Energy Research and Development Division

FINAL PROJECT REPORT

Effect of Variable Fuel Composition on Emissions and Lean Blowoff Stability Performance

Analysis of Nine Industrial Combustion Applications

California Energy Commission
Edmund G. Brown Jr., Governor

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PREFACE

The California Energy Commission’s Energy Research and Development Division manages the Natural Gas Research and Development program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

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• Industrial, Agriculture and Water Efficiency
• Renewable Energy and Advanced Generation
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• Energy-Related Environmental Research
• Natural Gas-Related Transportation.

Effect of Variable Fuel Composition on Emissions and Lean Blowoff Stability Performance is the final report for the project contract number 500-13-004, conducted by University of California Irvine, Combustion Laboratory (UCICL). The information from this project contributes to Energy Research and Development Division’s Energy-Related Environmental Research Program.

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ABSTRACT

One strategy for meeting future energy demands in a more environmentally sustainable way is to use renewable gaseous fuels mixed with fossil fuels in place of non-renewable fuels. However, this strategy requires consideration of how fuel composition variations influence nitrogen oxide (NO\textsubscript{x}) pollutant emissions and lean stability limits (range of acceptable air to fuel ratio), especially for technologies originally designed to burn natural gas or liquefied petroleum gas.

Researchers tested various two (binary) mixtures of methane (CH\textsubscript{4}) and hydrogen dioxide (H\textsubscript{2}), carbon dioxide (CO\textsubscript{2}), ethane (C\textsubscript{2}H\textsubscript{6}) and propane (C\textsubscript{3}H\textsubscript{8}) in nine prototype and commercial burners originally designed to use gaseous fossil fuels. They looked to understand the mechanisms within each burner controlling formation of different types of pollutants; and the relationship between lean stability trends (acceptable air to fuel ratio) and the type of pollutant emitted when a particular fuel mixture was burned. All nine burner applications were assessed using computational fluid dynamics models and chemical reactor networks.

Three of the nine combustion tests were validated at the UC Irvine Combustion Laboratory with the remaining six compared to emission trends available from previous studies conducted by the Gas Technology Institute and the Lawrence Berkeley National Laboratory. Results show the variation of NO\textsubscript{x} produced with common combustion parameters and fuel composition is far from consistent.

From this project, a numerical platform is developed to evaluate pollutant emissions and stability performance with varying fuel compositions for different types of burners. The establishment of this platform demonstrated the capability and potential of using numerical modeling to investigate emissions and stabilities with different fuel compositions. It also provided a base for future studies with more complicated compositions and other types of burners. The analysis and results from the numerical simulations can be used as a guide to determine the impacts on emissions and stabilities of different fuel compositions.

Keywords: Gaseous fuels; Binary fuels; Lean Blowoff; Hydrogen enriched natural gas; Biogas; Pollutant Emissions (NO\textsubscript{x}, CO)

Please use the following citation for this report:

# TABLE OF CONTENTS

Acknowledgements ......................................................................................................................... i

PREFACE ........................................................................................................................................... ii

ABSTRACT .......................................................................................................................................... iii

TABLE OF CONTENTS ............................................................................................................................ v

LIST OF FIGURES .................................................................................................................................... vi

LIST OF TABLES ..................................................................................................................................... vi

EXECUTIVE SUMMARY ........................................................................................................................... 7

Introduction ........................................................................................................................................ 7

Project Purpose and Process ............................................................................................................. 7

Project Benefits ....................................................................................................................................... 8

CHAPTER 1: Overview of Burner Configurations ............................................................................. 9

1.1 Low-Swirl Burner (LSB) ............................................................................................................ 9

1.2 Surface-Stabilized Combustion Burner (SSCB) ................................................................ 10

1.3 Micro-Turbine Combustor (MTC) - Capstone C65 ............................................................. 11

1.4 Oxygas Burner .......................................................................................................................... 12

1.5 High Speed Jet Burner (HSJ) ................................................................................................... 13

1.6 Turbine Combustor GT333 – FlexEnergy ............................................................................. 14

1.7 Radiant Tube (RT) .................................................................................................................... 15

1.8 Infrared Burner (IRB) ............................................................................................................... 16

1.9 Slot Burner (SB) ........................................................................................................................ 17

CHAPTER 2: Results and Analysis ...................................................................................................... 19

2.1 Emissions Trends ..................................................................................................................... 19

2.1.1 Effect of Hydrogen Addition to NG .................................................................................. 22

2.1.2 Effect of CO₂ Addition to NG ......................................................................................... 24

2.1.3 Effect of Heavier Hydrocarbons Addition to NG ............................................................ 24

2.2 Lean Blowoff Stability Trends ................................................................................................ 26

2.3 Oxygas Trends .......................................................................................................................... 28
LIST OF FIGURES

Figure 1: Comparative Results (CFD models) ................................................................. 11
Figure 2: C65 Combustor Outline with Injector Cross Section ..................................... 12
Figure 3: Burner Draft and Assembled Burner ................................................................. 13
Figure 4: Schematic Flow Distribution in a Turbine Combustor ....................................... 15
Figure 5: Typical Temperature Profile and Heat Pattern of a Radiation Tube .................. 16
Figure 6: Infrared Burner Configuration ......................................................................... 17
Figure 7: Contour of Temperature (CFD result) .............................................................. 18
Figure 8: Effect of Hydrogen Addition on NOx Trends for LSB and SSCB ....................... 20
Figure 9: Chemical Time as a Measure of the Reactivity of a Fuel ................................. 23
Figure 10: LBO Stability Trends vs. Mole Fraction of the Alternative Gaseous Fuel in the Binary Mix with NG ................................................................. 26
Figure 11: NOx Trends for Oxygas Technology ............................................................. 29

LIST OF TABLES

Table 1: Summary of the Nine Combustion Applications .................................................. 9
Table 2: General NOx, CO and Stability Results ............................................................... 20
Table 3: Acceptable Specification Ranges According to AGA Indices ............................. 21
Table 4: NOx, CO and Stability (Sbty) Results for Interchangeable Mixtures .................... 22
EXECUTIVE SUMMARY

Introduction

Fossil fuel reserves are being depleted at a global scale, and some studies indicate both oil and natural gas (NG) will be completely exhausted by 2042 (Shafiee and Topal, 2009). Furthermore, the rate at which the world consumes energy is increasing as populations increase and living standards rise in parts of the world that consumed little energy until recently.

One strategy for reducing the use of non-renewable, finite fuel sources while continuing to meet increasing energy demands is to replace them completely with renewable gaseous fuels, or mix renewable fuel with fossil fuels. Biogas, for example, is a byproduct of digesting organic matter by bacteria in an anaerobic environment. Biogas is generally composed of methane (CH₄) mixed with carbon dioxide (CO₂) and with other gases in residual concentrations. Another example is hydrogen (H₂), which can be separated from water molecules (H₂O) using an electrolyzer powered by a renewable source of energy like the wind or the sun. Mixtures of NG with hydrogen are generally known as hydrogen enriched natural gas. Using hydrogen enriched natural gas mixtures can be expected to provide more abundant future fuel supplies. However this strategy requires attention to how adopting these future fuels can impact pollutant emissions and operability of different burners, especially when these fuels are used in equipment originally designed for burning fossil gaseous fuels like NG and liquefied petroleum gas.

Project Purpose and Process

Using unprocessed fuels such as natural gas, coal bed methane, landfill and digester gases, biomass and coal-derived gases (such as synthetic natural gas), and hydrogen is expected to increase if these fuels are readily available and economical. As the spectrum of fuels available in California widens, it is essential to understand the impact fuels with different compositions will have on existing combustion equipment. Existing interchangeability (substituting one gaseous fuel for another) indices tend to focus on fuel throughput and do not specifically consider combustion characteristics that might otherwise impact operability and/or emissions characteristics of systems operated on a range of fuel types. Benefits of increased fuel flexibility will be offset if these fuels result in reduced combustion system efficiency, increased maintenance costs, or degraded air quality.

The team at the University of California, Irvine Combustion Laboratory studied the behavior of gaseous fuels, exploring how different types of renewable fuels and fuel composition impacts the performance of various burner configurations. The alternative fuels included two (binary) blends of biogases; hydrogen enriched natural gas and mixtures of NG with heavier alkanes like ethane and propane.

Researchers verified and tested the impact of alternative gaseous fuels on nine prototype and commercial burner designs examining the stability and pollutant emissions of systems using mixtures of alternative gaseous fuels. The pollutant emissions behavior of burners was studied when operated on biogas (CO₂/methane), hydrogen enriched natural gas, and natural gas with higher hydrocarbons. It is important to understand the influence of various fuel compositions
on pollutant emissions and lean-stability limits (range of acceptable air to fuel ratio), especially when these fuels are used in equipment originally designed for burning fossil gaseous fuels like natural gas and liquefied petroleum gas.

Project Results
Nine prototype and commercial burner designs and applications originally designed for burning natural gas on alternative gaseous fuel resources were tested. The results show the variation of pollutant emissions (NOx, CO) with common combustion parameters is not consistent.

For instance, in some designs, high pressure leads to markedly higher NOx, while in others the NOx decreases with pressure. Measurements suggest some of the complexity occurs because the external parameters change the size of the zones where NOx forms, in addition to changing the formation rate within the zones. The different fuel mixes and composition also plays a fundamental role on its chemistry and forming pollutant species; for example, experimental results on a jet stirred reactor show the addition of hydrogen to the fuel significantly decreases the NOx levels. In contrast, when adding hydrogen to a NG reaction stabilized with a high swirl burner the NOx levels measured only increased moderately, even for high H2 levels in the binary mixture. Furthermore, experimental tests conducted on a micro-turbine generator (MTG-Capstone C65) show, at high concentrations of H2 in the fuel, the NOx levels measured in the exhaust significantly increased.

From this project, a numerical platform is developed to evaluate pollutant emissions and stability performance with varying fuel compositions for different types of burners. The establishment of this platform demonstrated the capability and potential of using numerical modeling to investigate emissions and stabilities with different fuel compositions. It also provided a base for future studies with more complicated compositions and other types of burners. The analysis and results from the numerical simulations can be used as a guide to determine the impacts on emissions and stabilities of different fuel compositions.

Project Benefits
This project provides a guide about the expected variation of pollutant emissions and stability performance when changing the fuel composition. The project compiles the emissions and lean blowoffs stability trends for nine combustion applications including turbine combustors, boiler burners, radiant tubes, and porous burners. The project shows that emissions and stabilities vary based on fuel composition and burner type.
CHAPTER 1: Overview of Burner Configurations

Table 1 summarizes the nine configurations with their respective acronyms, along with technical specifications and reaction stabilization methods. Further details about NOx control strategies used by each burner technology will be presented in the following subsections.

**Table 1: Summary of the Nine Combustion Applications**

<table>
<thead>
<tr>
<th># Configuration</th>
<th>Acronym</th>
<th>Fire rate [kW]</th>
<th>Oxidant</th>
<th>Oxidant preheat temp. [K]</th>
<th>Compression ratio</th>
<th>Mixing strategy</th>
<th>Flame structure</th>
<th>Stabilization method</th>
<th>Premixed aerodynamic</th>
<th>Premixed on surface patterns</th>
<th>Non premixed (diffusion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Low-Swirl Burner</td>
<td>LSB</td>
<td>117</td>
<td>Air</td>
<td>Ambient.</td>
<td>--</td>
<td>Premix</td>
<td>Divergent</td>
<td>--</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Surface-Stabilized Combustion Burner</td>
<td>SSCB</td>
<td>117</td>
<td>Air</td>
<td>Ambient.</td>
<td>--</td>
<td>Premix</td>
<td>On surface</td>
<td>--</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Micro-Turbine Combustor - Capstone C65</td>
<td>MTC</td>
<td>222</td>
<td>Air</td>
<td>840 ±10</td>
<td>4:1</td>
<td>Premix</td>
<td>Jet</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Oxygas Burner</td>
<td>Oxy</td>
<td>586</td>
<td>O₂</td>
<td>Ambient.</td>
<td>--</td>
<td>Difuss</td>
<td>Flat flame</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. High Speed Burner</td>
<td>HSB</td>
<td>293</td>
<td>Air</td>
<td>840 ±10</td>
<td>4:1</td>
<td>Premix</td>
<td>Jet</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Turbine Combustor GT333 - FlexEnergy</td>
<td>TCFlex</td>
<td>1000</td>
<td>Air</td>
<td>877 ±10</td>
<td>4:6:1</td>
<td>Premix</td>
<td>Swirl</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Radiant Tube</td>
<td>RT</td>
<td>51</td>
<td>Air</td>
<td>Ambient.</td>
<td>--</td>
<td>Difuss</td>
<td>Jet</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Infrared Burner</td>
<td>IRB</td>
<td>22</td>
<td>Air</td>
<td>Ambient.</td>
<td>--</td>
<td>Premix</td>
<td>On surface</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Slot Burner</td>
<td>SB</td>
<td>23</td>
<td>Air</td>
<td>Ambient.</td>
<td>--</td>
<td>Premix</td>
<td>Jet</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each of these nine combustion studied in this project are shown with their respective acronyms, stabilization methods, conditions of the reactions and NOx control strategies.

1.1 Low-Swirl Burner (LSB)

Low-swirl combustion is an aerodynamic flame stabilization method for lean premixed combustion discovered in 1991 at the Lawrence Berkeley National Laboratory (LBNL). The emissions control technology used by the LSB is based on fuel-lean premixed combustion. Adaptation of this novel concept to heating equipment has been successful and resulted in commercial LSBs with NOx emissions below 9 ppm (at 3% O2). The LSB involves the application of a novel flame stabilization method that exploits the turbulent flame speed concept by enabling a detached flame to freely propagate in a divergent flow-field [7]. Further information about the LSB technology, its pollutant emissions and stability performances is widely discussed on a previous report (Burner Configuration #1—Low-Swirl Burner-CEC Agreement No. 500-13-004) [5].
The injector features swirl vanes in the outer annulus with a perforated plate in front of the inner annulus. The reactants flowing through the injector create a flow field with an outer swirling region with a non-swirling inner region that creates a divergent flow with linearly decaying velocity profile along the centerline [8]. When the reactants are ignited, the turbulent flame produced will stabilize in the inner non-swirling region at a location where the local turbulent flame speed matches the local axial flow velocity. This characteristic makes the LSB a fuel-flexible technology, since it dynamically stabilizes the reactions of multiple fuel compositions without any modification being required. Additional information about the LSB can be found elsewhere [9]–[14].

### 1.2 Surface-Stabilized Combustion Burner (SSCB)

The SSCB analyzed in this paper is the Duratherm™ ceramic-fiber burner by Alzeta Corporation. The porous radiant burner operation, emissions and stability performances is widely discussed in the report for the SSCB [6]. Premixed fuel and air flows through the porous fiber material. The mixture heats as it passes through the material, and combustion takes place on the outer surface. The combustion process continues in the gas phase as the flow leaves the hot face of the material so that peak gas temperatures occur slightly beyond the hot face. Heat transfer and diffusion of combustion products from the gas phase region back to the burner provide the feedback necessary to sustain stable combustion. The flow of fuel-air mixture through the fiber mat recuperates any inward conduction of heat from the outer surface such that the cold face of the mat is very near the incoming gas mixture temperature. When the burner flame is fully attached to the surface, the combustion occurs without any visible flame and without noise or pressure fluctuations [7]–[9].

One distinctive characteristic of the surface stabilized combustion is the extended volume of the reactions. The volume ratio of surface stabilized reaction volume over the volume of a dynamically stabilized reaction can be ~50 times (for the same firing rate). This comparison is presented in Figure 1. While for the dynamically stabilized reactions the flame structure varies as a function of the fuel composition and air availability, the reactions stabilized with the SSCB maintains a reaction structure with an approximately constant shape as the reactions attach to a solid surface. This characteristic is particularly advantageous when burning HENG blends, given their higher burning velocity their reactions attach more closely to the surface, which enhances the heat transfer reactions-surface, hence cooling down the reactions more efficiently than a when the flame is lift (unattached from the surface). Multiple studies have shown that the addition of either CO or H2 to the fuel reduces the NOx emissions when compared to pure hydrocarbon flames [10], [11].

Comparative results (CFD models) dynamically stabilized reactions with LSB and on surface patterns with a SSCB are shown in Figure 1.
1.3 Micro-Turbine Combustor (MTC) - Capstone C65

The C65 MTC features a single stage compressor and single stage turbine; the combustor has six injectors distributed in two planes (Figure 2). The first plane (plane A) of two premixed jets is followed by a second plane (Plane B) of four premixed jets followed by a dilution zone with secondary air. The fuel/air premixing occurs within the six individual fuel injectors with a fraction of the total combustion air. The Capstone combustor incorporates lean premixed combustion as strategy to control NOx. The flames are organized in an annular configuration that generates global swirl around the annular chamber. The recirculation of combustion products and interaction with the jet flames also provides cool and diluting gases to reduce the temperature of the reactions, again reducing NOx. To achieve global swirl, the combustor chamber counts with six fuel injectors slightly canted from purely radial orientation. The MTC includes a recuperator that provides preheated air to the combustor at a temperature of 840±10 K, regardless of the turbine load and/or the ambient temperature. The pressure ratio is nominally 4:1 and recuperation of the exhaust gas for preheating the incoming combustion air is incorporated to increase the overall efficiency.
Therkelsen et al., conducted experiments on a Capstone MTC with hydrogen enriched natural gas and up to 100% H₂, their experiments indicated a significant increase of NOx with the addition of hydrogen to NG [12]. Also, Hack and McDonell previously conducted experiments on a C65 MTC with mixtures of NG with heavier hydrocarbon fuels like ethane and propane, their results and trends indicate that the presence of higher hydrocarbons leads to appreciably higher NOx emissions, when compared to the system running on natural gas [13]. The emissions and stability trends for the C65 MTC are discussed on a previous report [14].

1.4 Oxygas Burner

For this project the Oxygen fuel burner Eclipse Primefire 300 has been modeled numerically in order to study how the emissions levels vary when changing the fuel type, the concentration of oxygen in the oxidant and the oxygen to fuel ratio. This burner is composed of two nozzles (one nozzle enclosed by the other nozzle). Both nozzle tips are flush with the pre-combustor chamber, which is a ceramic block made of insulating bricks. Figure 3 shows an isometric draft of the nozzles on the left and a picture of the burner and pre-combustor chamber on the right (extracted from [15]).
The inner nozzle conducts the fuel stream, whereas the oxidizer passes through the gap between the external walls of the inner nozzle and the internal walls of the outer nozzle. Both streams start mixing at the nozzle tip, where the pre-combustor chamber starts, in order to prevent high heat released. In the pre-combustor length some mixing occurs, however the oxygen stream keeps enveloping the fuel stream up to the entrance of the furnace chamber is reached. The purpose of this pre-combustor is to isolate the metallic burner tip from the radiation of the flame and furnace walls [16].

The burner produces a characteristic flat flame, which volume is increased considerably compared to the traditional round flames, thus improving the heat transfer to the load. Another important characteristic of this burner is that the flame presents a rich zone and a lean zone, referred to the concentration of the oxidizer, fact that promotes the soot creation and destruction in each zone, respectively. The presence of soot increases considerably the flame luminosity. The Eclipse Primefire 400 burner uses this characteristic, and by deviating a little amount of the oxygen to the fuel stream the creation of soot precursors, such as polycyclic aromatic hydrocarbons (PAH) are enhanced and therefore it is increased the flame luminosity. The flame luminosity plays an important role in the process since it is directly related to the radiant heat transfer, which is the main way to transfer heat in the most commons applications of this burner, such as glass melting, aluminum melting, etc. [15]–[18].

The oxygas burner operation, emissions and stability performances when varying fuel composition and excess of oxidant is widely discussed in the report for the burner configuration # 4 [19].

1.5 High Speed Jet Burner (HSJ)

Since burner nozzles can be modified to shape the flame based on desired design conditions, nozzle-mix burners are widely used in the industry given their high stability and fuel flexibility. Moreover high speed nozzle-mix burners avoid the risks of flashback, are capable of firing at high levels of excess air, and can operate at low firing rates while still providing recirculation of combustion products to help stabilize the reactions and control the emission of NOx. High
velocity burners are a type of nozzle-mix burner with a modified burner nozzle designed to stabilize the reactions in a high velocity jet; this type of burner uses mainly forced convection to quickly transfer heat to the load. Due to the ability of firing with high excess air, these burners can fire fuels with higher heating content (HENG mixtures for example) without flame stability or ignition issues. Consequently, higher local temperatures, NOx emissions, and differed flame shapes are associated with nozzle-mix burners.

The Gas Technology Institute conducted an experiment using a high velocity burner, the Thermjet (TJ100) by Eclipse, Inc. Given their operating conditions and emissions results, a 2-D model was created to determine the effects of the fuel composition on the emissions and stability performance of this configuration. The oxygas burner operation, emissions and stability performance when varying fuel composition and excess of oxidant is widely discussed in the report for the burner configuration # 5 [20].

1.6 Turbine Combustor GT333 – FlexEnergy

The configuration studied in this report is the GT333S Flex Turbine™ by FlexEnergy. The turbine combustor features an integral heat recovery unit contained within turbine enclosure; the recuperator is able preheat the air up to ~877K. The air and fuel are fully premixed before the primary combustion zone; then remaining air is injected downstream the primary zone to secure rapid cooling and dilution of the reactions (dry low NOX); furthermore the combustor features ultra-lean premixed combustion and a compression ratio 4.6:1.

Figure 4 shows a scheme of the fuel mixing process and air distribution throughout the multiple zones. The reactions in the first zone are ultra-lean premixed with an equivalence ratio for natural gas $\phi\sim0.51$. The remaining preheated air is distributed throughout the rest of the zones cooling down the reactions before the turbine inlet. GT333 operation, emissions and stability performance when varying fuel composition is widely discussed in the report for the burner configuration # 6 [21]
1.7 Radiant Tube (RT)

Radiant tubes are made of various types of metal alloys or cast ceramic. The infrared tube heater studied in this report is a positive pressure, single-stage radiant heater system. The performance is enhanced through using a specially designed stainless steel burner and black coated titanium stabilized and/or aluminized coated steel radiant tube exchangers. The configuration studied in this paper is the DX3 series by Reverberray. The radiant tube is 12.2 meter long and the nominal fire rate is 51kW. The burner features a long diffusion flame and the air for combustion is provided by an internal fan. The long diffusion flame transfer heat to the tube walls through convection and radiation. The external surface of the tube radiates heat to the load which secures indirect heat transfer from the reactions to the load. A schematic of the radiant tube assembly and the typical heat pattern is presented in Figure 5. The operation of the radiant tube, emissions and stability performance when varying fuel composition is widely discussed in the report for the burner configuration # 7 [22]
1.8 Infrared Burner (IRB)

The burner studied in this report is the RadMax™ infrared burner by MAXON Corp (Figure 6). The infrared burner is a technology designed to deliver uniform, high intensity radiant energy while maintaining low levels of NOx emissions and CO. The burner is designed for NG and propane. The infrared burner can be classified as one burner that uses a surface to stabilize combustion reactions. The operation of the burner can be summarized as follows: fully premixed fuel and air flows through the ceramic or metal foam tiles. The surface of the material acts as a flame retainer and stabilizer; the passages are small enough to avoid flash back of natural gas flames. The mixture heats as it passes through the material and combustion takes place on the outer surface. The reactions transfer heat to the tiles and the tiles reradiate that heat to the load. The effect is an enhanced heat transfer from the reactions to the load. The cooling effect through an extended surface is the main feature that guarantees low NOx and CO emission. The infrared burner emissions and stability performance with varying fuel composition and excess of air, is discussed in the report for the burner configuration #8 [23].
1.9 Slot Burner (SB)

The slot burner studied in this report is the Extruded Band Burner BB102A by Flynn Burner Corp. This type of burner is generally used in food processing industry and has been designed to operate on natural gas, propane, and butane. Fuel and air are mixed within the venturi before entering the extruded burner with the length of 36 inches. The premixed fuel/air mixture is finally injected into the atmosphere through the ribbon slot, where the flame stabilizes by sudden expansion. The firing rate of the burner is around 42kW with a stable turn down to 2.5kW. Figure 7 indicates the temperature contour obtained by numerical modeling of the burner with firing rate of 23kW. The actual flame configuration was modeled using periodic boundary conditions. The dynamic behavior of the flame is similar to the premixed jet flames as illustrated. To determine the emission of the burner, the chemical reaction network is created following the flow characteristics provided by CFD results. Heat loss to the atmosphere plays an important role in the emission calculation and needs to be correctly estimated in order to obtain reasonable results compared to the existing experimental data.
Figure 7: Contour of Temperature (CFD result)
CHAPTER 2: 
Results and Analysis

2.1 Emissions Trends

Figure 8 shows NOx experimental trends for the LSB and SSCB when substituting NG with up to 70% H2 by vol. All the experiments were carried out at fixed fire rate (117kW), atmospheric pressure and without preheating the air or fuel streams. Interestingly for the LSB, the addition of hydrogen to NG significantly promotes the formation of NOx and raises its concentration in the exhaust gases; thereby extending the lean stability limits from $\phi_{LBO\_LSB\_NG} = 0.78$ to $\phi_{LBO\_LSB\_70H2} = 0.45$. In sharp contrast, for the SSCB, the addition of H2 significantly reduces the concentration of NOx and also extends the flammability limits from $\phi_{LBO\_SSCB\_NG} = 0.45$ to $\phi_{LBO\_SSCB\_70H2} = 0.32$. Moreover previous experiments, [12] conducted at the UCICL by Therkelsen et al. on a Capstone C65 Combustor indicated that the addition of H2 to NG significantly impact the formation of NOx in the six jets cyclic combustor. Therkelsen found that at 100% H2 substitution the NOx concentration increased in the exhaust increased around ten times even when the temperature at the combustor exit was held constant for all fuel compositions. These three results demonstrate again that the variation of NOx with the fuel composition is far from consistent.

Notice however, that in all cases the LBO limit is associated with the lowest NOx levels; therefore NOx concentration in the exhaust can be used to diagnose the proximity of the premixed reactions to the onset of instability in the form of LBO. The following subsections uncover the underlying mechanisms controlling the increase/reduction of NOx for the eight combustion technologies. CFD and CRN models were used to understand the phenomena governing the formation of pollutant species (aerothermochemistry) for each technology.
Figure 8: Effect of Hydrogen Addition on NOx Trends for LSB and SSCB

The general NOx, CO and stability results for eight combustion applications and three fuel classes are presented in Table 2. The variation of the emissions and LBO stability limit were quantified using Eq. (1) and Eq. (2)

Table 2: General NOx, CO and Stability Results

<table>
<thead>
<tr>
<th></th>
<th>LSB</th>
<th>SSC</th>
<th>MTC</th>
<th>Oxygas</th>
<th>HSJ</th>
<th>GTC</th>
<th>RT</th>
<th>IRB</th>
<th>SB</th>
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<td>NOx</td>
<td>CO</td>
<td>Sta</td>
<td>NOx</td>
<td>CO</td>
<td>Sta</td>
<td>NOx</td>
<td>CO</td>
<td>Sta</td>
</tr>
<tr>
<td>I</td>
<td>CH4+H2</td>
<td>+</td>
<td>+</td>
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<td>+</td>
<td>-</td>
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<tr>
<td>II</td>
<td>CH4+CO2</td>
<td>+</td>
<td>-</td>
<td>-</td>
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<td>+</td>
<td>+</td>
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<td>-</td>
</tr>
<tr>
<td>III</td>
<td>CH4+C2/H</td>
<td>+</td>
<td>+</td>
<td>-</td>
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</table>

The fuels reflect the broadest range within each fuel class, and as a result, would not be considered interchangeable. To be considered interchangeable, the current work drew from the guidelines within Rule 30 [26]. According to Rule 30 the gas shall have a minimum Wobbe Number of 1279 Btu/scf and shall not have a maximum Wobbe Number greater than 1385 Btu/scf. In 1946 the American Gas Association (AGA) carried out extensive experimental research on fuel gas interchangeability [24]. AGA Tests were done on a specially developed partial premix Bunsen-type burner and focused on establishing criteria for blending “supplemental” or “peaking gases” with base load supplies or adjustment gases; those adjustment gases were the three most historically representative natural gases available in the U.S at that time [25]. Based on this experimental work, AGA developed several empirical indices to address the effects of fuel interchange on Yellow Tipping ($I_Y$), Flame Lifting ($I_L$) and Flash Back ($I_F$) (Figure 3). The methodology to calculate these indices is presented in the AGA bulletin#36 of 1946 [24]. These indices may not be applicable to the typical complex turbulent premixed flames or surface stabilized combustion systems. The inaccuracies expected
from applying AGA indices to current fuels may be even greater, since current fuels of interest include coal derived syngas, landfill and biomass gases, imported liquefied natural gas (LNG) and hydrogen augmented fuels whose composition is completely different to those natural gases used to set the stability criteria. Nonetheless, these indices were considered as the most advanced methods and effective tools to predict interchangeability in the United States and should be considered as a starting point.

According to Rule 30, the gas shall meet American Gas Association’s Lifting Index \((I_L)\), Flashback Index \((I_F)\) and Yellow Tip Index \((I_Y)\) interchangeability indices for substitute gases relative to a typical composition of NG in the utility system serving the area. The acceptable values for interchangeable mixture are presented in Table 5. The empiric correlations to calculate \((I_L)\), \((I_F)\) and \((I_Y)\) can be found elsewhere [24].

<table>
<thead>
<tr>
<th>Table 3: Acceptable Specification Ranges According to AGA Indices</th>
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<tr>
<td>Lifting Index ((I_L))</td>
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<tr>
<td>Flashback Index ((I_F))</td>
</tr>
<tr>
<td>Yellow Tip Index ((I_Y))</td>
</tr>
</tbody>
</table>

Conceptually, the lifting index is associated with the tendency of the flame to become unstable. Hence the fuel in question should not change the stability limit compared to the base fuel by more than 6%. This is mostly an issue for less reactive fuels such as biogas or diluted methane. The flashback index is essentially the opposite of the lifting index. If a fuel is reactive enough (e.g., hydrogen, higher hydrocarbons), when operated as a premixed fuel/air jet, it can result in the reaction propagating upstream of the jet exit. Yellow tipping is an indicator of sooting tendency. Larger molecules, and especially certain types, such as those with ring structures like benzenes, will have a tendency to form soot. The hot soot radiates in a yellow/orange color. This can cause issues with marking of surfaces and also have higher radiative heat transfer. It is important to recognize that these indices were really developed for small laminar flames associated with cook stoves or water heater burners. Practical turbulent combustion systems are more complex, so the ability of these indices to predict performance is questionable. However, in as much as end use devices have been adjusted to maintain these performance parameters and they have been long used to define acceptable variability in fuel composition, they are still looked to for guidance.

Based on interchangeable fuels, a similar emission and stability analysis was conducted for the binary mixtures presented in Table 4. Those mixtures are interchangeable with natural gas according to the Wobbe index and rule 30 was used for the interchangeability analysis.
As indicated previously the results are technology dependent and far from consistent. The following subsections elaborate on the underlying mechanisms controlling the observed trends. Experimental data, CFD and CRN results were used for the analysis.

### 2.1.1 Effect of Hydrogen Addition to NG

In aerodynamically stabilized reactions, the mass flow of exhaust recirculated into the gaseous reaction zone is variable and depends on the fuel composition, excess of air and aerodynamics in the chamber imposed by the nozzle and chamber design. In general, for less reactive fuels such as biogas, the effect of the recirculation of products on the flame is more intense, since the slower reactions will give enough time for the reactants to mix with the combustion products before they react. Conversely, highly reactive fuels as hydrogen will be less affected by the mixing with the surroundings. The “reactivity” of the fuel can be quantified using a theoretical variable called the “chemical time [s]” and can be calculated as the ratio of the flame thickness ($\delta[cm]$) over laminar flame speed ($S_L[cm/s]$). These can variables were estimated using the unidimensional premixed laminar reaction model (Premix) available in Chemkin and combined with a full reaction mechanism (GRI 3.0). The chemical time of biogas and hydrogen enriched fuel is compared to natural gas in Figure 9. As shown, at lean conditions, which favor low temperatures and low emissions, the impact of fuel composition is more significant that it is at conditions near stoichiometric point (Equivalence ratio approaching 1.0).
Figure 9: Chemical Time as a Measure of the Reactivity of a Fuel

**NOx Increases with the Addition of Hydrogen**

The addition of hydrogen to NG increases the formation of NOx in the following five configurations: 1. LSB; 3. MTC; 4. Oxygas; 5. HSJ; 7. RT; 9. SB. The common factor among these 5 configurations is the aerodynamic stabilization strategy. Furthermore the control strategy for the MTC and RT fixes the temperature at the combustor exit. For aerodynamically stabilized reactions the addition of NOx reduces the size of the reaction and the flame thickness. A consequence of the high reactivity of hydrogen is a shorter flame length. A high reactivity or fast chemistry counteracts the effect of the mixing with the combustion products. The interaction of the flame structure with the exhaust gas recirculation products has a direct effect on the emissions. With the addition of hydrogen the chemistry becomes faster than the mixing, therefore the effect of the exhaust gas recirculation is less efficient in diluting the reactions and reducing the temperature.

At a fixed equivalence ratio, the addition of hydrogen to natural gas increases the concentration of NOx in the exhaust gases. At temperatures above 1900K, NOx produced through the Zeldovich route or thermal mechanism is dominant for all the fuels. Also the addition of H2 promotes the formation of intermediate species like OH and H, which form more NOx through the NNH, thermal and N2O routes compared to pure hydrocarbon flame. On the other hand, the prompt path is initiated by rapid reactions of hydrocarbon radicals with molecular nitrogen; therefore the addition of H2 to the fuel reduces the formation of NOx through the prompt route. As a result the following configurations 1. LSB; 3. MTC; 4. Oxygas; 5. HSJ; 7. RT; 9. SB. show an increased production of NOx for the hydrogen enriched fuels.

Since the Oxygas and RT technologies use diffusion flames, the higher concentration of NOx observed when enriching the fuel with H2 is attributed to the higher local temperatures and higher concentrations of OH radicals and H-atoms when compared to NG diffusion and
premixed reactions. Furthermore the NNH route has been found to be an important contributor to NOx production when H and O atoms are present. Combustion of hydrogen and air in a gas turbine engine provides large amounts of dissociated H2 and O2. NNH dissociation to H and N2 is shown to be expected under all conditions; yet due to the nearly thermoneutral nature of NNH=H+N2 at high temperatures, NNH formation from H and N2 is also rapid. The formation of NO via the NNH pathway occurs in both hydrogen and methane flames for all equivalence ratios. The amount of NO produced that is attributed to the NNH pathway, however, depends greatly on temperature, equivalence ratio, and pressure [12].

**NOx Reduction with the Addition of Hydrogen**

NOx emissions are a function of the fuel composition, temperature of the reactions, availability or excess of oxidant, pressure and aerodynamics of the chamber. The reactions can transfer heat to the load through direct contact (conduction/convection) and radiation. The SSCB and the IRB enhance the radiative heat transfer from the reactions to the thermal load by using extended surface areas and materials with excellent emissivity. The reactions of very reactive fuels like hydrogen attach closely to the surface of the burner, which efficiently reduces the temperature of the reactions and increases the radiative heat flux out of the reaction zone. Since the SSCB and IRB porous material make the premixed flow laminar, therefore avoiding the recirculation of combustion products it can be concluded that the observed NOx reduction is solely attributed to the enhanced reaction heat losses.

2.1.2 Effect of CO2 Addition to NG

For the eight technologies, the addition of CO2 to the fuel simultaneously reduced the flammability limits and the production of NOx. This is a consequence of the cooling effect of CO2 that reduces the temperature of the reactions hindering the formation of NOx through the Zeldovich route. On the other hand the addition of CO2 tends to promote the production of CO emissions.

In general, a peak of CO is observed at the leanest mix ratio point matching the lowest NOx concentration, which can be linked to the LBO. Close to that limit, the flame temperatures is low, which affects the reactivity of the mixture as the concentration of OH radicals is reduced causing incomplete combustion leading to emissions of CO and unburned hydrocarbons.

An advantage of the biogas flames over the natural gas is its natural increased CO2 concentration that gives it better radiation properties. Since the CO2 mean absorption coefficient is ~5 times the coefficient of H2O. Nevertheless the high dilution with CO2 also reduces the temperature, burning velocity and simultaneously increases the flow velocity. These two factors contribute to lift the flame off the surface or nozzle.

2.1.3 Effect of Heavier Hydrocarbons Addition to NG

The presence of higher hydrocarbons leads to elevated NOx levels when compared to 100% methane. Even with similar firing temperatures the NOx trends are shifted upwards when adding heavier alkanes, which suggests that either NOx formation mechanisms enabled by the presence of higher hydrocarbons or that localized temperature effects are impacting the NOx
behavior. These explanations assume that the fuel/air mixing is independent of fuel composition.

Two fuel mixtures of methane with heavier alkane gases like ethane and propane were assessed with the CRN methodology. The CRN is able accurately predict a similar NOx and LBO trends for different fuel compositions regardless of the reaction mechanism used for the evaluation [27]. The variable presence of heavier hydrocarbons represents the expected differences in natural gas content within the United States [25]. In 2008 Hack & McDonell tested the effect of heavier hydrocarbons in NG on the performance of a MTC [13]; their results confirm that higher concentrations of ethane and propane in NG lead to higher NOx levels when compared to pure NG.

To achieve low NOx emissions, combustion temperatures are purposefully maintained at relatively low values (e.g., below 1900 K) to avoid the formation of NOx through the most commonly discussed mechanism, known as thermal NOx. When the reactions are highly diluted and the flame temperatures remain under 1850 K, it is not expected that the thermal NOx pathway is responsible for most of the measured NOx in the exhaust. The conditions that lead to high thermal NOx are avoided by using very low equivalence ratios, which leads to a lean reaction at a controlled temperature below that where thermal NOx starts to form quickly. At low temperature, the contribution of NOx formed via the prompt and the NNH mechanisms is fairly small, although the Prompt route is enhanced with the addition of heavier alkanes, as these species react and dissociate into CH, CN, HCN, CH2, C2H radicals that form NOx. Prompt NOx formation is proportional to the number of carbon atoms present per unit volume and is independent of the parent hydrocarbon identity. All those species resulting from fuel fragmentation have been suggested as the source of prompt NOx in hydrocarbon flames, but the major contribution is from CH+N2→HCN+N. The quantity of HCN formed increases with the concentration of hydrocarbon radicals, which in turn increases with equivalence ratio. Prompt NOx continues to play an important role at reaction temperatures below 1800 K; even so, in lean premixed systems, it has been indicated that prompt NOx is not a major source of NOx until the equivalence ratio exceeds approximately 0.65.

Still most of the NOx emitted from lean premixed burners is formed through the nitrous oxide (N$_2$O) and Zeldovich pathway, about ~90% of the total NOx emissions. The thermal NOx dominates at high reaction temperatures, typically above 1900K. On the other hand N$_2$O pathway becomes responsible for a substantial portion of the NOx when the system is compressed above the atmospheric pressure; the N$_2$O mechanism is pressure dependent [28]; the N$_2$O pathway plays a significant role in the overall levels of NOx emitted from lean premixed reactions with equivalence ratios less the 0.80. The N$_2$O Intermediate mechanism is explicated by the following reactions.

\[
\begin{align*}
O + N_2 + M &\leftrightarrow N_2O + M \quad \text{Eq. (3).} \\
N_2O + H &\leftrightarrow NO + NH \quad \text{Eq. (4).} \\
O + N_2O &\leftrightarrow NO + NO \quad \text{Eq. (5).}
\end{align*}
\]
The pressure influence on NO formed from this mechanism is evidenced in Eq. (3), with “M” representing a chemically unchanged third body species. Per Le’ Chatelier’s principle, increasing pressure drives to the right, thus enabling NO formation through the subsequent reactions. The addition of heavier hydrocarbons increases the production of O, H, and N₂O species; especially the O atom is the most significant since it is the precursor of the N₂O intermediate formed through the triple collision of N₂+O+M.

2.2 Lean Blowoff Stability Trends

Lean blow off (LBO) is one of the most important parameters for low NOx fuel premixed combustor design. It is also difficult to predict as it is inherently transient. LBO occurs when heat generated by the reactions is not enough to ignite the incoming mixture of fresh reactants. In low-NOx combustor design, this limit is bound by the onset of combustion instability in the form of LBO. As the flame temperature is decreased to reduce NOx, the chemical reactions slow to the point where temperature becomes the rate limiting factor and the onset of LBO is triggered. For the equivalence ratios close to the LBO limit the NOx emissions are at a minimum. This is consistent with the design goal of lean systems to operate as close to the stability limit as possible to minimize NOx.

Figure 10 summarizes the LBO stability trends as a function of the mole fraction of the alternative gaseous fuel in the binary mix with NG.
It can be inferred from the trends that the addition of hydrogen to NG widens the stable operating region by enhancing the resistance of the reactions to be blown off from the attachment point. Several studies have focused on H₂/CH₄ flames and shown that small additions of H₂ substantially enhance the mixture’s resistance to extinction or blowoff. For example, fundamental studies show that the extinction strain rate of methane flames is doubled with the addition of 10% H₂ [29]. For instance, the SSCB running on pure natural gas has a LBO at an equivalence ratio equal to 0.45, while for a hydrogen enriched natural gas up to 90% H₂-10% CH₄ this limit is 0.30. In general, the lean stability range of the synthetic gases is wider compared to natural gas. This is also related to the higher laminar burning velocities (shorter chemical times) of syngas compared to NG. In the case of surface stabilized combustion technology (IRB and SSCB) the addition of hydrogen to the fuel extends LBO limits and the range of radiant operation mode, which main characteristic is the attachment of the reactions to the surface. At this operation mode the heat transfer from the reactions to the thermal load is significantly enhanced, thanks to the excellent radiation properties of the surface material. This effect simultaneously increases the efficiency and reduces the NOx emissions. In addition, the stability limits of CO and H₂ are wider compared to those of CH₄. Thus the addition of these two fuels to natural gas widens the stability limits of the mixture. The wider stability limits can be explained by the properties of the species that compose the syngas, i.e. H₂ and CO. Both H₂ and CO produce higher adiabatic flame temperatures at stoichiometric conditions in air than CH₄, i.e., 2383 K and 2385 K, as compared to 2239 K. Additionally, H₂ and CO also have lower flammability limits $\phi_{CO} = 0.34$, respectively than CH₄ ($\phi_{CH₄} = 0.45$), and higher maximum adiabatic laminar flame speeds ~320 cm/s and 55 cm/s versus 40 cm/s for methane.

In contrast, the addition of CO₂ to the fuel cools down the flame temperature and increases the velocity of the flow at the surface straining the reactions and forcing them to blowoff at higher equivalence ratios. The general stability trends for the addition of CO₂ to the fuel are presented in Figure 9 b). Diluents like water (H₂O) and CO₂ and N₂ in the fuel impact the flame stability in at least three ways, through changes in (1) mixture specific heat and adiabatic flame temperature, (2) chemical kinetic rates, and (3) radiative heat transfer. The addition of N₂ apparently has straightforward effects, as it is only manifested through the first item above, an influence that can be easily quantified with standard equilibrium calculations. It is remarkable that the addition of CO₂ to NG up to 20% doesn’t affect significantly the stability of the system. Notice in Figure 9 b) that up to 20% CO₂ the stability trends are almost horizontal then around 40% CO₂, the trends rapidly shift upwards contracting the LBO limits and moving them close to the stoichiometric point. As noted by the second point, CO₂ and H₂O do not act as passive diluents in the fuel but interact kinetically reducing the flame speed of the mixtures [29]. Diluting natural gas with diluents like H₂O, CO₂ or N₂ reduces the stability limits.

The addition of heavier hydrocarbons to natural gas slightly increases the stability limits. Again with lower flammability limits and similar but slightly higher flame temperatures and flame speeds, the addition of C₂H₆ and C₃H₈ modestly improves the stability of the mixture when compared to natural gas.
2.3 Oxygas Trends

Of particular interest are the NOx trends for the oxygas technology as a function of the excess of oxidant (equivalence ratio) and fuel composition. Figure 11 (a-f) presents the NOx trends for HENG; biogases, and methane/propane-methane/ethane when burned with an oxidant is 99% O2-1% N2. The NOx trends are presented on a concentration basis in the form ppmvdv corrected to 0% O2 Figure 10 (a-c) and in the form of emission index (EI), which measures the emissions on a mass basis Figure 10(d-f). The EI is usually presented as mass of pollutant emitted per mass of fuel burned ($\frac{m_{NOx}}{m_{fuel burned}}$); as mass of pollutant emitted per energy contained in the fuel ($\frac{m_{NOx}}{kWh_{fuel burned}}$), or including the efficiency of the system by dividing the mass of pollutant by the useful electricity generated ($\frac{m_{NOx}}{kWh_{electricity generated}}$). At first sight, the NOx trends seem counterintuitive, since the NOx concentration rises when increasing the excess of air. The opposite trend is observed in lean premixed systems with air where the further dilution of the reactions with additional air reduces the temperature, hence reducing NOx emissions; however in oxygas systems the temperature in the chamber is very high (CFD simulations show localized peaks of temperature around 2700K for oxygas combustion of NG) and the residual N2 in the oxidant stream or that leaks into the combustion chamber acts as the limiting reactant, since at this temperature conditions most N2 available will break apart forming other N-species (NH, N2O, NNH, NOx…). Equilibrium calculations for stoichiometric mixtures of methane with an assumed oxidant 99% O2 -1% N2 show equilibrium temperatures above 3,000K.

Diffusion flames inherently present local zones where the combustion process happens at overly fuel-lean or overly fuel-rich conditions, both situations are responsible for the emission of products of incomplete combustion [18], [30].

It can be observed in all Figures, that, for all fuel mixtures the NOx trends collapse around the stoichiometric point ($\phi = 1$), which confirms again that the residual nitrogen available in the chamber is the limiting agent controlling the formation of NOx. It is clear that in oxygas systems, increasing the flow rate of oxidizer up to 200% ($\phi = 0.5$) does not lower the temperature of the reactions enough to counteract for the additional availability of nitrogen, which is turned in the combustion chamber into reactive nitrogen in the form of NOx.

For a fixed equivalence ratio, the addition of CO2 to the fuel mixture reduces the concentration of NOx produced; the thermal or Zeldovich route becomes the main pathway to NOx creation at temperatures above 1800 K [18]. This temperature is exceeded for all fuel compositions and is
These trends are a function of the equivalence ratio and the fuel composition – a) HENG, b) biogases, c) Ethane and Propane addition

For a fixed equivalence ratio, the addition of CO$_2$ to the fuel mixture reduces the concentration of NOx produced; the thermal or Zeldovich route becomes the main pathway to NOx creation at temperatures above 1800 K [18]. This temperature is exceeded for all fuel compositions and is the consequence of removing the N2 molecules that represent a thermal burden for the exothermic reactions. Subsequently the addition of CO$_2$ to NG yields significant drop of the NOx produced at a fixed fire rate. Moreover, CO$_2$ participates actively in the reactions and helps to deplete the formation of OH radicals, which are essential intermediate species in the reactions leading to NOx emissions.

Furthermore it was observed that, at stoichiometric conditions, the dilution of CH$_4$ with CO$_2$ yields to a decrease on the production of CO. The flame temperature reduction that results from mixing the fuel with CO$_2$ yields a reduction of CO, at $\phi \sim 1$ the high reaction temperatures
guarantee the conditions to dissociate CO2 into CO and O-atoms; this pathway is strongly and directly dependent on the temperature [31], thus working in slightly lean conditions helps to complete the combustion reactions.

Also, it was observed that addition of CO2 leads to a better premixing of the reactants in the pre-combustor, which diminishes localized zones with overly fuel rich conditions and promotes the oxidation of CO into CO2 [18]. The variation of the flame type from non-premixed to partially premix was observed in the CFD simulations. For improved levels of premixing, the OH and temperature contours appear more uniform, likewise the temperature and concentration gradients between neighboring cells are less significant when compared to non-premixed reactions. Better levels of uniformity are achieved with further fuel dilution with CO2. More uniform contours of the OH concentration and temperatures that are achieved with premixed flames yield to a NOx reduction.

The differences between emission trends for various fuel mixtures become less sharp when using emission index (mgNOx/kWh) to quantify the emissions. Only when adding significant amounts of CO2 to the fuel, the NOx concentration decreases drastically due to the diluting effect of CO2. The use of biogas in oxygen enriched reactions introduces another diluent gas (CO2) with the fuel, which acts as a direct substitute of the N2 fraction in air. For biogas reactions, the additional CO2 is proportional to the fire rate, therefore in order to maintain a fixed thermal power with all the fuels, the flow rate of biogas is always greater that of NG for the same fire rate.

The addition of hydrogen yields an increase of NOx concentration, mainly due to the higher temperatures that are reached with mixtures with high content of hydrogen. The most important route to form NOx in oxy-fuel combustion is the thermal or Zeldovich route. Furthermore the Fenimore or prompt route is also activated and shows a negative net production rate of NOx [30], [32]. The addition of H2 also enhances the formation of intermediate species like OH and H, which promotes NOx formation through the Zeldovich, NNH and N2O pathways. The thermal route is enhanced by the addition of H2 since the mechanism is comprised of the three following reactions: $\text{N}_2 + \text{O} = \text{N} + \text{NO}$; $\text{N} + \text{O}_2 = \text{NO} + \text{O}$; and $\text{N} + \text{OH} = \text{NO} + \text{H}$. The NNH reactions enhanced include $\text{NH} + \text{N} = \text{N}_2 + \text{H}$; $\text{NH} + \text{NO} = \text{N}_2 + \text{OH}$; $\text{NNH} + \text{M} = \text{N}_2 + \text{H} + \text{M}$; $\text{NNH} + \text{O}_2 = \text{HO}_2 + \text{N}_2$; $\text{NNH} + \text{O} = \text{OH} + \text{N}_2$; $\text{NNH} + \text{H} = \text{H}_2 + \text{N}_2$; $\text{NNH} + \text{OH} = \text{H}_2\text{O} + \text{N}_2$; and $\text{NNH} + \text{CH}_3 = \text{CH}_4 + \text{N}_2$. The reactions that explain the effect of hydrogen addition on the N2O intermediate mechanism are the following: $\text{O} + \text{N}_2 + \text{M} = \text{N}_2\text{O} + \text{M}$; $\text{N}_2\text{O} + \text{H} = \text{NO} + \text{NH}$; $\text{O} + \text{N}_2\text{O} = \text{NO} + \text{NO}$. Besides at a fixed equivalence ratio the addition of hydrogen affects the flame length and width, the flame becomes shorter and narrower with the addition of H2. Shorter flames yield less recirculation of the product gases into the reaction zone, and less radiation emitted from the reduced flame. These two conditions also explain the NOx increase. Still the high availability of O2 in the oxidant increases the concentration of O-atoms, which also participates in all NOx pathways.

The emission index (EINOx) sheds light on the NOx production on a mass basis. When comparing the EINOx for the different mixtures, the differences become less pronounced, in particular for reactions close to $\phi = 1$ all the trends collapse around the same value.
(EINOx~150mg/kWh_fuel_burned). However when increasing the excess of air the difference between the trends becomes more evident and follows the same results observed in the concentration form (ppmdv). Furthermore the use of emission index when compared to the concentration form, makes clear that once the water is dropped out of the system, the dry emissions are virtually shifted upwards indicating a higher concentration (ppm_NOx_dry basis>ppm_NOx_wet_basis). The virtual shift caused by the removing the water from the sample is only significant for hydrogen containing fuels.
CHAPTER 3: Conclusions

- The emissions trends presented in this project demonstrate that the variation of NOx with the fuel composition is far from consistent. For instance, after adding H2 to NG at a fixed fire rate and air to fuel ratio, the NOx emissions of LSB drastically increase, in sharp contrast, under the same conditions the addition of H2 to the fuel causes a significant drop of the NOx concentration when stabilizing the reactions with a SSCB.

- To predict the emissions trends when varying the fuel composition it is necessary to evaluate each particular technology. The project results indicate that the fuel composition drastically change the size of the zones in the combustor where NOx forms, in addition to changing its rate of formation within the zones.

- The CFD simulations provide visual details about the mixing patterns in the combustion chamber, the formation of recirculation zones and the heat interactions of the reactions and streams with the walls. Those details are fundamental to understand the effect of the fluid dynamics on the formation of pollutant species like CO, UHC, VOC, and NOx.

- In low-NOx combustor design, the lowest NOx levels are bound by the onset of combustion instability in the form of LBO. As the flame temperature is decreased to reduce NOx, the chemical reactions slow to the point where temperature becomes the rate limiting factor and the onset of LBO is triggered. This result can be used to predict the proximity of the reactions to the LBO limit just by analyzing the NOx concentration in the exhaust.

- It was observed that the addition of CO2 to the fuel always yields a reduction of the production of NOx. CO2 in the fuel cools down the flame temperature and participates as an active agent in the reactions. The addition of CO2 to the fuel at constant fire rate increases the velocity of the flow and reduces the burning velocity, therefore the biogas reactions can be blown off higher equivalence ratios, when compared to pure natural gas.

- For all burner configurations it was observed that the addition of hydrogen to NG widens the stable operating region by enhancing the resistance of the reactions to be blown off from the attachment point (leaner LBO limit). However, for premixed reactions the addition of hydrogen also increases the burning velocity, hence making hydrogen enriched blends more prone to flashback. In sharp contrast, the addition of CO2 to the fuel always contracts the stable region of operation.

- The addition of ethane or propane to NG slightly widens the stable region while enhancing the emissions of NOx and CO.

- The emission index sheds light on the production of pollutants on a mass basis. This form of quantifying the amount of pollutant yields a definite measure that is not affected by other conditions. The use of emission index when compared to the concentration
form, makes clear that once the water is dropped out of the system, the dry emissions are virtually shifted upwards indicating a higher concentration (ppm_{NOx\_dry basis}>ppm_{NOx\_wet\_basis}). The virtual shift caused by the removing the water from the sample is only significant for hydrogen containing fuels.
<table>
<thead>
<tr>
<th>Term</th>
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<td>Unburned hydrocarbons/Total Hydrocarbons</td>
</tr>
<tr>
<td>ULN</td>
<td>Ultra-low NOx</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compounds</td>
</tr>
<tr>
<td>WI</td>
<td>Wobbe index</td>
</tr>
</tbody>
</table>
REFERENCES


APPENDICES

The following appendices are available as separate publications:

APPENDIX A – Burner Configuration #1: Low Swirl Burner
CEC-500-2017-026-APA

APPENDIX B – Burner Configuration #2: Surface Stabilized Combustion
CEC-500-2017-026-APB

APPENDIX C – Burner Configuration #3: C65 Microturbine
CEC-500-2017-026-APC

APPENDIX D – Burner Configuration #4: Oxy-Fuel Burner
CEC-500-2017-026-APD

APPENDIX E – Burner Configuration #5: High Velocity Burner
CEC-500-2017-026-APE

APPENDIX F – Burner Configuration #6: Gas Turbine Combustor
CEC-500-2017-026-APF

APPENDIX G – Burner Configuration #7: Radiant Tube
CEC-500-2017-026-APG

APPENDIX H – Burner Configuration #8: Infrared Burner
CEC-500-2017-026-APH

APPENDIX I – Burner Configuration #9: Slot Burner
CEC-500-2017-026-API