability due to acoustic interactions between the flame and the nozzle. The acoustic oscillations experienced would occasionally have an effect on the overall performance of the LSI. Burning a methane flame in a sudden expansion nozzle did have acoustic interactions (Therkelsen, et al., 2013). They found that the vortices shed from the rim of the injector would get sucked into the outer shear layer of the injector causing self-induced acoustic instabilities. The solution to limit the instabilities of this floating flame was to use a quarl. The quarl is a cone shaped nozzle that gives a guide for the outer shear layer to attach and stops outer recirculation, interaction between the rim and the outer shear layer, and acoustic waves reflected from the enclosure. Both nozzle styles are shown in Figure 6 as they were physically implemented.

![Figure 6: Dump Plane Nozzle (left) and Quarl Nozzle (right)](image-url)
2.5.4 Low-Swirl Injector Summary

In one study a set of low-swirl injectors was parametrically changed in order to observe effects on lean blow off and emissions. The vane angle was changed to three different angles and for each angle chosen three different center channel sizes were used. The result was a test on nine different combinations of low-swirl injectors burning on methane flames into the open atmosphere. This study found no change in lean blow off limits or emissions with the changing parameters. This study failed to test the effects that a parametrically changed blockage could have on the lean blow off or emissions, the effects of having an enclosure, and how the performance would change with renewable fuels (Therkelsen, et al., 2012).

A second study was performed on a low-swirl injector starting in atmospheric and non-preheat conditions and increasing to gas turbine conditions at 8atm and 580K preheat. The results showed that the low-swirl burner could operate on a range of hydrogen or methane and operated similarly at boiler or gas turbine conditions. This study did not test the flexibility of the injector for low BTU fuels or what would change with a different geometry (Cheng & Littlejohn, 2009).

Another study used simulated digester gas while measuring the flowfield with particle image velocimetry. The flowfields collected suggested flowfield similarity and that regardless of the bulk velocity the flame height will not change a lot based on a given fuel despite the varying load conditions. The testing did not show how the flowfield would adjust with a changing blockage. Also the flame was burned in the open and an enclosure; however, the enclosure was not a simulated boiler (Cheng, et al., 2008).
A study was done over a wide range of methane flames using a dump plane nozzle in order to test the effects of enclosures on performance. The results with two different enclosures suggest that the enclosure only plays a role when it becomes too large because it introduces large outer recirculation zones. The blockage was changed at one point in order to adapt the injector to allow for the burning of hydrogen. The effects on the LSI were found to be largely dependent on fuel and the nozzle used. The fuel used was not a renewable fuel and the enclosure size was large but did not simulate a boiler (Cheng & Littlejohn, 2008).

One study was done using a low-swirl burner in an enclosure that simulated a boiler type environment. The fuel used during these tests was natural gas in one case and partially reformed natural gas in another; both cases had exhaust gas recirculation but the results showed an improvement in flame stability when partially reformed natural gas was used. This study did not include testing on variable geometry or a renewable fuel like digester gas (Littlejohn, et al., 2002).

One study used high-hydrogen fuels and methane fuels to determine the effects of the flow field on acoustic oscillations. The findings showed that both fuels had significant impacts on stability because the outer shear layer would shed ring vortices that would hit the flame front and introduce a perturbation. The tests done in this study suggest that adjusting flame heights or flow splits might change the effects the outer shear layer have on stability. This test was not done in a boiler, had no geometry changes, and the fuels did not simulate renewable fuels (Davis, et al., 2013).

Another study burned syngas, a renewable fuel with high hydrogen content, in the open atmosphere and at elevated pressures and preheat. The results shows the basic LSI could operate
on high hydrogen fuels up to 60% without the need for geometry changes. This study did not use geometry changes or a simulated boiler enclosure (Littlejohn, et al., 2010).

One of the last studies reviewed was an evaluation of enclosures on the performance of the injector. The results found that the different enclosures relative to each other had no changes on performance. The NO$_x$ emissions were calculated to be less than 10 ppm corrected to 3% oxygen for all the enclosures. These tests failed to test the effects of a variable blockage, digester gas as the fuel, and the enclosures did not draw heat like a boiler (Yegian & Cheng, 1998).

The last reviewed study did explore the possibilities of using different blockages to affect the stability. In this study the findings showed that as the blockage was increased the lean blow off limit increased allowing a wider operation range. This study used much lower input heat rates and had lower velocities through the injector than in this study. This study also had no enclosure and used only natural gas as the fuel (Yegian & Cheng, 1996).

Table 2 provides a summary of the previous paragraphs in section 2.5.6. The previous research has in very few cases looked into certain aspects researched in this study but never have they been simultaneously tested. The blockage effects were only tested in one of the studies, same as the digester gas. The enclosure effects were tested in multiple studies but these usually did not have heat removal systems like the boiler.
The previous research done on variable geometry injectors all show that there is potential to increase performance by properly utilizing the geometries. The previous enclosures used did not have a large heat flux out of them and were more closely simulated as adiabatic enclosures. Most tests used natural gas as the main fuel and the few that used renewable fuels did not

<table>
<thead>
<tr>
<th>STUDY</th>
<th>EXPLORED</th>
<th>UNEXPLORED</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Therkelsen, et al., 2012)</td>
<td>Lean blow off and emissions as they are affected by vane angle and center channel sizes.</td>
<td>Enclosure effects, blockage effects on LBO and emissions, and renewable fuels.</td>
</tr>
<tr>
<td>(Cheng &amp; Littlejohn, 2009)</td>
<td>Tested wide ranges of preheat and pressures, enclosure effects in a gas turbine, and hydrogen</td>
<td>Did not test digester gas or blockage effects; the enclosure was not a boiler.</td>
</tr>
<tr>
<td>(Cheng, et al., 2008)</td>
<td>PIV results showed similarity in flow field despite changing heat loads. Ran digester gas blends in some tests.</td>
<td>The PIV data does not include the effects of a changing blockage or an enclosure.</td>
</tr>
<tr>
<td>(Cheng &amp; Littlejohn, 2008)</td>
<td>Found an impact on outer recirculation due to enclosure. Changed the blockage at one stage to burn hydrogen.</td>
<td>Did not use digester gas or a simulated boiler enclosure.</td>
</tr>
<tr>
<td>(Littlejohn, et al., 2002)</td>
<td>Test was to observe performance of injector in a simulated boiler environment.</td>
<td>The tests did not vary any geometry and used only methane flames.</td>
</tr>
<tr>
<td>(Davis, et al., 2013)</td>
<td>This test investigated the acoustic instabilities of burning methane and hydrogen flames.</td>
<td>These tests did not use digester gas, enclosures, or a variable geometry.</td>
</tr>
<tr>
<td>(Littlejohn, et al., 2010)</td>
<td>Demonstrated the burning of syngas in the LSI without geometry changes.</td>
<td>The renewable fuel was not digester gas, no enclosure effects were included, and no geometry changes.</td>
</tr>
<tr>
<td>(Yegian &amp; Cheng, 1998)</td>
<td>Tested various enclosures on performance; found that all enclosures gave less than 10 ppm of NOx.</td>
<td>The enclosures did not have heat absorption, no digester gas was burned, and the geometry was not changed</td>
</tr>
<tr>
<td>(Yegian &amp; Cheng, 1996)</td>
<td>Using a 2” LSI with low heat input a stability increase was found with increasing blockage.</td>
<td>Did not have an enclosure, burned at much lower heat rates, and only burned natural gas.</td>
</tr>
</tbody>
</table>
demonstrate blockage or enclosure effects. The effects that a boiler would play on the performance of a burner are largely unaccounted for and the combination of inner recirculation and heat flux will likely play a large role. I hypothesize that as the blockage is increased the flame will move closer to the injector, this will decrease exhaust gas recirculation, reduce the effects of acoustic oscillations, and help maintain the flame structure by imparting stronger swirl; all of these effects will increase the flammability range of the fuels, specifically renewable fuels such digester gas, in an environment, such as a boiler, that is non-conducive to flame stability. The need to investigate how a variable geometry low swirl injector would perform in a simulated boiler environment on a variety of digester gas compositions is clearly prevalent. As a result this thesis will explore the answers to these open research questions.
CHAPTER 3: APPROACH

The goal of the thesis is to answer these open research questions by completing these tasks:

3.1 Task 1: Develop and Execute Test Plan

The test data were gathered in a distinct manner in order to optimize the time and significance of the data. As an aid during this process design of experiments was used in order to help determine what points in the data would be significant. Besides these generated points multiple parameters had to be compared in order to draw conclusions. The parameters used for testing were the screen blockage for the injector, each one of these was tested over a wide range of equivalence ratios as well as being tested over a wide composition of digester gas blends. The unique flow patterns expected as a consequence of the fuel and blockage changes require optical measurements such as particle image velocimetry. In addition, the measurements of flame luminosity via a fiber optic probe will help with verification of flame stability. Each data point collected was repeated three times for precision. Upon completion of tests in a dump plane configuration another set of identical tests was done for a quarl configuration.

3.2 Task 2: Install a Low-Swirl Burner with Variable Geometry

A burner was designed to operate using a low-swirl injector at a fixed heat input of 400,000 BTU/hr (117 kW) in an enclosure with water jackets in order to simulate a boiler. A key component of this burner was to have a well premixed system to ensure low emissions and test flexibility of all fuels under possible flashback conditions. Multiple sampling ports were positioned to measure inlet temperature, pressure, provide a seeder injection point, and allow optical access. The most essential portion of the burner was to have access to the injector in
order to easily change in different screen blockages. The injector was parametrically tested and compared as a function of screen blockage holding other parameters constant.

3.3 Task 3: Design a Fuel Flow Control Circuit

The flow circuit will be providing consistent flow rates of fuel and air in order to maintain operation at 400,000 BTU/hr (117 kW). In addition to maintaining a heat rate, the flows will be adjustable to different turndown conditions. In order to accomplish this sonic orifices were selected, calibrated, and installed in order to consistently provide a given flow rate. A mass flow controller will be installed in the air circuit to give fine tune control over the adjustment of the equivalence ratio. The fuel circuit will have two separate lines, one for CO$_2$ and one for CH$_4$ that will recombine to provide any composition of digester gas while still meeting the heat requirement.

3.4 Task 4: Establish Diagnostics

In order to observe the effects that screen blockage played on the overall flow field of the injector becoming familiar and installing a particle image velocimetry system was essential. In reacting flows a 532nm filter was placed in front of the filter in an attempt to block the light from the reaction. OH/CH imaging equipment was installed to gather images of the flame front during reaction. Emissions from the burner were captured in the exhaust stream by an emission analyzer; this was also used to back calculate the equivalence ratio as a check for leaks. The intensity of the flame was captured through fiber optic cables. Mass flow controllers were calibrated and installed to allow optimal control of flow rates. All the devices used including thermocouples and pressure transducers were hooked up to a data acquisition box which relayed the information to an excel spreadsheet.
3.5 Task 5: Data Analysis and Design Tool Utilization

During this task the results were compared and scrutinized to determine the performance of a variable screen and the best regions to operate in. The flow fields, OH* imaging, emissions, stability, and flame luminosity (intensity) were all taken into account during this step to determine the effects on flame height and stability for certain fuels and screen blockages. The determination of significant effects due to the blockage was calculated using analysis of variance.
CHAPTER 4: EXPERIMENTAL SETUP

4.1 Burner Design and Geometry

4.1.1 Low-Swirl Injector

The burner used for this experiment was focused around a 2” low-swirl injector. The low-swirl injector used had an overall diameter of two inches and an inner diameter of 1.125 inches. Eight swirl vanes at an angle of 37 degrees surround the inner cylinder and the baseline screen had an open area of 0.457 square inches. The parameters used for determining swirl number for the stock low-swirl injector were the ratio of radii $R = 0.49$, vane angle $\alpha = 37$, and a mass flow split of 0.286 all which gave a swirl number $S = 0.464$. The other swirl numbers were calculated using the ratio of the effective areas of the different blockages and the swirl vanes, the results are shown in Table 2. The only changing geometry for this experiment was the blockage so the mass flow split, $m$, was the only changing parameter in the swirl number equation (Equation 3):

$$S = \frac{2}{3} \tan \alpha \frac{1 - R^3}{1 - R^2 + [m^2 \left( \frac{1}{R^2} - 1 \right)^2] R^2}$$  

Equation 3
### 4.1.2 Upper Section of Burner

The upper section of the burner is graphically referenced in Figure 8 and includes the low-swirl injector, the nozzle, and the mounting hardware. The low-swirl injector is held in a 2” female pipe coupling with set screws on either side to secure it in the middle. Downstream of the injector is either a 2.75” sudden expansion nozzle or a quarl depending on the application. In Figure 8 the mounting hardware is clearly seen in the figure to the left. The top and bottom plate are 9” diameter rods with 2” holes in the center for the nozzle and burner body to pass through. The rods are 0.5” long and have a circular bolt pattern located at a diameter of 8” consisting of six evenly spaced 0.25” through holes. The top plate sits on top of the test stand, a 41” square piece of aluminum that is 0.5” thick and attached to a traverse table allowing positioning in all three planes. In the center of the test stand is a 6.5” diameter hole and around that is an identical bolt circle to the one mentioned before. The top plate sits on the aluminum test stand with ¼-20 bolts going through the 6 holes and threading into 2” long hexagonal standoffs. The hexagonal standoffs are the same length as the female pipe coupling that holds the low-swirl injector so that when the bottom plate is bolted on it squeezes the pipe coupling and holds the entire burner in place. As mentioned before the bottom plate attaches to the bottom of the hexagonal standoffs by tightening six ¼-20 bolts.

The two types of nozzles used in this experiment were the sudden expansion dump plane and the quarl. The initial experiments were done with the sudden expansion nozzle as seen in

<table>
<thead>
<tr>
<th>Open Area (in²)</th>
<th>0.298</th>
<th>0.357</th>
<th>0.405</th>
<th>0.457</th>
<th>0.507</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Split m</td>
<td>0.2476</td>
<td>0.273</td>
<td>0.2856</td>
<td>0.3389</td>
<td>0.393</td>
</tr>
<tr>
<td>Swirl Number</td>
<td>0.4885</td>
<td>0.4719</td>
<td>0.4635</td>
<td>0.4278</td>
<td>0.3917</td>
</tr>
</tbody>
</table>
Figure 7; this nozzle is special because it provides access to particle image velocimetry measurements. During testing calcium silicate insulation was placed around the sudden expansion nozzle to bring the boiler plane up to the same level as the nozzle. The quarl was used for the second set of tests in order to increase the stability of the burner.

4.1.3 Middle Section of Burner

This section of the burner consists mainly of the pipe that houses diagnostic equipment and a settling length between the bottom of the burner and the exit plane. This section is dimensioned in Figure 10 but consists of a single 18” long 2” steel pipe. Figure 9 shows the three ports one for a thermocouple, one for a pressure tap, and one for an injection point for seeder. The top port is a ¼” NPT thread 2” from the bottom of the low-swirl injector and serves as the pressure port for measuring pressure drop across the low-swirl injector. A Swagelok fitting serves as an adapter from the ¼” NPT fitting to the ¼” tubing that runs to the transducer. Near the bottom are two more ports for the thermocouple and the injection point for the seeder. The seeder port uses the same sizes and adapters as the pressure port above but was placed 3” above the bottom of the 18” long pipe. Opposite the seeder port a 1/8” NPT hole was tapped for a Swagelok fitting that would hold a thermocouple in place.
4.1.4 Lower Section of Burner

Attached to the bottom of the 18” long pipe was a 2” pipe cross as seen in Figure 10. The bottom part of the cross was installed with a 2” to ¼” bushing to allow concentric access for optical devices such as a fiber optic. On the left and right sides of the cross were two 2” fully threaded pipe nipples with 2” pipe unions. The unions allowed for easier access to the cross for
certain tasks as well as connecting the flexible tubing. After the pipe union there was a 2” pipe to 2” hose barb fitting for the connection of flexible tubing. The requirement of this burner was to have a perfectly premixed fuel and air source so the design of the base of the injector was no mistake. Two flexible lines were chosen as opposed to one in order to allow one more chance for mixing as the flows were directed towards each other from opposite ends of the cross.

4.1.5 Peripheral Components of Burner

Outside of the main burner as seen from Figure 9 some extraneous components are essential in achieving optimal performance of the burner as well as providing control of position of the burner. Off of the cross on the burner are two 9’ long 2” flexible tubing lines that reconnect to a 1” pipe cross at the point of fuel injection. The flexible tubing lines were chosen to allow the traverse of the boiler test rig to be open for any possible position required during the testing phase. The flexible tubing runs from the burner head down to a 2” to 1” reducing coupling and attaches to either side of a 1” pipe cross. The airline comes in from one side of the cross and then splits to go into the flexible tubing. The fuel injection point comes in from ½” tubing opposite the airline and is injected counter flow to induce rapid mixing. The fuel and air mix in the 1” cross rapidly then split into the left and right flexible tubes to mix by diffusion before being recombined in the 2” pipe for more mixing; the multiple places for mixing ensure that the fuel and air are well mixed.
4.1.6 Premixing Validation

The point where the flame was situated was 10.5’ from the point where the fuel was first introduce into the air. This gives an L/D of 63 which gives adequate time for turbulent mixing.
and diffusion based transport. In addition to the large residence time found in the length of pipe the initial injection point of the fuel into the air is in a counter flow manner to induce large turbulent mixing. Before the flow is sent into the boiler to be burned it is recombined near the base of the 18” long pipe; at this point another mixing point is induced as the two flows collide before continuing upwards. All these steps were to ensure the assumption of premixed fuel and air is valid for this experiment.

4.2 Boiler and Exhaust Enclosure

The enclosure over the burner is designed with windows and water jackets to simulate the effects of operating a boiler while giving the benefits of optical access. The enclosure can be seen in Figure 11 for reference but it consists of a few key parts.

4.2.1 Boiler Geometry

The enclosure placed over the burner is shaped as an octagonal cylinder with an exhaust stack attached to the top. The sides of the octagon are 12” wide and 3’ tall made of stainless steel. The base of the enclosure is held in place over an aluminum plate. The aluminum plate is a 41” square with a 6.5” diameter hole cut in the center; it is secured to a traverse table giving it precise positioning in all three Cartesian coordinates depending on the application. The area inside the enclosure is covered with ½” high-temperature calcium silicate cut into shapes to surround the top plate of the burner. On the top of the enclosure is an attached exhaust stack. The exhaust stack is made of stainless steel with access for a water cooled exhaust probe for sampling emissions. The base that directly attaches to the octagonal enclosure mentioned before is a sort of octagonal cone. The bottom is the same shape and size as the top of the enclosure but slowly shrinks before it combines into an 8” diameter cylinder. The total height of the exhaust
stack is 3’ with the octagonal base being 1’ tall and the 8” diameter cylinder being 2’ tall on top of that. The top of the exhaust stack has a damper installed in order to adjust the backpressure for certain applications.

![Figure 11: View of Rig Water Jackets and Exhaust Stack](image)

### 4.2.2 Windows

On the bottom 11” of the enclosure is a cutout where the windows are attached. The windows are held in place and sealed by a metal frame held on with wing nuts and high temperature ceramic paper between both surfaces of the glass and metal. The windows have the dimensions of 7.5” by 9.5” and are made of high temperature VYCOR. The metal frame with dimensions 9” by 10.5” is made of .75’ thick steel with 8 wing nuts attached to ¼-20 bolts.
attached to the enclosure. The windows are useful for providing optical access for lasers or fiber optic measurements.

4.2.3 Water Jackets

The boiler has eight 12” wide water jackets that stretch 23” long and start 13” from the aluminum base plate. The jackets have an inlet loop for cold water along the bottom portion and an outlet for the hot water along the top. The mass flow rate of water through the system is approximately 0.56 kg/s and the initial temperature of the water is usually 74°F but during operation can reach about 100°F. The closed loop water system is responsible for maintaining these temperatures. The system works by taking chilled water from the campus and running it in a closed loop through the first heat exchanger. This first heat exchanger is connected to a main loop that runs throughout the lab mainly to cool lasers. This main loop consists of a pump, a reservoir, and lines that run to multiple labs. During tests that are run using the water jackets on this boiler a secondary cooling loop is used. This secondary loop flows into a heat exchanger located outside of the test cell and exchanges heat with the primary loop mentioned before. The secondary loop, similarly to the primary loop, consists of a pump, a reservoir, and plumbing that run into the test cell. The plumbing into the test cell provides water to the water jackets as well as a water cooled sampling probe.

4.2.4 Water Cooling Sample Probe

The water cooled sample probe allows the insertion of a stainless steel probe into the hot exhaust stream without damage. The probe runs off of the same supply line as the water jackets but the return line comes back on a separate line. This probe is a half inch piece of stainless tubing that has a cooling loop welded into it with multiple ports allowing the sample to be sucked into the analyzer.
4.3 Peripheral Equipment

4.3.1 Air Supply

The air supply lines for all the test cells in the lab come from Ingersoll Rand air compressors. An Ingersoll Rand air compressor supplies 145 psi air to the test cell. The flow control used for the air during the testing came from two sources one mass flow controller and one sonic orifice. The sonic orifice used has an orifice size of .4” and is capable of supplying air in the range of 60 to 250 scfm. The mass flow controller used was a Brooks 5853e which is capable of providing air flow rates from 0 to 35 scfm.

4.3.2 Fuel Supply

An important requirement of the testing for this study was to have a robust system for mixing multiple compositions of digester gas. Natural gas and carbon dioxide feeds were needed at relatively high flow rates of around 6.6 scfm each at max load. In order to source carbon dioxide at that flow rate, dewars of liquid carbon dioxide were used as the supply of gaseous carbon dioxide. In order to prevent frosting or having too low of temperature in the inlet gas the length of the supply line for the fuel was made long to ensure adequate timing for heat transfer. The dewar tank was supplied into a manifold of three regulators as seen on the top of Figure 12. The CO\textsubscript{2} supply pressure was set with a regulator but was usually chosen to be around 110 psi, at the same time the natural gas supply pressure was set to 120 psi from the compressor. Depending on the required flow rate of CO\textsubscript{2} a different sonic orifice was used; the far left sonic orifice was 0.07”, the middle was 0.047” and the right was 0.031”. Between these three sonic orifices a flow rate of CO\textsubscript{2} from 0.3 to 6.6 scfm could be reached. On the bottom row of regulators a natural gas line was connected to the manifold. The far left regulator used 0.029” sonic orifice, the middle 0.043”, and the right 0.067”; this configuration was capable of flowing 0.43 to 8 scfm.
Each regulator was designed in the same way and with the same parts except for the sonic orifice. The fuel from the CO₂ or natural gas lines came in from ½” stainless steel tubing to a manifold where it was split into the three different regulators. The regulator had one pressure gauge to provide the set pressure just upstream of the conic orifice. The exit of the regulator was connected to a ¼” stainless steel nipple with the sonic orifice built into it. This then connected to ¼” tubing that runs to the bottom regulator and splits in the middle to end on a valve. After the valve the fuel runs into a ½” copper line and eventually a ½” Teflon tube to be injected into the pre-mixer.

One important thing to note is between the top and bottom regulators is a line with a valve that runs into the main fuel line for injection into the burner; because the line connects the two operating one regulator was found to make back pressure on the other regulator. This back pressure had negative effects on the accuracy of the calibration of the sonic orifices. In order to rectify this, the maximum loads of natural gas and CO₂ that were expected were put on opposite ends to prevent back pressure effects.
4.3.3 Hydrogen Torch

During the testing a pilot torch was necessary to ensure safe operation during startup. The torch used in the experiments was designed to run off of a compressed bottle of hydrogen gas. Attached to the tank was a regulator that dropped the output pressure to 40 psi before reaching a sonic orifice. After the sonic orifice the H$_2$ ran into a ¼” stainless steel tube that was placed inside the boiler. The initial light off was accomplished through the use of a spark igniter, afterwards it was pulled back to the wall. Hydrogen has extremely high reactivity and very lean blow off limits so using this as the torch ensured that in every test condition the pilot would stay lit. During light off the pilot was placed in the flow so that as fuel was added it was continuously ignited. Once the required test condition was reached the pilot torch was pulled to the wall and the valve was closed stopping the hydrogen flow.

4.3.4 Particle Image Velocimetry

The determination of the flow field generated by the LSI was accomplished using particle image velocimetry (PIV). PIV works by using software, Lavisions’s Da-vis Imaging software for this experiment, to process the movement of particles and turn it into velocities. PIV works by sending one pulse of a sheet of light into a flow with refractive particles that scatter the light incident upon them. A camera, Lavision Imager Intense CCD, takes a picture of the first pulse of light and stores it and within a few microseconds a second sheet of laser light is fired. The camera takes a picture of the second pulse and sends both frames to the software to be analyzed. In the software the subsequent images of the light scattered by the particles are analyzed using the Davis Imaging Software. The software places a grid over the images and then processes each square individually; each square is a separate zone that tracks and records the displacement of
the particles. Finally, the time difference between the frames is known and using this information, a vector field can be determined.

The first step in setting up the PIV system was to set up a seed injector; this device atomizes a media and injects it into the flow to make a homogeneous dispersion of particles. The key in selecting the media is choosing one that will evenly distribute within the main fluid and at the same time have little to no interaction with the flow. The particles must be fine enough to track the motions of the gas. For the conditions of this experiment, particles nominally 3 microns in diameter are sufficient. A Stokes number analysis was used in order to determine the flow following characteristics of the seeder used; the calculations done in Equation 4 assumed a worst case scenario due to the variation in particle sizing and gave a stokes number of .0978. The Stokes number is less than .1, even with the largest particle size, and this means the difference between the flow and the particle path is less than 1%.

\[
Stk = \frac{\rho_d d_d^2 U_o}{18 \mu_g d_c}
\]

- \(\rho_d\) is the density of the seed particle
- \(d_d\) is the diameter of the seed particle
- \(U_o\) is the bulk velocity of the flow
- \(\mu_g\) is the dynamic viscosity of the medium the particles reside in
- \(d_c\) is the characteristic diameter

For this setup a tank was filled with olive oil and a nozzle placed into the olive oil; the blast atomizer used was a Laskin model as described by (Raabe, 1976). About 3 scfm of air was sent into the nozzle and would bubble up creating a mist of olive oil particles. The olive oil and air mix was then sent down a \(\frac{1}{4}''\) Teflon tube and into the base of the burner where it mixed and dispersed into the flow. When calculating the equivalence ratio or other parameters at a certain
operating condition the additional air flow used for seeding was incorporated into those calculations.

A dual head Continuum Nd:YAG laser (Surelite III-PIV) is used to fire high energy 532nm wavelength light in rapid succession. The output from the laser was chosen to be about 2.5 watts because that reduced the reflection intensity from the enclosure while maximizing the illumination of each particle. The pulsing and timing of the laser is selected and executed from the Da-vis software used for PIV. The swirling motion in this flowfield produced complications for choosing optimal timing and sheet width. The time between pulses had to be long enough to allow adequate movement of particles but also fast enough to capture the swirling particles before they move out of the plane; the proper timing between pulses to satisfy this criteria was about 9 μs. The first pulse is triggered by the software and the beam is sent through a cylindrical lens (plano-concave, f = -150 mm) to turn it into an expanding sheet. After 1 foot of expansion the beam hits a spherical lens (plano-convex, f = 1.87 m); this lens slows the expansion of the sheet and more or less makes it parallel. The center of the test section is located 65.5 in. away from the spherical lens; at this distance the beam is not at the focal length so the sheet is slightly thicker. The thicker beam is used to keep the swirling flow inside the plane of the laser sheet slightly longer. The beam waist over the test section was calculated to be 1 mm in Equation 5.

\[
w_o = \frac{\lambda f}{\pi w} ; w(z) = w_o \left[ 1 + \left( \frac{\lambda z}{\pi w_o^2} \right)^\frac{1}{2} \right]^{\frac{1}{2}} \tag{Equation 5}
\]

- \(w_o\) is beam waist radius at focal point
- \(w(z)\) is beam waist radius at \(z\) away from focal point
- \(\lambda\) is wavelength of the light used
- \(f\) is focal length of lens used
- \(w\) is the beam waist radius before the lens
The beam then hits the point where the flow is exiting and illuminates the particles. The software was set to sample at 10 Hz so this action was repeated. The software looks at small sections of the image and finds the general displacement of the particles and uses the time differential to draw a vector field.

In certain cases reactive imaging is necessary to obtain results with a reacting flow; in these cases the light from the reaction interferes with the camera recordings. In this case a 532nm filter was placed in front of the camera to filter out all but 532nm light. This filter blocks out all the flame light but allows the reflected laser light from the particles to be transmitted. The benefit of choosing olive oil as the seed particle as compared to silica is its smoke point. By choosing olive oil with a low smoke point the seed will evaporate as it crosses the flame; in this way only the flow before and up to the flame front will be illuminated during the lasing. In Figure 13 the layout for the PIV setup in the test cell can be seen.
4.3.5 Exhaust Emissions

The emission data for all the testing were analyzed by a Horiba PG-250. The analyzer is capable of measuring NO\textsubscript{x}, CO, O\textsubscript{2}, CO\textsubscript{2}, and SO\textsubscript{x}, but for the purposes of the present effort, the SO\textsubscript{x} was not used. The sample from the exhaust stack was sent from the water cooled sample probe to an electric sample chiller in order to drop out the water vapor in the exhaust. After the water was dropped out it was sent to a sample pump that drew in from the exhaust stack and sent to the PG-250. The span and zero of the PG-250 were done each day to ensure the most accurate readings. Pure nitrogen was used to zero the analyzer while a bottle of 41.40 ppm of carbon monoxide, 4.01\% of carbon dioxide, 18.01\% of oxygen, and the remainder nitrogen was used for
the subsequent gases. A second bottle of 40.6 ppm of nitrogen oxide was used for the span of the NO$_x$.

4.3.6 Fiber Optic Sensor

Previous work has found correlations between NO$_x$ emission levels and the radiation intensity from radical species in the flame as measured by a fiber optic. In (Demayo, et al., 2002) the CH* radical was found to increase the intensity of light emission linearly as NO$_x$ increased; the correlation had an R$^2$ value of 0.83. In (Miyasato, et al., 2006) the NO$_x$ emissions were correlated to the CO$_2$* radiation intensity. The initial testing for this thesis used a fiber optic placed at the edge of an aluminum base plate outside the boiler; later testing had the fiber optic placed concentrically inside the burner head. The fiber optic cable is made by Ocean Optics (P400-2-UV/VIS), it is designed to pick up light sources in the UV to visible range (300-1100 nm). The end facing the flame has a fiber optic sensor connected to it, this sensor was made by Amphenol. The opposite end of the fiber optic cable was connected to a photomultiplier tube made by Hamamatsu (C1053-51, No. 500091), the photomultiplier tube is designed for high bandwidth applications from DC to 5MHz. The photomultiplier was supplied by a Bertran Series 230 high voltage power supply and a Proto-Board 203A low voltage power supply. The Bertran power supply was set to 800kV and the Proto-Board supplied 15V. The tests were done with the lights off so all the light read from the equipment was sourced by the flame.

No physical filters were applied to the fiber optic in order to eliminate some of the light bands. In order to alter the signal to something more easily readable a digital filter was added via LabVIEW. The filtering on the signal was accomplished by a low-pass inverse Chebyshev filter
with order three and a cutoff frequency of 20 Hz. This filter seemed to remove the noise while maintaining the overall data trend most efficiently.

The recorded information using the fiber optic consisted of averaged or root mean squared (RMS) values and the peak to peak values of the input data. The root mean squared method is advantageous for this particular application because it can find the average magnitude of a signal even if it has negative values. A typical average of a sine wave will give an average value of zero however the RMS value of a sine wave will be positive and of some non-zero value. The peak to peak values are taken from the highest peak to the lowest peak and an absolute magnitude between the two is taken. This peak to peak value gives a good understanding of the maximum amplitude of the signal in both directions.

The tests with the quarl nozzle installed had no optical access through the traditional means because the quarl physically blocked vision of the flame. During these tests an alternative approach was used to install the fiber optic probe upstream of the exit plane of the burner. In order to accomplish this, the fiber optic probe was secured to the center hole in the blockage of the low swirl injector. The end of the fiber optic probe was one inch from the blockage and was approximately 3-4 inches from the flame front. The fresh products flowing around the fiber optic probe kept the probe cool during the testing as it was close in proximity to the flame. At the bottom of the rig, where the two flexible tubes connected to the cross, a Conax compression fitting sealed the fiber optic cable in place and prevented any leaks out of the bottom.

4.3.7 Thermocouples

Thermocouples played an integral role in measuring the temperature of the rig at various essential locations. All the thermocouples used are Omega type K thermocouples with a
measuring range from -328°F to 2282°F. Thermocouples are placed in multiple points along the water jackets to measure the water temperature, the inlet and outlet of the water jackets each had their own dedicated thermocouple. Along the inside of the enclosure were three thermocouples placed where two water jackets met to measure wall temperatures as seen from Figure 14.

Figure 14: Three Thermocouples Located Between Two Water Jackets

These thermocouples stuck in 0.25” and were spaced one 18” from the bottom, one 9” above the previous one, and the last one 9” above the middle one. A thermocouple was placed in the base of the burner to measure the temperature of the inlet fuel and air. The last thermocouple used was placed in the exhaust stack to measure the temperature of the final products.

4.3.8 Pressure Transducer

The pressure drop across the low-swirl injector was measured using a Dwyer MS-111 differential pressure transducer. The high side was connected just below the LSI and the high side was connected to a Swagelok fitting between two windows near the base. The differential pressure allowed checking for pressure change due to blockages as well as checks for leaks if the pressure drop changes drastically.
4.3.9 System Configuration

The pressure transducers, thermocouples, mass flow controllers, and emissions sampler were all connected to a FieldPoint 1000 data acquisition board. The FieldPoint module worked directly with LabVIEW and gave analog input, analog output, and thermocouple reader connections. By integrating all the peripheral equipment to one central device, a single computer could control, monitor, and record all the data. Figure 15 gives a visual representation of the flow network present during this experiment.

![Figure 15: Basic Flow Diagram of Experimental Setup](Image)

4.3.10 OH*/CH* Imaging

One series of tests done on the dump plane nozzle was radical imaging. In order to determine where the reaction was occurring the location and concentration of OH* and CH* radicals needed to be discovered. For this test an ICCD Andor Camera was used in conjunction with a 550 nm filter for OH* and a 426 nm filter for CH*. During each test condition 15 frames
were captured; after the frames were recorded Matlab was used to average all the images together.

4.4 Experimental Approach

Once the test condition was stabilized, about a minute of waiting, the data were recorded. The data were continuously collected at regular equivalence ratio intervals until the flame reached the lean blow off point. The equivalence ratio where blow off was achieved was the limit of stability. To give an indication of sensitivity of the result, a second and third series of tests were run in order to verify the accuracy of the original result.

A proposed test for stability was to measure the peak to peak fluctuations of the flame as measured by the fiber optic probe; the theory behind it was as the flame becomes more unstable it will start to flicker and produce a greater range of peaks as perceived by the fiber optic. Figure 16 shows why this was not chosen as an accurate method of determining stability; the fluctuations between values for each equivalence ratio were too high for proper determining even when averaged. The flame was found to flicker too much throughout all ranges of equivalence ratio, even in “stable” regions, making it impossible to discern actual instability versus normal flame operation. When the values were not taken as an average and instead taken in real time as seen from Figure 17 the fluctuations would occasionally dip into unstable regimes and for a computer controlled device this would trigger a false positive blow off event.
Figure 16: Equivalence Ratio vs. Light Pk-Pk for 0.298 Blockage with 100% CH₄ Averaged Values

Figure 17: Equivalence Ratio vs. Light Pk-Pk for 0.298 Blockage with 100% CH₄ Real Time Results
Looking back at RMS values as compared to those found in Figure 16 the strength of a possible trendline drawn between the lower equivalence ratio and the higher is much greater. The accuracy of the $R^2$ value of the trendline from RMS values was in most cases, very high $R^2 = 0.9978$; because of the high level of accuracy when using the RMS as opposed to the Pk-Pk the RMS was chosen as the accurate measure of stability. The trendline from RMS values can be very useful when implemented into a computer control loop. An initial run through would determine the limits of stability as well as give the corresponding light intensity; from that point forward a signal from the fiber optic probe would give the computer accurate knowledge of what the stability is using 100% CH$_4$. 

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CHAPTER 5: RESULTS

For this specific experiment two configurations were possible for testing; one setup utilized a dump plane nozzle that allowed optical access but at the expense of some performance the other setup utilized a quarl nozzle which eliminated optical access but improved the performance. The initial tests on the dump plane, sudden expansion nozzle, had to be undertaken to understand how the reaction would perform with recirculation and shearing from the nozzle tips. Each test during this period involved using PIV and OH*/CH* imaging to capture data on the flow field effects due to blockage changes. In addition, the blockage changes had to be compared relative to emissions and stability regimes. After the initial testing some preliminary conclusions were drawn and the data were used in analysis of variance to determine statistical significance of some results as well as, any results or correlations not seen initially. Further testing was done on the quarl nozzle and then the two nozzles were compared and conclusions were drawn. Section 5.1 includes the tests accomplished with the sudden expansion nozzle and section 5.2 includes the tests from the quarl nozzle; the quarl physically blocks optical access so this section does not include PIV or OH/CH imaging. Section 5.3 is the analysis section; it includes results from using Design Expert for analysis of variance.

5.1 Dump Plane Reacting Results

For the determination of blow off limits the initial test point was set at 0.95 equivalence ratio with 400,000 BTU/hr (117 kW) of heat input. The heat input was held constant for the sake of being able to compare the different cases. The fuel and air mixtures had air added to them at increments to bring the equivalence ratio closer and closer to the true blow off limit. For lean
blow off limits the test parameter was the intensity of the light from the reaction, 300-1100 nm, as detected by a fiber optic probe.

5.1.1 0.298 Blockage Lean Blow off and Emissions

The first set of tests began with 100% CH\textsubscript{4} at a flow rate of 6.59 scfm with 66 scfm of air to bring the equivalence ratio to 0.95; as the test progressed more air was added to bring the equivalence ratio to 0.8. Figure 18 shows the light RMS for each equivalence ratio, the far left points all stop around an equivalence ratio of 0.8 because this was the lowest that could be achieved before blow off. Therefore the stability or lean blow off limit for the 0.298 blockage running 100% CH\textsubscript{4} was found to be an equivalence ratio of 0.8.

![Figure 18: Equivalence Ratio vs. Light Intensity for 0.298 Blockage LSI operating on 100% CH4](image)

In terms of actual lean blow off the equivalence ratio is a bit lower, around 0.77, but because the data cannot be collected when the flame actually blows off a point slightly above was chosen.
Adding in some CO$_2$ gave another strongly correlated trendline for the 20% CO$_2$ case as seen in Figure 19. Looking even further at Figure 20 the 40% CO$_2$ case is present and when comparing Figure 18, Figure 19, and Figure 20 an interesting trend can be observed for the 0.298 blockage; regardless of the fuel type the lowest equivalence ratio for each fuel seems to be related to the intensity of the flame. As the flame becomes less stable and approached blow off all the intensities regardless of the fuel being used approach the same number of 0.8 to 0.9.

![Equivalence Ratio vs. Light Intensity for 0.298 Blockage LSI operating on 80% CH4 / 20% CO2](image)

The trendline for the most dilute fuel in Figure 20 is not as solid as the others but it is still strong enough to make the prediction or assumption that it follows a linear path. As suspected the lean blow off stability degrades as more CO$_2$ is added and the flame becomes diluted with inert fuel. The more CO$_2$ added to the flame the less air can be added in order to increase the lean blow off and in Figure 21 all three fuel types are put into one graph. Figure 21 shows that
as more CO₂ is added the equivalence ratio at lean blow off starts to approach stoichiometric. It also shows as mentioned before the similar intensity values for the different fuels at the lowest equivalence ratio. It is clear the averaged values correlate well when looking at light intensity and equivalence ratio however an important question is how real time results look when determining the stability; Figure 22 shows how the un-averaged values overlay on Figure 18. Figure 22 shows that the real time RMS data have merit in showing the true value of flame stability as opposed to peak to peak values.

![Graph showing equivalence ratio vs. light intensity](image)

**Figure 20: Equivalence Ratio vs. Light Intensity for 0.298 Blockage LSI operating on 60% CH4 / 40% CO2**
Figure 21: 0.298 Blockage Equivalence Ratio vs. Light RMS for All Three Fuels With A Line Showing Blow off Similarity

Figure 22: 0.298 Blockage Equivalence Ratio vs. Light RMS with Overlaid Un-averaged Results
Using the same range of equivalence ratios as was found to be stable before the emission data were gathered at the same time. The lean premixed nature of the burner keeps the emissions low and maintains minimal CO emissions. Figure 23 shows the NO\textsubscript{x} emissions corrected to 3% versus the equivalence ratio. The results are agreeable with the idea that as more CO\textsubscript{2} is added to the fuel the flame temperature lowers and the thermal NO\textsubscript{x} mechanism is reduced. An interesting observation is the NO\textsubscript{x} emissions at the point before all the different flames reach the lean blow off limit. All the fuels have a lower limit on NO\textsubscript{x} in the region of 8 to 9 ppmvd corrected to 3%.

The emission range for the pure CH\textsubscript{4} case ranges from 29 ppmvd at $\phi=0.95$ down to 10 ppmvd at $\phi=0.8$. With 80% CH\textsubscript{4} the range is from 22 ppmvd at $\phi=0.95$ to 10 ppmvd at $\phi=0.8$. The last case with 60% CH\textsubscript{4} ranged from 10 ppmvd at $\phi=0.95$ to about 9 or 8 ppmvd at $\phi=0.9$.

Figure 23: NO\textsubscript{x} Emissions Corrected to 3% Oxygen vs. Equivalence Ratio for 0.298 Blockage
Looking further a connection between the light intensity and the emissions can be made due to the connection made earlier between intensity and AFT. NO\textsubscript{x} is so heavily reliant on flame temperature when burning CH\textsubscript{4} or CO\textsubscript{2} that this factor can be largely considered the only factor to be considered when reducing NO\textsubscript{x}. Figure 24 shows the relation between NO\textsubscript{x} and light intensity which is very similar to the NO\textsubscript{x} vs. AFT graphs. The relation is linear and the point of minimum NO\textsubscript{x} has a high population of data as all the different fuels and equivalence ratios have the same NO\textsubscript{x} emissions and light intensity at points very near to the lean blow off limit.

The CO emissions from this blockage, and all the rest, are very close to zero all within about 2 ppmvd of zero which is expected for a lean premixed injector. The fluctuations in the emission measurement device alone were in the range of 1 ppmvd for CO and once the data were actually put into the Design Expert software it revealed that there was an 85% chance that the data were due to noise. Due to these conclusions and the expectations of zero CO in the main operating range the CO data are not significant to be shown and can be safely assumed to be 0.
Figure 24: NO\textsubscript{x} Emissions Corrected to 3\% Oxygen vs. Light Intensity for 0.298 Blockage

5.1.2 0.357 Blockage Lean Blow off and Emissions

The range of stability for the 100\% CH\textsubscript{4} case with the .357 blockage did not change significantly and this finding is also backed up by the statistical analysis reported in Section 5.3. The values at blow off were slightly lower meaning more air was able to be added but this is not a significant enough of a change at this moment to declare an improvement in stability. With this injector blockage the light intensity values changed slightly but the same strong linear correlation was found. In Figure 25 the equivalence ratio range is from about 0.77 to 0.95 with the corresponding RMS value from 0.6 to 1.5 as compared to Figure 18 with a range of equivalence ratios 0.8 to 0.95 and RMS from 0.8 to 1.8.
As more CO$_2$ is added the resulting trends can be seen in Figure 26 and Figure 27. Similar to what was found above the recorded lean blow off numbers seem a bit lower but this is also because during testing a point above the true lean blow off number had to be chosen in order to prevent actual blow off and allow recording of data points. Besides the lean blow off number discrepancy the values found due to the light intensity for 0.357 are skewed as compared to 0.298. Two possible reasons for this are: (1) the flame height changed enough that the most luminous section of the flame was out of view or (2) more than likely the sensor was moved slightly out of position between tests. The movement out of position is of little consequence because the trend still holds between the intensity and the equivalence ratio. The R$^2$ values for Figure 25-Figure 27, are very high further backing up the relation; the 0.357 data actually has a
Figure 26: Equivalence Ratio vs. Light Intensity for 0.357 Blockage LSI operating on 80% CH4 / 20% CO2

Figure 27: Equivalence Ratio vs. Light Intensity for 0.357 Blockage LSI operating on 60% CH4 / 40% CO2
better correlation for the 60% CH\textsubscript{4} case than the data from the 0.298 blockage. Looking at Figure 28 the same result as before can be seen; as the different fuel types approach their lean blow off limit they start to give off the same light intensity values.

Figure 28: 0.357 Blockage Equivalence Ratio vs. Light RMS for All Three Fuels

Figure 29 includes the NO\textsubscript{x} emissions gathered using the three different fuel types for the 0.357 blockage. The results for this blockage show a similar equivalence ratio range and emission level as the previous. It is surprising that the range is similar; for this blockage there was no influence on stability due to the different blockages. The data in Figure 30 were gathered for the relation of NO\textsubscript{x} emissions to light intensity; it is a much better fit for this set of data. The linear fit is much stronger showing the direct correlation of NO\textsubscript{x} to AFT or light intensity with the use of digester gas mixtures.
Figure 29: NOx Emissions Corrected to 3% Oxygen vs. Equivalence Ratio for 0.357 Blockage

Figure 30: NOx Emissions Corrected to 3% Oxygen vs. Light Intensity for 0.357 Blockage
5.1.3 0.405 Blockage Lean Blow off and Emissions

The baseline blockage of the LSI provided by LBNL gave the median results for our range of blockages and what was found was similar to the first two blockages but with slightly more variability. In Figure 31 the case with pure CH₄ shows that the stability ranges were no different but there was a slight decrease in observed intensity towards the lower equivalence ratios and the R² value was not as high as previous results. The R² value was more than likely a result of slight fluctuations in the diagnostic equipment.

![Graph showing correlation between equivalence ratio and light intensity for 0.405 Blockage LSI on 100% CH₄](image)

**Figure 31: Equivalence Ratio vs. Light Intensity for 0.405 Blockage LSI operating on 100% CH₄**

As more CO₂ was added to the flame similar shifts were seen towards lower stability however in the case of 80% CH₄ the stability limit did not change much. This suggests that the addition of 20% CO₂ did not have a drastic impact on the flame kinetics and that in order for significant lean blow off changes to be established a stronger concentration of CO₂ was
necessary. At 40% CO₂ as in Figure 33 the results show that the lean blow off limit was decreased quite a bit all the way down to a 0.87 equivalence ratio.

![Equivalence Ratio vs. Light Intensity for 0.405 Blockage LSI operating on 80% CH₄ / 20% CO₂](image)

Figure 32: Equivalence Ratio vs. Light Intensity for 0.405 Blockage LSI operating on 80% CH₄ / 20% CO₂

Looking at Figure 34 for the 0.405 blockage an almost exact same result is seen as compared to the two smaller blockages. The results expected with changing blockage are still not present. The stability was expected to increase with more blockage in the center especially when burning a highly dilute CH₄ and CO₂ mixture but the results suggest no correlation between blockage and stability. Figure 34 further reinforces the finding that regardless of fuel type the light intensity will correlate to the leanest condition achievable before lean blow off.
Figure 33: Equivalence Ratio vs. Light Intensity for 0.405 Blockage LSI operating on 60% CH4 / 40% CO2

Figure 34: 0.405 Blockage Equivalence Ratio vs. Light RMS for All Three Fuels Showing Blow off Similarity
In Figure 35 the emission for the pure CH₄ case is slightly higher than the previous
blockages. 100% CH₄ gave NOₓ emissions of 30 ppmvd at $\phi=0.93$ as compared to the previous
emissions of 30 ppmvd at $\phi=0.95$; because the equivalence ratio is higher for this blockage it will
be a colder flame and the thermal NOₓ will reduce yet it gives the same emissions as higher
equivalence ratios. If the trend were extrapolated up the emissions could be expected to be
approximately 35 ppmvd at $\phi=0.95$ for 100% CH₄ in the 0.405 blockage injector. These higher
emissions are only found when the hottest flames are present when more CO₂ is added or more
air is added the drop in the flame temperature reaches a point where the NOₓ emissions drop
back to previous blockages emissions levels.

![Graph](image)

Figure 35: NOₓ Emissions Corrected to 3% Oxygen vs. Equivalence Ratio for 0.405 Blockage
Figure 36 shows the connection between the light intensity and NO\textsubscript{x} emissions and looks very similar to Figure 30 except for the highest equivalence ratio for 100\% CH\textsubscript{4}. The discrepancy found in NO\textsubscript{x} emissions at this equivalence ratio in other blockages is seen in Figure 36 where there seems like a small patch of points are too high and off the main trend. The emissions at these conditions were triple checked for the accuracy and indeed there is an influence on NO\textsubscript{x} emissions at higher equivalence ratios, or points far from lean blow off.

![Graph](image)

**Figure 36:** NO\textsubscript{x} Emissions Corrected to 3\% Oxygen vs. Light Intensity for 0.405 Blockage

### 5.1.4 0.457 Blockage Lean Blow off and Emissions

The final blockage tested yielded similar results to the first three but had the most consistent results with the highest R\textsuperscript{2} values; the testing procedure by this point had been thoroughly practiced and the human error during the testing had been minimized. Figure 37 shows the stability limits with the 0.457 blockage installed and similar to before it seems to be limited to around the 0.8 equivalence range. This test was able to get closer to the true lean blow
off limit of the dump plane injector at an equivalence ratio of 0.77; in all the cases with 100% CH₄ up to this point 0.77 equivalence ratio was the absolute limit before lean blow off.

**Figure 37: Equivalence Ratio vs. Light Intensity for 0.457 Blockage LSI operating on 100% CH₄**

Figure 38 and Figure 39 shows results that match those previously found. As more CO₂ is added the flame intensity and stability gets worse and narrows, up to 20% does not have a large impact on the results but as 40% approaches the flame reactivity is greatly diminished. As noticed before all the trendlines between the light intensity and equivalence ratio are very high and give strong correlations between each other. At this point the limits of the fuels are well known, for a fuel composition of 100% CH₄ the lean blow off equivalence ratio is around .8. Running 6.59 scfm of CH₄ and 1.65 scfm of CO₂ gives the 80% CH₄ / 20% CO₂ fuel composition when combined with 78.7 scfm of air the lean blow off limit for this fuel is reached.
Figure 38: Equivalence Ratio vs. Light Intensity for 0.457 Blockage LSI operating on 80% CH4 / 20% CO2

Figure 39: Equivalence Ratio vs. Light Intensity for 0.457 Blockage LSI operating on 60% CH4 / 40% CO2
at an equivalence ratio of 0.8. Finally flowing 6.59 scfm of CH₄ and 4.41 scfm of CO₂ gives the 60/40 concentration and combined with 70.1 scfm of air the lean blow off equivalence ratio of 0.9 is achieved. These lean blow off limits hold true for all blockages and are only influenced by the fuel or equivalence ratio.

Figure 40 shows the effect of fuel on the injectors performance with the 0.457 blockage installed. It shows the effect of the CO₂ addition to the fuel does not start to play a dramatic role until you get above 20%. Regardless of the fuel used the minimum light intensity seems to coincide with the same value at the lean blow off limit.

![Figure 40: 0.457 Blockage Equivalence Ratio vs. Light RMS for All Three Fuels Showing Blow off Similarity](image)

Figure 41 has the same range of equivalence ratios for each fuel but in the case of each individual fuel the higher equivalence ratios have higher NOₓ emissions. The 100% CH₄ fuel
has about 37 ppmvd of NO\textsubscript{x} at a 0.96 equivalence ratio, 22ppmvd at a 0.85 equivalence ratio, and 10 ppmvd at an equivalence ratio of 0.78. All the emissions for the 100% CH\textsubscript{4} fuel are about 2 ppmvd of NO\textsubscript{x} higher than compared to the smaller blockages. Looking similarly at the 80% CH\textsubscript{4} case the emissions are higher across the board until the lower equivalence ratios are reached. At a 0.95 equivalence ratio the emissions for 80% CH\textsubscript{4} are around 29 ppmvd as compared to 20 ppmvd for the 0.405 blockage with the same fuel composition and same equivalence ratio.

![Diagram](image-url)

**Figure 41: NOx Emissions Corrected to 3% Oxygen vs. Equivalence Ratio for 0.457 Blockage**

A linear trend with a high R-squared value develops when the emissions are plotted against the light intensity. At this point with the high accuracy received when plotting plots such as Figure 42 the fiber optic probe would serve as an accurate and reliable NO\textsubscript{x} sensor once the initial correlation of NO\textsubscript{x} to light intensity had been made.
Figure 42: NOx Emissions Corrected to 3% Oxygen vs. Light Intensity for 0.457 Blockage:

5.1.5 PIV Imaging Results

All the images gathered using the PIV were sampled using the dump plane configuration. Each blockage had 3 different fuel compositions measure: 100% CH\(_4\), 80% CH\(_4\), and 60% CH\(_4\) with the remainder being CO\(_2\). The 100% and 80% CH\(_4\) cases used the three equivalence ratios of 0.95, 0.86, and 0.8. The 60% CH\(_4\) case used two equivalence ratios 0.95 and 0.9. Each image featured in the following sections was an averaged image of 50 individual frames gathered under reacting circumstances.

Depending on the equivalence ratio and the fuel being burned the upstream velocities will vary quite a bit. Table 4 summarizes the bulk velocity for each test point:
Table 4: Bulk Velocities of Fuel and Air Upstream of the Injector

<table>
<thead>
<tr>
<th>Phi</th>
<th>Fuel</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95</td>
<td>100</td>
<td>15.86</td>
</tr>
<tr>
<td>0.86</td>
<td>100</td>
<td>17.36</td>
</tr>
<tr>
<td>0.8</td>
<td>80</td>
<td>18.56</td>
</tr>
<tr>
<td>0.95</td>
<td>80</td>
<td>16.25</td>
</tr>
<tr>
<td>0.86</td>
<td>80</td>
<td>17.76</td>
</tr>
<tr>
<td>0.8</td>
<td>60</td>
<td>18.96</td>
</tr>
<tr>
<td>0.95</td>
<td>60</td>
<td>16.86</td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td>17.67</td>
</tr>
</tbody>
</table>

5.1.5a Open Area Blockage 0.298 in²

The smallest blockage used during the tests was the 0.298 blockage which diverted most of the flow to the swirl vanes. Table 3 presents the swirl number and the flow split for the 0.298 blockage, it is clear that the swirl with this blockage is quite high and the flow through the central region will be relatively low.

Table 5: 0.298 Blockage Data

<table>
<thead>
<tr>
<th>Open Square Inches</th>
<th>0.298</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Split</td>
<td>0.2476</td>
</tr>
<tr>
<td>Swirl Number</td>
<td>0.4885</td>
</tr>
</tbody>
</table>

The 0.298 blockage has the least amount of fuel and air going to the central un-swirled region out of the group of blockages. The flames should all burn closer to the LSI because the central region’s velocity profile will be smaller. In order for the flame to match its flame speed with the injector speed it must burn at a position much closer to the injector. As the equivalence ratio increases a general trend of increasing velocities should be seen in the PIV images because there is more airflow in the mixture bringing the velocities up. Another thing to note is that as more CO₂ is added the flame velocity and the vectors near the flame front should decrease and become smaller. The following figures will show this trend and show the flow field behavior of the different test conditions.

In Figure 43 the first thing noticeable about the flow field is the lack of outer recirculation zones. The center region as expected does not show any regions where recirculation occurs because of the divergence zone created between the central flow and the
swirling region. The outer region does have recirculation zones and those can be seen slightly at the bottom left and right corners of some of the images; the images shown below are averaged vector fields so the resolution or recirculation seen as compared to an individual image is not as clear. The flame in Figure 43 is 100% CH₄ so the flame front has vectors in the 4 to 5 m/s range and as more CO₂ is added as in Figure 44 and Figure 45 the vectors near the flame front drop into the 3 to 4 and 2 to 3 m/s region respectively. In all the figures the velocities across all sections as well as the flame front height change with the equivalence ratio in the expected way. As more air is added the velocities in all sectors increase and the flame front heights all increase slightly showing the increasing velocity gradient.

Figure 43: PIV Images for 0.298 Blockage with 100% CH₄, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
The top left image in Figure 43 lost some of the flow pattern in the bottom right because of an inadequate choice of beam thickness for the laser sheet. The images only represent the vertical and radial component of velocity; however the tangential component due to the swirl causes some particles to move in or out of the laser sheet. When a sheet thickness, as chosen by the convex lens positioning, is too thin or too thick it can cause the software to be incapable of discerning the seeder and leads to a blank spot. In this particular case the flow uniformity suggests that the flow will be a mirror image of the flow on the left and the important section near the center and flame front region is still undisturbed so the image was acceptable.

Figure 44: PIV Images for 0.298 Blockage with 80% CH4/20% CO2, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
A final note on the images is that the vectors are in odd directions with various speeds in a seemingly random pattern along the flame front region. This section just past the flame front has a lower amount of seed particles so it is difficult for the software to produce accurate vectors and in addition, the turbulent nature of the reaction allows for packets of vectors to make it across the front. The unburned seeder drops caused small vectors to be calculated into the software, so for all intents and purposes these vectors can be ignored.

Figure 45: PIV Images for 0.298 Blockage with 60% CH4/40% CO2, 0.95 Equivalence Ratio (Top), 0.9 Equivalence Ratio (Bottom)

5.1.5b Open Area Blockage 0.357 in²

The next largest blockage has 0.357 square inches of open area and lets a little more fuel and air to be sent through the middle region. This flow will also position the flame front slightly
higher than the previous smaller blockage.

<table>
<thead>
<tr>
<th>Open Square Inches</th>
<th>0.357</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Split</td>
<td>0.273</td>
</tr>
<tr>
<td>Swirl Number</td>
<td>0.4719</td>
</tr>
</tbody>
</table>

In Figure 46 the three equivalence ratios for 100% CH₄ with the 0.357 square inch blockage. The first noticeable difference between these images and the previous blockage is the lower velocity in the swirl region with this blockage. More of the flow is diverted to the center reducing the swirl number and as suspected the swirl velocity is lower through this region.

Figure 46: PIV Images for 0.357 Blockage with 100% CH₄, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
Because the flame height is slightly higher with this injector the turbulence in the flow causes less individual frames to have perturbations that push the flame front close to the injector mouth. The result when averaging all these slightly higher flame positions resulted in a more full looking middle section which is indicative of more flow split sent to the center. The images in Figure 47 do not show much change as compared to those in Figure 46 but an ever so slight change in the velocities present at the flame front. The images in Figure 47 show a decrease in velocities near the flame front as the slower burning mixture of fuel reacts.

Figure 47: PIV Images for 0.357 Blockage with 80% CH4/20% CO2, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
Further still as more CO$_2$ is added up to 40% the flame speed drops even further near the flame front as seen in Figure 48.

![PIV Images for 0.357 Blockage with 60% CH4/40% CO2, 0.95 Equivalence Ratio (Top), 0.9 Equivalence Ratio (Bottom)](image)

**Figure 48: PIV Images for 0.357 Blockage with 60% CH4/40% CO2, 0.95 Equivalence Ratio (Top), 0.9 Equivalence Ratio (Bottom)**

**5.1.5c Open Area Blockage 0.405 in$^2$**

The results and trends for 100% CH$_4$ are similar to those seen before this point; the only difference is the higher velocities in the center and higher flame heights.
Table 7: 0.405 Blockage Data

<table>
<thead>
<tr>
<th>Open Square Inches</th>
<th>0.405</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Split</td>
<td>0.2856</td>
</tr>
<tr>
<td>Swirl Number</td>
<td>0.4635</td>
</tr>
</tbody>
</table>

The flame heights in Figure 49 are in the region of 35 mm from the injector dump plane as compared to those sitting about 20 mm from the injector plane as seen in Figure 43. Figure 49 continues to back up the trends established before about the increasing size of open area allowing more flow, higher velocities, and a higher flame height.

Figure 49: PIV Images for 0.405 Blockage with 100% CH4, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
At this point it is clear that some of the images that represent 60% CH$_4$ such as Figure 45, Figure 48, and Figure 51 all have flame heights that are much lower than those that have 100% CH$_4$. All of the intuition and research suggests that a higher flame speed will burn closer to the injector and this is still the case. What is being seen in those three figures is the lower turbulent intensity found with a lower flame speed. A study found a linear relation between turbulent intensity and turbulent flame speed so that as the flame speed decreases by adding more CO$_2$ the turbulent intensity lowers (Cho, et al., 1986). This means the propagation speed is lower and the flame will not move as high during its turbulent fluctuations. Once all the images are averaged together the smaller fluctuations found with a lower flame speed will not show up on the averaged images.

Figure 50: PIV Images for 0.405 Blockage with 80% CH4/20% CO2, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)
5.1.5d Open Area Blockage 0.457 in²

The blockage with the most open area used was 0.507 but because that one was outside the swirl range and gave no reaction the last blockage to look at is the 0.457. The 0.457 blockage allowed the most fuel and air through the center and gave the largest velocity profile through the middle. This larger velocity profile also gave a higher flame anchoring height as seen from Figure 52 as compared to the others.
The blockage ratio, the swirl number, and the mass flow split are shown in Table 8.

Table 8: 0.457 Blockage Data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Square Inches</strong></td>
<td>0.457</td>
</tr>
<tr>
<td><strong>Mass Split</strong></td>
<td>0.3389</td>
</tr>
<tr>
<td><strong>Swirl Number</strong></td>
<td>0.4278</td>
</tr>
</tbody>
</table>

The flame height for this blockage was around 40mm from the dump plane; at this height the flame is floating high into the chamber and should be at its most unstable point. The acoustic oscillations from the wall and the outer recirculation zones are at their largest point with this
flame height.

Figure 53: PIV Images for 0.457 Blockage with 80% CH4 / 20% CO2, 0.95 Equivalence Ratio (TL), 0.86 Equivalence Ratio (TR), 0.8 Equivalence Ratio (Bottom)

Overall the flow field structure between all the different blockages does not seem to show much of a difference. The main difference is not found in structure but in velocities. Because of the change in velocities a subsequent change in flame height is observable from the image.
Figure 54: PIV Images for 0.457 Blockage with 60% CH4/40% CO2, 0.95 Equivalence Ratio (Top), 0.9 Equivalence Ratio (Bottom)

5.1.6 OH-CH Images

The correlation between the emissions and blockage was an unexpected result, so checking the flame structure using OH* and CH* imaging was the next step. The images were taken at the two extreme blockages to allow for any differences between the images to stand out and give a clear indicator of what is going on. Figure 55 and Figure 56 shows the OH* and CH* images of the two blockages. The top row of Figure 55 consists of all the OH images and the bottom row is all of the CH images; the last two images in both rows are cases with 60% CH4 and the remaining four are all with 100% CH4 in both rows. The first image is with an equivalence ratio of 0.95, the next is at 0.9, then 0.85, and lastly 0.8, after that the final two have
an equivalence ratio of 0.95 and end at 0.9. Figure 56 has a similar format to Figure 55 with the
top row being OH* and the bottom being CH*. The first four pictures in every row are using
100% CH₄ fuels and the last two are with 60% CH₄ fuels. The first four equivalence ratios are
for the 100% CH₄, are from 0.95 to 0.8 in intervals of 0.05; the last two are 0.95 and 0.9.

![Figure 55: 0.298 Blockage OH Images (Top) and CH Images (Bottom)](image_url)

Looking at the images the red zones represent regions of high concentration down to the
dark blue which is a region of low concentration. The NOₓ correlation with blockage is seen
between these two images by looking at the concentration of the reaction. As the blockage was
increased more flow was sent to the central channel and the reaction was focused more in the
center as seen in Figure 56 where the red zone is much bigger and brighter in the center as
compared to Figure 55. More reaction occurring in the center means a higher core flame
temperature and less heat is lost through the extremities of the flame; this higher flame
temperature increase the amount of thermal NOₓ as was seen during the testing. Then as more
air was added and the flame as a whole became less reactive both blockages achieved the same minimum emissions as was seen in the previous graphs.

![Figure 56: 0.457 Blockage OH Images (Top) and CH Images (Bottom)](image)

At the lean blow off limit the emissions were the same regardless of the blockage and this is seen as the profiles are the same despite the different blockages at the lean blow off limit, the fourth profile from the right. The last thing to note is the long and weak reaction when more CO₂ was burned on the right profiles as compared to the compact and reactive profiles on the left from 100% CH₄.

### 5.2 Quarl Reacting Results

The optimization of the injector is accomplished through the addition of a quarl; the quarl is a conical injector that gives a physical guide for the flow to follow. This guide eliminates the shear layer and outer recirculation zones by removing sharp edges that produce recirculation. In addition the quarl will shield the flame form acoustic oscillations that may affect the stability. Using the quarl will eliminate any outside factors that may influence stability and allow focus on the blockages effect on stability.
5.2.1 0.298 Blockage Lean Blow off and Emissions

With the addition of the quarl the outer recirculation zones are eliminated and this allows the overall lean blow off limit to be much lower than compared to the dump plane. Looking at Figure 57 this can be seen as the range of equivalence ratios is much larger and a more dilute fuel blend up to 50/50 was able to be burned. Comparing the emissions of NO\textsubscript{x} from this nozzle as compared to the dump plane nozzle at the same equivalence ratio reveals a large difference; the quarl has higher emissions near stoichiometric and transitions to lower near blow off. The quarl used for these tests was made with a refractory material that insulated the flame and therefore less heat was lost during the reaction leading to a higher flame temperature and higher emissions. The emissions stay higher all the way through until around a 0.7 equivalence ratio for 100% CH\textsubscript{4} but after that they continue to drop and the overall emissions with the quarl are better than the dump plane.

The emissions given off by the quarl are ultimately lower and better at the lower equivalence ratios; in addition, the 50/50 fuel was able to burn as compared to the dump plane nozzle which could not anchor the flame. The lean blow off limits for the 0.298 blockage are a 0.63 equivalence ratio for 100% CH\textsubscript{4}, 0.65 equivalence ratio for 80% CH\textsubscript{4}, 0.71 equivalence ratio for 40% CH\textsubscript{4}, and a 0.81 equivalence ratio for 50% CH\textsubscript{4}. The emissions for all fuel types all reached approximately 4 ppmvd corrected to 3% right before their lean blow off limits.
Table 9 shows the few cases where CO actually started to become a problem due to the lower flame temperatures. In some cases at very lean conditions the reaction would start to quench and emit CO in small packets that were above the +/-1 ppmvd noise of the emissions analyzer. The last two points were taken over the same region at different times and are different because the CO was emitted in spikes as the flame would oscillate between extreme instability and marginal instability.

Table 9: CO Emissions from 0.298 Blockage with Quarl Nozzle

<table>
<thead>
<tr>
<th>Fuel (% CH₄)</th>
<th>Equivalence Ratio</th>
<th>CO (ppmvd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.627</td>
<td>4.69</td>
</tr>
<tr>
<td>80</td>
<td>0.65</td>
<td>11.38</td>
</tr>
<tr>
<td>80</td>
<td>0.65</td>
<td>4.63</td>
</tr>
</tbody>
</table>
5.2.2 0.357 Blockage Lean Blow off and Emissions

The emissions from the 0.357 blockage fall in a similar range as the previous blockage as can be seen in Figure 58. The emission range for the case with 100% CH₄ is from 50 ppmvd at an equivalence ratio of 0.9 to 5 ppmvd at an equivalence ratio of 0.64, with 80% CH₄ it ranges from 40 ppmvd at an equivalence ratio of 0.9 to 4 ppmvd at an equivalence ratio of 0.67, 60% CH₄ ranges from 20 ppmvd at 0.92 equivalence ratio to 4 ppmvd at a 0.75 equivalence ratio, and finally 50% CH₄ starts at a 0.9 equivalence ratio with 10 ppmvd and goes to a 0.8 equivalence ratio at 4 ppmvd. The stability regime for the injector is unchanged with the larger blockage it still has the lean blow off limit of 0.65 with 100% CH₄, 0.67 equivalence ratio with 80% CH₄, 0.75 equivalence ratio with 60% CH₄, and 0.8 equivalence ratio with 50% CH₄.

![Figure 58: 0.357 Blockage with Quarl Nozzle NOx Emissions vs. Equivalence Ratio](image)

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The graphs shown for the stability section with the dump plane nozzle were able to be shown with light intensity as it relates to the flickering or stability of the flame however with the quarl installed, the fiber optic probe had to be relocated to monitor the flame directly. In the section covering the 0.405 blockage, data will be shown with light intensity; the data in this section were gathered using a specially designed rig that incorporated a fiber optic probe to the low-swirl injector to gather how it would compare to the previous results found with the dump plane nozzle.

The CO emissions for the quarl nozzle with the 0.357 blockage were not significant except for one case. Yet again this case was at the lowest equivalence ratio for the given fuel; the point that gave off 11.4 ppmvd of CO was found using 50% CH$_4$ at an equivalence ratio of 0.8. At this point the adiabatic flame temperature was very low, 1846 K, and the fluctuations in the flame gave rise to periods of incomplete combustion and quench zones.

5.2.3 0.405 Blockage Lean Blow off and Emissions

Looking at Figure 59 the emission profile does not change when compared to previous blockages as it did when the dump plane nozzle was used. The 0.457 blockage still needs to be checked but at this point no correlation between emissions and blockage is clearly evident and the stability or lean blow off limits are still unchanged. The lean blow off limits of 0.62 for 100% CH$_4$, 0.65 for 80% CH$_4$, 0.73 for 60% CH$_4$, and 0.8 for 50% CH$_4$ are the same as they have been for the two previous blockages. In addition, the emissions, more or less within the experimental uncertainty, overlap each other at every point.

This blockage was used with the quarl nozzle in order to place a fiber optic in the center of the injector head looking up at the flame in order to see how it would perform with similar
tasks as before.

Figure 59: 0.405 Blockage with Quarl Nozzle NOx Emissions vs. Equivalence Ratio

Figure 60 and Figure 61 give a good comparison to the graphs used before. Placing the fiber optic extremely close to the flame gave very good results for determining NOx and lean blow off limits for all the fuels. In Figure 60 the R² value is 0.9786, so highly accurate and linearized. Future injectors could safely integrate a fiber optic probe into the injector and monitor the intensity to give a good indicator of NOx emissions in place of an emission analyzer.

Figure 61 is the best representation of the lower limit of intensity before lean blow off for all the fuel types. Having the injector positioned so close and focused on the center of the flame gave the best results.
Figure 60: NOx Emissions Corrected to 3\% Oxygen vs. Light Intensity for 0.405 Blockage in Quarl Nozzle

Figure 61: 0.405 Blockage Equivalence Ratio vs. Intensity for All Three Fuels With Blow off Similarity and Quarl Nozzle
It is clear from this graph that taking 100% CH$_4$ through to 50% CH$_4$ fuels all the way to their lean blow off limit gave the same value for the light intensity moments before blow off.

Knowing that any fuel has the same light intensity before blow off would allow the fiber optic to be installed in the burner head and determine air flow rates that would keep the flame lit without knowledge of the fuel composition.

The flame intensity plotted against the equivalent adiabatic flame temperature and NO$_x$ emissions reveals what has been suspected up to this point; as the flame temperature of the fuel changes so does the light intensity and emissions in a strong linear fashion. Figure 62 is a plot of the adiabatic flame temperatures and NO$_x$ emissions versus the light intensity for the different fuels.

![Figure 62: Adiabatic Flame Temperature and Corrected NOx vs. Light Intensity for 0.405 Blockage with Quarl Nozzle](image-url)
All the fuels except for the 50% CH₄ case fall on a very similar line. The square points on the graph correspond to the AFT vs. the light intensity while the diamonds correspond to the NOₓ vs the light intensity. This graph shows the strong connection between the AFT and the light intensity as the flame temperature is increased the flame is more luminous. Because the flame is burning hotter and thermal NOₓ is such a large contributor for lean premixed CH₄ flames the NOₓ emissions also increase with light intensity or with AFT.

The CO emissions were not a problem throughout most of the testing but at three points near lean blow off the CO started to rise. Table 10 gives the summary of the emissions recorded; they all occurred with 50% of the fuel being CH₄ and 50% being CO₂ so the probable reason is that the low flame temperature with the slow chemical kinetics led to some of the fuel being left un-oxidized.

Table 10: CO Emissions from 0.405 Blockage with Quarl Nozzle

<table>
<thead>
<tr>
<th>Fuel (% CH₄)</th>
<th>Equivalence Ratio</th>
<th>CO (ppmvd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.85</td>
<td>7.47</td>
</tr>
<tr>
<td>50</td>
<td>0.8</td>
<td>11.95</td>
</tr>
<tr>
<td>50</td>
<td>0.8</td>
<td>14.91</td>
</tr>
</tbody>
</table>

5.2.4 0.457 Blockage Lean Blow off and Emissions

The last blockage to test with the quarl nozzle was the 0.457 blockage. The emissions from this blockage are not as consistent as before and so the results have a few outliers as compared to the previous tests with other blockages. Figure 63 shows that despite the outlier emissions in certain areas the equivalence ratio range for each fuel is the same with this blockage as it is for others. The lean blow off number for 100% CH₄ is a 0.65 equivalence ratio, 80% CH₄ blows off at a 0.65 equivalence ratio, 60% CH₄ blows off at 0.7 equivalence ratio, and 50% CH₄ at a 0.8 equivalence ratio. Looking at all the blockages used in the quarl there is no stability change and no change in emissions. Something essential to be noted is that the sudden
expansion nozzle gives a change in emissions with stability while the quarl nozzle does not. However, in any case the blockages did not change the lean blow off of the low-swirl injector only the nozzles had an effect on the stability.

Figure 63: 0.457 Blockage with Quarl Nozzle NOx Emissions vs. Equivalence Ratio

5.3 Analysis

In the following section the Design Expert software is used to perform a statistical analysis of the effects during testing. The first plot that will be displayed is a half normal plot. The normal plot takes all the observed effects and compares them to what they would look like if they were in a normal distribution; if the points do not represent a normal distribution, meaning they are significant, they will be seen as outliers on the plot. A half normal plot is the same as a normal plot except the line is anchored at a zero point and compares the absolute value of the effects rather than the line being anchored to the center set of points as in the normal plot. In the
sections that display the tables with analysis of variance data the “Prob > F” values are key in understanding effects. If the values are much smaller than 0.0001 then the results are significant and that means the predicted model and the results do not vary by significant amounts.

5.3.1 Dump Plane Design of Experiments, Stability

After looking at the results from a non-rigorous view point a more factual statistical approach was used to determine what factors had an effect on the stability. The three factors measured and input into the Design of Experiments software were the equivalence ratio, the fuel composition, and the blockage. After compiling all the data collected into one giant spreadsheet the factors that play a significant role are selected into making correlations and models. The first graph used was a half-normal plot as shown in Figure 64; the graph allowed a clear graphical display of outliers that would be significant factors in developing the model. When the fuel composition, equivalence ratio, and the combination of the two were selected the plot found those to be the only factors to be significant. When the blockage factor was selected as in Figure 66 no new knowledge was gained as it did not have a significant effect on changing stability.
Figure 64: Analysis of Variance for all Blockages Showing Significant Factors

Figure 66 shows that the blockage, when selected, does not change the overall layout of the graph. The point of the graph is to identify factors that have an impact on the collected data and as those points are selected the red line will move to be in line with the insignificant factors. A comparison between the actual results and the predicted results can be seen in Figure 65. The equation used for the predicted results produces similar results as compared to the actual and only utilizes the three parameters chosen above: fuel, equivalence ratio, and the combination of the two.
Figure 65: Actual vs. Predicted Results of Stability (RMS) vs Equivalence Ratio for 0.298 Blockage with Sudden Expansion

Figure 66: Analysis of Variance for all Blockages Showing Significant Factors and Blockage as Insignificant

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Table 11 is a numerical representation of Figure 66 and shows that the developed model is significant and that the lack of fit is insignificant. This essentially verifies that there is indeed an impact on stability due to the model developed. The factors that are significant in the model have p-values that are less than 0.0001; factor A (equivalence ratio), factor B (fuel composition), and factor AB (the combination of the two effects) all play significant roles. However, looking at factor C (blockage) the p-value is 0.1031 which is greater than 0.0001 so this is not a significant term in developing the model. Table 11 goes to show that with the dump plane configuration the blockage does not play a role in influencing stability.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Value</th>
<th>Prob &gt; F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>11.93</td>
<td>4</td>
<td>2.98</td>
<td>145.95</td>
<td>&lt; 0.0001</td>
<td>significant</td>
<td></td>
</tr>
<tr>
<td>A-Phi</td>
<td>4.57</td>
<td>1</td>
<td>4.57</td>
<td>223.65</td>
<td>&lt; 0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-FuelCH4</td>
<td>2.37</td>
<td>1</td>
<td>2.37</td>
<td>116.16</td>
<td>&lt; 0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-Blockage</td>
<td>0.055</td>
<td>1</td>
<td>0.055</td>
<td>2.70</td>
<td>0.1031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>0.70</td>
<td>1</td>
<td>0.70</td>
<td>34.27</td>
<td>&lt; 0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>2.08</td>
<td>102</td>
<td>0.020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>2.08</td>
<td>101</td>
<td>0.021</td>
<td>33.78</td>
<td>0.1363</td>
<td>not significant</td>
<td></td>
</tr>
<tr>
<td>Pure Error</td>
<td>6.108E-004</td>
<td>1</td>
<td>6.108E-004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>14.01</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Taking Figure 65 and overlaying the predicted equation from Table 11, which includes the blockage factor, results in Figure 67. Comparing the predicted points in red to the predicted points in green, which include the blockage as a parameter in the equation, the difference is insignificant; in addition, the two predicted equations match the actual data closely. It is clear
that the addition of the blockage factor does not bring additional information to the equation and therefore the blockage does not play a role on the stability.

Figure 67: Overlay of Equation from Table 11 Showing Insignificance of Blockage Factor

The combinations of the three factors that have influences on the stability give Equation 6. The equation is:

\[
\textit{Stability} = 3.49552 - 4.19779 \times \textit{Phi} - 0.075973 \times \%CH_4 + 0.10428 \times \textit{Phi} \times \%CH_4
\]

Equation 6

If the above equation is taken for the lean blow off limits established earlier: 100% CH\(_4\) with a 0.77 equivalence ratio, 80% CH\(_4\) with a 0.79 equivalence ratio, and 60% CH\(_4\) with a 0.86 equivalence ratio the stability number found should be relatively close.
The applied equation does indeed give very close intensity values at lean blow off for each fuel. The 60% CH$_4$ cases were generally gathered at a 0.9 equivalence ratio however, Figure 40 does have a data point with the equivalence ratio at 0.87 which suggests that the true lean blow off limit for the 60% CH$_4$ case would be at an equivalence ratio of around 0.86. This is a powerful equation because it shows that the blockage plays no role in stability and at the same time suggests that independent of fuel type or equivalence ratio a stability region can be developed based only on light intensity of the flame.

The continual conclusion that the lean blow off limit for any fuel is correlated to the intensity seems to suggest an underlying connection. When the conditions for equivalent intensity are looked at more closely a relation does start to show. The adiabatic flame temperature (AFT) for the three conditions in Table 12 are all very similar. Looking at Table 13 the comparison becomes clearer; in addition, Figure 40 shows that at an equivalence ratio of 0.86 the 100% CH$_4$ flame has a higher intensity than the 80% CH$_4$ and looking at the last two rows in Table 13 the AFT for 100% CH$_4$ is greater than that with 80% CH$_4$.

<table>
<thead>
<tr>
<th>Phi (Equivalence Ratio)</th>
<th>Fuel (% CH$_4$)</th>
<th>Stability (Intensity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.77</td>
<td>100</td>
<td>0.695</td>
</tr>
<tr>
<td>0.79</td>
<td>80</td>
<td>0.691</td>
</tr>
<tr>
<td>0.86</td>
<td>60</td>
<td>0.707</td>
</tr>
</tbody>
</table>
Table 13: Adiabatic Flame Temperatures Related to Light Intensity of Flames

<table>
<thead>
<tr>
<th>Phi (Equivalence Ratio)</th>
<th>Fuel (% CH₄)</th>
<th>Stability (Intensity)</th>
<th>AFT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.77</td>
<td>100</td>
<td>0.695</td>
<td>1949</td>
</tr>
<tr>
<td>0.79</td>
<td>80</td>
<td>0.691</td>
<td>1956</td>
</tr>
<tr>
<td>0.86</td>
<td>60</td>
<td>0.707</td>
<td>1958</td>
</tr>
<tr>
<td>0.86</td>
<td>100</td>
<td>1.3</td>
<td>2068</td>
</tr>
<tr>
<td>0.86</td>
<td>80</td>
<td>1.2</td>
<td>2025</td>
</tr>
</tbody>
</table>

5.3.2 Dump Plane Design of Experiments, Emissions

Analyzing each blockage separately using the Design Expert software gave individual trends on the NOₓ emissions as a function of equivalence ratio and fuel composition. The 0.298 blockage gave an equation with significant factors of fuel composition and equivalence ratio as expected. The processing gave Equation 7 for NOₓ as:

\[ \text{NO}_x = 97.6 - 126.6 \times \Phi - 2.04 \times \text{Fuel} + 2.72 \times \Phi \times \text{Fuel} \]  

Equation 7

Moving on to the next blockage, 0.357 squares inches of open area, gave Equation 8 that is very similar:

\[ \text{NO}_x = 97.45 - 127.09 \times \Phi - 1.99 \times \text{Fuel} + 2.69 \times \Phi \times \text{Fuel} \]  

Equation 8

Equation 8 is very similar to the one found for the 0.298 blockage which suggests a lack of blockage effects on emissions at first glance. Using the Design Expert software for the original 0.405 blockage the software found another relation between NOₓ and the two factors:

\[ \text{NO}_x = 53.21 - 79.5 \times \Phi - 1.53 \times \text{Fuel} + 2.19 \times \Phi \times \text{Fuel} \]  

Equation 9

The R² value for this model is 0.9982 when compared to the raw experimental data so it suggests a strong correlation between the NOₓ emissions and the factors that change it. However,
comparing Equation 9 to the two that were found before presents a large discrepancy. The difference between the equations suggests the presence of a third factor that has an influencing role; the only factor that was left off of this analysis was the blockage. This draws the conclusion that the blockage, although it does not affect the stability, has an impact on the emissions.

Taking this analysis one step further gave an equation for the 0.457 blockage as follows:

$$\text{NO}_x = 82.68 - 112.02*\Phi - 1.95*\text{Fuel} + 2.7*\Phi*\text{Fuel}$$

Equation 10

Equation 10 is again different than all the ones listed before further reinforcing the conclusion suggested before; blockage plays a role on the emissions. Therefore, an analysis was done on the NO\textsubscript{x} emissions with a third factor, blockage.

Using the Design Expert software the blockage was included as a factor and when selected it was shown to play a significant role in the NO\textsubscript{x} emissions. Figure 64 shows that the half-normal plot suggested the selection of the blockage as a positive effect on the accuracy of the model; by adding the blockage the red line falls on top of the green points.
The analysis of variance table found all the above factors to have a p-value that is less than 0.0001 so that falls far under the insignificance value of 0.1 or greater. The equation for this data has an $R^2$ value of 0.9450; this gives a powerful tool to determine the NO\textsubscript{x} in this burner as a function of equivalence ratio, fuel composition, and blockage. Equation 11 is written as:

$$\text{NO}_x = (8.76 - 10.84 \times \text{Phi} - 0.20 \times \text{Fuel} + 2.39 \times \text{Blockage} + 0.28 \times \text{Phi} \times \text{Fuel})^2$$ \hspace{1cm} \text{Equation 11}

Using Equation 11 across a range of blockages can be seen in Table 14:
The results of the equation line up very closely with the raw collected data; there is a slight discrepancy with the smaller blockages but the overall trend with blockages and NO\textsubscript{x} are present. Now that the emissions and stability for the dump plane configuration have been thoroughly discussed the next step was to optimize the performance (addition of the quarl) and see if the stability can be affected by the blockage or determine the reason behind the NO\textsubscript{x} correlation with blockage.

### 5.3.3 Quarl Design of Experiments, Stability

Due to the lack of optical access for a fiber optic there was a lack of data to carry out analysis of variance on the light intensity for the quarl. The stability range in section 5.2 showed that despite the changes in blockage there was not a change in the lean blow off limits. The software was not necessary to check to see if there was a significant effect because observations clearly point out that no significant effect is present. Lastly, the analysis done in section 5.3.1, similarly, did not find a change in stability with the blockage when the dump plane nozzle was used.

### 5.3.4 Quarl Design of Experiments, Emissions

A similar analysis was done using the emissions data from the quarl as was done with the sudden expansion nozzle. The first step as before was to use the half-normal plot to determine significant factors. Figure 69 shows that the half-normal plot predicted that the blockage, in addition to the fuel composition and equivalence ratio, was significant. Another observation

<table>
<thead>
<tr>
<th>Blockage (in\textsuperscript{2})</th>
<th>Phi</th>
<th>Fuel(% CH\textsubscript{4})</th>
<th>NO\textsubscript{x}(ppmvd to 3%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.298</td>
<td>0.95</td>
<td>100</td>
<td>34.4</td>
</tr>
<tr>
<td>0.357</td>
<td>0.95</td>
<td>100</td>
<td>36.1</td>
</tr>
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<td>0.405</td>
<td>0.95</td>
<td>100</td>
<td>37.5</td>
</tr>
<tr>
<td>0.457</td>
<td>0.95</td>
<td>100</td>
<td>39</td>
</tr>
</tbody>
</table>
from the half-normal plot is the relative distance from the orange line that the blockage effect is located in comparison to the equivalence ratio and fuel composition. The results from this plot and the model developed in the analysis of variance suggest that the blockage is a factor in influencing emissions with the quarl. This is contrary to the solution developed as to why the blockage effects the emissions; however further analysis on the effects and their weights shows that the blockage as expected plays a negligible role with the quarl nozzle.

Figure 69: Half-Normal Plot of the Significant Factors in NO\textsubscript{x} Production with the Quarl

The model developed by the software, Figure 70, produces a model that does not actually fit or accurately predict the data collected. The software included extra terms in order to try and make the fit more accurate and get a higher order polynomial but it was unable to produce a
significant model. Because the software could not produce a significant model and the observations from the graphs in section 5.2 do not suggest a relation with blockage and emissions the original solution found for the correlation between emissions and blockage as found with the sudden expansion nozzle hold.

![Analysis of Variance Showing the Significant Lack of Fit for the Quarl Model](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>p-value</th>
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</thead>
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<td>Model</td>
<td>36349.70</td>
<td>6</td>
<td>6058.28</td>
<td>309.73</td>
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<td>21260.94</td>
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<td>AB</td>
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<td>112.54</td>
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<tr>
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<td>Cor Total</td>
<td>40476.86</td>
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</table>

Figure 70: Analysis of Variance Showing the Significant Lack of Fit for the Quarl Model

In Figure 71 the predicted equations are plotted against the actual results for NO\textsubscript{x} emissions as a function of equivalence ratio. The red data are the predicted results from the equation that includes the blockage as a parameter. The green data are the predicted results from the equation that does not include blockage as a parameter. Comparing the two equations, the results are similar with most of the R\textsuperscript{2} values between the lines being one. Due to the similarity between the two equations the blockage factor does not add an additional information to the fit; in addition, the lack of fit of the equations is significant because the values below an equivalence ratio of 0.7 cannot follow the trend.
Now that both the quarl nozzle and sudden expansion nozzles have been tested with different blockages for a change in stability the performance can be judged. The sudden expansion nozzle showed no sign of stability or lean blow off improvement when the blockage was changed. The flame heights had no significant impact on the stability; a flame burning at a high flame height is as stable as one burning very close to the injector. In other words, a flame that is exposed to large acoustic disturbances and high recirculation zones does not show a change in performance by adjusting its exposure to these effects. After inserting the quarl nozzle the lean blow off limits became better because of the elimination of the exhaust gas recirculation and elimination of the outer shear layer. This played a larger role on the elimination of acoustic effects on the injector than the blockage changes did, as seen by the stability increase. The role
that acoustic oscillations play on the stability of the low-swirl injector in this study is most likely negligible because of the lack of change when introducing other blockages.

The sudden expansion nozzle likely displayed no stability changes because of the way it stabilizes and burns the flame. It generates a linear decaying profile down the center of the injector and any flames that match the injector velocity at this point will sit where the flame speed and the injector velocity match. This range is already very wide and the change of the profile that was introduced with the blockage by changing the swirl number is not enough to affect the stability with fuels such as methane and digester gas. The swirl number in the case of the low-swirl injector does not play a role on the recirculation zones like a high swirl injector so higher swirl does not necessarily mean better performance. The low-swirl injector’s unique flame stabilization technique eliminates the need for most variable geometry needs in order to change the performance characteristics.

5.3.6 Dump Plane vs. Quarl Results

In the area of stability the dump plane and the quarl have two different results and ranges. The dump plane nozzle had poor stability ranges in comparison to the quarl; the dump plane generally had a lean blow off limit of 0.8 with pure methane. The quarl nozzle was able to decrease the lean blow off to around 0.6 with pure methane. The operability ranges of the quarl were much wider and because the lower equivalence ratios could be reached so could a lower adiabatic flame temperature. With the lower AFT achievable by the quarl nozzle so was a lower level of NOx emissions achievable. The dump plane nozzle could achieve around 9 ppm of NOx at 3% O2 while the quarl was able to reach as low as 3 ppm NOx at 3% O2. The lower overall emissions limit is better with the quarl but it does not happen across the whole range of equivalence ratios. The quarl has higher emissions than the dump plane for all similar
equivalence ratios; in other words the quarl is effectively only a better solution for emissions in the equivalence range of 0.6 to 0.7, where the dump plane nozzle cannot reach. The insulation inside the quarl keeps the temperatures high, the walls eliminate outer recirculation, and the nozzle’s guide prevents shear layer effects; these three effects help the quarl to reach the lower equivalence ratios but at the same time it keeps the flame temperature high at all other conditions.

Both the quarl and the dump plane nozzle are unaffected stability-wise by the changing blockages. The emissions can be adjusted by the blockage but only when using the dump plane nozzle, when the quarl is used the flow split plays no role in adjusting core temperatures because of the insulation retaining all the heat. The dump plane nozzle does approach the same emissions at the lower equivalence ratios for all blockages so at points near lean blow off there is no difference.

The fuel compositions that the dump plane can burn are not as wide in composition range as the quarl nozzle. This is mainly due to the internal flame temperatures with the quarl as compared to the dump plane. The quarl retains more of the reactions heat so it is able to burn the digester gas compositions that are more dilute and thus have lower flame temperatures.
CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary
The goal of this thesis was to determine the flame stability and emissions of variable geometry low-swirl injector technology in a simulated boiler environment operating on natural and digester gas. Previous research has found that changing the vane angle or ratio of radii has no effect on the stability of a low-swirl injector; however, the tests for changing mass split or blockage have not been done to isolate the effects of the blockage. Lastly, there have been previous cases where a low-swirl injector had the blockage replaced in order to burn different fuels indicating a possibility for the increase in fuel flexibility and stability with a variable blockage.

A rig was designed to hold a low-swirl injector with access for exchanging different screen blockages in the center. The interchanging of this blockage would allow this parameter to be changed without effecting any other parameter and change in the flow split and thus swirl number for the low-swirl injector. A flow panel was designed in order to provide a constant input of 400,000 BTU/hr (117 kW) of heat while also allowing a varying composition of digester gas from 100% CH₄ to 50% CH₄/50% CO₂. The first stage of testing involved a dump plane nozzle for each blockage, five in total, and for each blockage and fuel PIV images were taken to give a view of the flow field. In addition to the vector flow field from the PIV, the reaction zone was found using OH and CH imaging to further characterize the blockage effects. Diagnostic data were collected along the walls of the boiler and in the exhaust stack for temperature and emission characterization of the reaction. After the testing with the dump plane had finished the quarl nozzle was installed and tested to determine how it would respond to the variable blockage.
6.2 Conclusion

- This section summarizes conclusions drawn from the study with results on stability, then transitions into emissions correlations, then fuel findings, and finally fiber optic probe relations.

- **Stability, as defined by lean blow off limits, was not changed through the changing of the center blockage of the low-swirl injector.** The low-swirl injector operates on a unique principal of matching flame speeds with injector speeds in order to stabilize a flame. The stability did not change with the swirl number because of the way the low-swirl injector works as compared to typical injectors. The swirl in the low-swirl injector does not influence the stability by changing the outer shear layer or changing the flow structure like other injectors, instead it changes the velocity profile in the center region and this in turn will change flame heights. Looking at the PIV images the blockage did indeed change the velocity profile and as a result it also changes the flame height. The flame height had no effect on stability; the flow structure held together equally well either being far or close to the exit plane. The acoustic oscillations and reflections from the chamber also played no role on the flame stability so changing flame height to influence these features had no effect.

- **The operation of a low-swirl injector on digester gas is possible without any modifications. The optimal performance would be achievable with an increase in blockage to the center channel.** The low-swirl injector was able to burn all concentrations of digester gas in the same stability regions, regardless of the flow blockage used in the center channel. The optimal performance in terms of reducing emissions would be to increase the swirl; however, this condition only holds when
operating near stoichiometric. As the burner is brought to leaner conditions near blow off the emissions for any of the blockages becomes the same. Increasing the central blockage, up to a swirl number of 0.55, would give the lowest emission profile across the widest range of equivalence ratios. If the swirl number were to be taken above 0.55 vortex breakdown would ensue and an increase in emissions would be observed as the low-swirl injector transitioned into a high swirl injector.

- **The quarl nozzle greatly improves the lean blow off limit and decreases the NO\textsubscript{x} emissions by almost 50%**. The quarl nozzle is a great improvement for the low-swirl injector because it helps shield and guide the flame. The quarl provides a guide for the flow to follow as well as eliminating sudden expansion zones; the elimination of these regions removes the shear layer from the flow to help hold the structure and it removes outer recirculation zones which can lower stability. The quarl nozzle allowed a whole extra fuel composition to be tested because of the increased lean blow off limits; the testing of 50/50 blends was possible with the quarl.

- **The NO\textsubscript{x} emissions increased as a less restrictive blockage was used in the center of the low-swirl injector with a dump plane nozzle**. The data collected shows a trend of increasing NO\textsubscript{x} with increasing open area in the middle. As more flow is sent through the center of the injector the reaction in the core of the flame is much greater. This produces a higher flame temperature in the center which in turn makes more thermal NO\textsubscript{x}. This effect does not occur in the quarl nozzle because the insulation in the nozzle keeps all the heat in so the split of more to the center or outer region will not affect the overall flame temperature. The effect also diminishes at low equivalence ratios or high
concentrations of CO₂ when the flame temperature is far from the thermal NOₓ trigger temperature.

- **CO emissions as suspected for a lean premixed burner are extremely low and in most cases negligible.** The CO emissions throughout the dump plane nozzle tests were all zero and the emissions only became a slight problem when using the quarl. The quarl would allow lower equivalence ratios that in certain cases would cause slight flame perturbations to give a spike in CO emissions for a period of 10 to 15 seconds only in the lowest of equivalence ratios.

- **Emissions from the digester gas are lower at the same equivalence ratio as that from natural gas.** The digester gas equivalence ratio range is not as large but in each equivalence ratio the NOₓ emissions are lower as compared to those from natural gas. The equivalence ratio range is smaller for digester gas but if emissions are the only requirement then it operates as well as natural gas because the narrow operation range can still achieve equivalence emissions.

- **Digester gas as fuel does not start to change properties and reactivity until the composition increases above 20% CO₂. The reactivity of greater than 20% CO₂ digester gas starts to drop off rapidly and produces high instabilities.** After the fuel composition increased the CO₂ above 20% the reactivity started to noticeably change as well as the flame speeds. Using 80% CH₄ or more cause the flame maintain its flame speeds similar to 100% CH₄ and the lean blow off limit did not change within a significant amount. In the sudden expansion nozzle the flames with greater than 20% CO₂ experienced high levels of oscillations and very limited stability regions.
• The digester gas flames are much longer than those of the methane and the reaction occurs over a longer residence time. The OH and CH images of the flame present when burning digester gas, 40% CO₂, as compared to natural gas are much longer and the reaction is not focused in any specific region. The long reaction zone increases the residence time but because the overall reaction intensity is so low the reaction does not spend more time in a hot zone so the thermal NOx is still low. The long flames from digester gas are even present with the naked eye as the flames run much higher into the boiler.

• The light intensity for any composition of digester gas cuts off at the same value at the lean blow off limit for each fuel. The light intensity given off for each fuel at the lean blow off limit was the same number. This means that regardless of the fuel used a fiber optic sensor placed in or near the reaction will relay to the user how far the flame is from blow off. The user does not need to know what fuel they are burning only the value of light intensity at lean blow off and they can tell how close they are.

• Light intensity vs. NOx emissions or equivalence ratio is a linear fit with a strong correlation. The emissions of NOx for natural gas or digester gas are largely dependent on thermal NOx as the main driver. A flames luminosity is closely related to its AFT for almost all fuel types as found before and this then relates to the NOx emissions and equivalence ratio. A flame with high luminosity will have a high AFT and therefore high NOx emissions. This relation is a strong linear fit so a fiber optic probe could be used to tell stability, equivalence ratio, and NOx emissions all in one.

• Fiber optic probes integrated into the heads of an injector give very good results and are a viable option for many systems. The fiber optic probe was successfully
integrated into the center of the injector without any impacts on performance. The bonus was it gave the best results with the least amount of interference. The results for this setup gave the strongest fits of emissions, equivalence ratio, and lean blow off limit all from one fiber optic probe.

6.3 Recommendations
In order to improve upon the results and come up with alternative areas to test the following recommendations have been made.

- To better understand the flame velocities and turbulence levels a laser doppler velocimetry (LDV) system would be a powerful tool to implement. The velocities gathered from PIV data were adequate for rough approximations but they sample at a much slower rate and the software to process the whole vector field is time consuming. An LDV system can focus all the measurements to one section of the burner where the flame is sitting and can sample at a much higher rate. If this tool was implemented the flame speeds of the different fuel types could be more exactly calculated and the turbulence level of the flame could be an influential factor to gather. As it stands the screen blockage effects on turbulence are not exactly classified and LDV could clarify some of the mystery involved here.

- A smaller injector and associated hardware would allow a larger pressure drop across the injector. This could possibly allow a better control of performance by increasing the bulk velocity or giving more control over the flow velocities across the injector. The current setup is slightly oversized for the current flow rate and a smaller injector and plumbing could perform better by having a larger change in velocity with equivalence ratio.
The control of the burner could be simpler and more automatic if the controls or flow system moved over to mass flow controllers. The current set up is all manual control and requires an extra person so no true “active computer control” exists. If mass flow controllers were to be added into the flow circuit the system would approach a more realistic state and could be controlled completely by a computer using the diagnostic feedback equipment.

As mentioned before the turbulence of the flow is not fully categorized so making the system have less bends and longer lengths of tubing could improve the development of the flow in addition to remove some turbulence. A piece of honeycomb or flow straightener could be added in the upstream piping to guide the flow and help it settle more rapidly in an attempt to improve the results.

The experimental correlations found when using the quarl did not produce significant results and the resulting accuracy between the actual and predicted values was low. Getting a more accurate experimental fit could require more parameters in the equation or a higher order fit. The current fits were linear but using a second or third order polynomial fit could bring the lack of fit values to insignificant levels.

The testing of this burner used an equivalence ratio that was solely determined by the mixture in the primary zone of the flame. For burners using primary zone equivalence ratios at a higher level and then adding dilution air the analysis would be different. The relation between the parameters discussed before and the light intensity would be not as conclusive. For burners incorporating a dilution zone the air added to the fuel at the flame front and the air added to control the temperature, post combustion, is uncoupled.
Due to this reason some of the conclusions would need to be reworked for systems with a primary zone and a dilution zone.
CHAPTER 7: REFERENCES

7.1 Acknowledgements
Dr. Vince McDonell
Dimas Avila
Andres Colorado

7.2 Bibliography


8.1 High Swirl Injector Geometry

The high swirl injector (HSI) is configured in a way that a recirculation is formed in the center in order to serve as an aerodynamic source of ignition. One hollow cylinder forms the outer shell while a solid cylinder placed concentrically forms the solid bluff body in the center. In between the two cylinders are angled vanes that impart swirl on the gas. In some cases the center body has a center hole in it to serve as an igniter during light off. During typical use the premixed fuel and gas enters the swirler and a tangential velocity is imparted on the gas. In the case of a high swirl injector the center bluff body serves as a dead zone where recirculation occurs. The absence of a pilot means that a source of ignition is required to hold the flame; the recirculation of hot exhaust gases from the inner recirculation zone serves this purpose. The HSI’s flame will attach to the lip of the bluff body during operation and this will form a characteristic V shape off of the center channel. Depending on the size of the combustion chamber post injector, there can be large or small outer recirculation zones (Johnson, et al., 2005).

8.2 High Swirl Injector Performance

The emission signature of a high swirl injector is relatively low because it is usually uses a lean premixed combustion method. In addition to the lower emissions from operating lean premixed the center and outer recirculation zones serve the purpose of introducing exhaust gas recirculation; EGR as discussed before will lower flame temperatures to reduce NOx emissions. Along the same lines the inner recirculation zones can also have the opposite effect by creating a very hot zone in the core of the reaction. During operation of the high swirl injector a problem
arises when trying to operate at very lean conditions, the central recirculation zone can start to break down, the mixture will start to lose its uniformity in the recirculation zone, and acoustic feedback from flame oscillations can lead to premature blow-off (Cheng & Levinsky, 2008).

8.3 Surface Stabilized Burners

Cutting edge burners used in boilers consist of surface stabilized burners; these injectors stick into the chamber and stabilize flames on the surface. These burners have low NO\textsubscript{x} emissions because the flames are premixed and small thus reducing the flame temperatures. The hotter the surface becomes on the injector the better it performs, however, as it becomes hotter the propensity for flashback increases. Burning hydrogen in these injectors designed for natural gas would not be an option because the pressure drop across the surface might become too great, the flashback propensity would greatly increase, and the heat transfer from the exhaust products of hydrogen is not as good (Bizzi, et al., 2003).

Injectors such as the one mentioned above can meet emissions for the moment but are only designed to operate on one fuel, so meeting emission regulations in the future is exceptionally difficult. If another fuel had to be used the injector would fail to work or have a drastic reduction in performance. The call for more fuel flexible injectors has sparked the creation of injectors like the low-swirl injector.

8.4 Dump Plane Reaction with Hydrogen and Methane Mixtures

Some of the testing accomplished included some hydrogen and methane mixtures. The tables listed below include the results from hydrogen and methane fuel compositions with varying blockages. The nozzle used during these tests was the dump plane configuration.

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<th>% CH4</th>
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**METHANE/HYDROGEN**

**Sudden Expansion**
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