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Research and Development of Natural Draft Ultra-Low Emissions Burners for Gas Appliances

Peter Therkelsen, Robert Cheng, Darren Sholes

Energy Technologies Area

September, 2016

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PREFACE

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Research and development of natural draft ultra-low emissions burners for gas appliances is the final report for the research and development of natural draft ultra-low emissions burners for gas appliances project contract number PIR-14-002 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

Combustion systems used in residential and commercial cooking appliances must be robust and easy to use while meeting air quality standards. Current air quality standards for cooking appliances are far greater than other stationary combustion equipment. By developing an advanced low emission combustion system for cooking appliances, the air quality impacts from these devices can be reduced.

This project adapted the Lawrence Berkeley National Laboratory (LBNL) Ring-Stabilizer Burner combustion technology for residential and commercial natural gas fired cooking appliances (such as ovens, ranges, and cooktops). LBNL originally developed the Ring-Stabilizer Burner for a NASA funded microgravity experiment. This natural draft combustion technology reduces NOx emissions significantly below current SCAQMD emissions standards without post combustion treatment. Additionally, the Ring-Stabilizer Burner technology does not require the assistance of a blower to achieve an ultra-low emission lean premix flame. The research team evaluated the Ring-Stabilizer Burner and fabricated the most promising designs based on their emissions and turndown.

Keywords: NO_x, Natural Gas, Burner, Appliance

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EXECUTIVE SUMMARY

Introduction

In 2012, residences and commercial businesses consumed over 50% of end-use natural gas consumption in California. This large group of consumer products still utilizes some of the oldest combustion technologies that emit a significantly larger amount of NO_x than their larger commercial and industrial counterparts. Therefore, an advanced, simple and low-cost combustion technology for these appliances will have a large impact on emissions reduction and performance improvement.

Project Purpose

Our research aims to adapt a simple, cost-effective, and passive low NO_x control technology developed by LBNL for NASA's microgravity combustion program, a Ring-Stabilizer Burner, to residential cooking applications. The goal is to perform laboratory research to develop a new type of simple ultra-low NO_x natural draft gas burners (no need for electric fans) that can be readily scaled and adapted to reduce NO_x emissions from commercial and residential cooking devices such as cooktops and ovens. This low emission burner technology can also be adapted to hot water heaters (storage, tankless, heat pump, and pool heaters); furnaces, space heaters, and small boilers.

Project Results

The lowest measured operational NO_x levels are below 20 ppm at 3% O_2, meeting one of the goals of this project. CO emissions are acceptable only at the lowest operational equivalence ratios. The fuel venturi used for these experiments enabled lean operation up to 5 kBtu/hr, with a turndown ratio of 2:1.

Project Benefits

This technology demonstrates the potential to achieve major NO_x emissions reductions while maintaining compliance with emission limitations adopted by the South Coast Air Quality Management District (SCAQMD) for other air pollutants (e.g., carbon monoxide). Experiments have shown the multi-port Ring-Stabilizer Burner reduces NO_x emissions to levels significantly below current AQMD standards, moving cooking appliances towards meeting the long-term goal of an 80% reduction in emissions. Additionally, the new burner will maintain energy efficiency for most applications and increase energy efficiency for combustion devices that fire into the open air (e.g. gas burners for cooking and baking.

1.0 Introduction

In 2012, residences and commercial businesses consumed over 50% of end-use natural gas consumption in California (California Energy Commission, n.d.). This natural gas is used to heat homes and offices, wash and dry clothes, and cook and prepare food. However, this large group of consumer products still utilizes some of the oldest combustion technologies that emit a significantly larger concentration of NO_x than their larger commercial and industrial counterparts. Therefore, an advanced, simple and low-cost combustion technology for these appliances is needed in order to have a large impact on emissions reduction and performance improvement.

Testing conducted at LBNL for NASA’s microgravity combustion program proved that the ring-stabilizer technology is viable for low-emissions operation. The first demonstration of adapting the technology to a residential gas appliance was conducted at the University of Alberta by Professor Larry Kostiuk. The ring-stabilizer (1 inch port diameter) was integrated with a set of single port burners for a residential fan-assisted induced-draft furnace. The Ring-Stabilizer Burners reduced the furnace emissions to below 15 ppm NO_x @ 3% O2 without affecting efficiency (Johnson, 1995). Further parametric studies report NO_x emissions as low as 2.1 ppm @ 3% O_2, values that are significantly lower than today’s air quality regulations (Johnson, 1998).

The following chapters describe the experimental methodology for adapting the ring-stabilizer technology for operation without a fan so that it is a natural-draft system. This design will enable its integration into residential and commercial cooking appliances without the added cost of electrical components. This report also details efforts to characterize emissions. The low-emission burner technology can also be adapted to hot water heaters (storage, tankless, heat pump, and pool heaters); furnaces, space heaters, and small boilers.

2.0 Forced Draft Prototype: Multi-Port Ring-Stabilizer Burner

2.1 Introduction

Initial experiments using forced draft air were conducted in order to determine the optimal size and ring-stabilizer configuration for gas fueled cooking appliances. Electronic flow controllers supply both fuel and air to the burner in a forced draft configuration. Natural-draft burners are not used for initial experiments as there is no practical way to measure the air-flow through the burner that would be entrained by the relatively low fuel supply pressure (8″ water column or 0.3 psi). The ability to measure air flow is necessary to obtain the deliverable of accurate measurement of the fuel/air ratio so that the data can be compared directly with previous studies (Johnson, 1998).

This report outlines the design process for scaling the ring-stabilizer port, as well as the experimental methodology for characterizing the following performance and design variables:

- Lean blowoff
- Flashback
- Emissions
- Turndown
- Crossover ignition, and
- Design selection.

2.2 Survey of Existing Technology

A vendor survey was conducted in order to establish the typical thermal outputs range for residential and commercial cookstoves. The results of this survey guided sizing of the first iteration of Ring-Stabilizer Burners.

Typical thermal output ranges from 5,000 to 17,000 Btu/hr per burner for residential stovetops (Figure 1) and 28,000 to 33,000 Btu/hr per burner for commercial stovetops (Figure 2). Typical flame port diameter for conventional burners is around 0.1 inch (2.54 mm). The previous version of the Ring-Stabilizer Burner had a port diameter of 1 inch and a power output of 40,000 Btu/hr (Johnson, 1995).

For the range of typical thermal outputs, it was necessary to decrease the ring-stabilizer port diameter for this study. However, due to manufacturing limitations and the volume of reactants flowing through the ring-stabilizer to maintain lean operation, the port diameters for the ring-stabilizers must be larger than the conventional flame port of 0.1 inch. The larger port diameter may necessitate a redesign of the traditional burner head in a commercialized product. The size of the ports is based on power requirements, manufacturing limitations, and the prevention of flashback and lean blowoff.

Figure 1: Traditional Residential Gas Range Burner Head

Photo credit: http://www.cheapapplianceparts.com/upload/item/gas-burner-head-w-spark-electrode-black.jpg

Figure 2: Traditional Commercial Gas Range Burner Head

Photo credit: http://www.tmrep.com/images/030686.jpg

2.3 Ring-Stabilizer Geometry

2.3.1 Definition of Terms and Dimensions

The Ring-Stabilizer Burner consists of a port with an internal ring, separated from the burner rim using small tabs. Figure 3 shows the schematic of the ring-stabilizer for a single port burner, with parameter definitions that follow the equation:

$$D_P = D_r + \delta_r + \delta_g$$

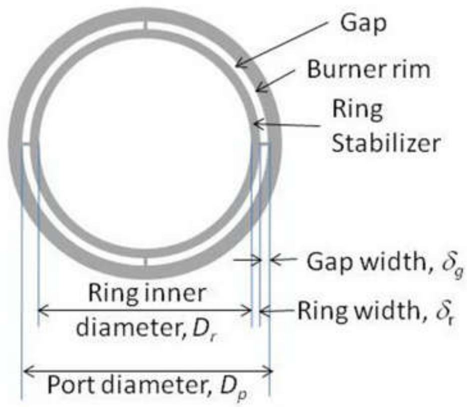


Figure 3: Definitions of Ring-Stabilizer Parameters

The burners were configured in various patterns on plates machined from 0.060" thick low carbon steel.

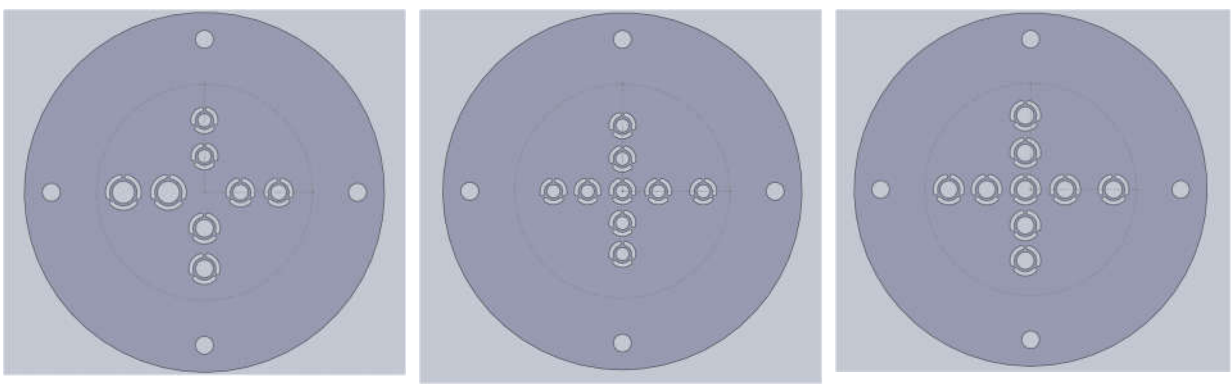


Figure 4: Forced Draft Ring-Stabilizer Plates

The different configurations enable the testing of port-to-port interactions and the effect of varying port diameter (Figure 4). Additional information regarding final geometry is provided in Section 4.2 Design Methodology.

2.3.2 Scaling the Ring-Stabilizer Port

Plates with different ring-stabilizer configurations were designed to be fabricated with a water-jet cutting tool. Water-jet cutting is ideal for cost-effectively producing multiple two-dimensional parts out of metal as water-jets are accessible, affordable and provide quick turnaround for multiple variations of a part. However, due to limitations of the water-jet the minimum gap width (δ_g) is 0.060 inches. The ring width (δ_r) is 0.035 inches and the port diameter (D_P) is varied.

A primary design consideration is the minimization of flashback potential. Flashback may occur when the reactant bulk flow burner exit velocity (U) is reduced below the laminar flame speed for a given fuel/air mixture. In order to prevent flashback, the maximum port diameter and number of ports per plate for a given power (based upon fuel flow rate) and equivalence ratio (Φ) was determined. Equivalence ratio is a nondimensional quantity, calculated by normalizing the actual fuel-oxidizer ratio of the mixture by the stoichiometric fuel-oxidizer ratio (i.e. an equivalence ratio of 1 means the mixture is stoichiometric). The effective area of the ports, combined with the power and equivalence ratio, dictates the flow velocity through each port.

Ports were sized as to not incur flashback, be representative of thermal outputs based upon the residential and commercial thermal output survey, and cover the range of equivalence ratios used in Johnson & Kostiuk[1] to obtain low NO_x emissions. The maximum diameter of each port and the number of ports per plate was determined to prevent flashback. In order to keep a reasonable ratio of gap width to inner ring diameter, and due to the minimum gap width of 0.060 inches, a minimum port diameter of 0.375 inches was also established.

We elected to use a linear port configuration instead of a seven port hexagonal cluster in order to study crossover ignition and port-to-port interactions. The edge distance between ports was incrementally increased along the plate, and the effects were recorded in the proceeding experiments.

Parts were machined from designs made with a 3-D Computer Aided Design (CAD) program. The CAD file was created using equation driven dimensions to enable rapid scaling and quick turnaround for the different plate configurations. Future iterations of the plate will be created faster as a result.

2.4 Experimental Methodology

2.4.1 Test Stand

A test stand was developed for the forced draft prototype experiments. The test stand consists of:

1. Plumbing for methane mass flow controller (experimental substitute for natural gas) and forced draft air mass flow controller,

2. Custom computer control program allowing for finite control of both fuel and air while logging of data (flow rates and emissions),

3. Burner apparatus with burner plate mounting including: support frame, burner expansion section (throat), turbulence plate, flame arrestor (prevent damage in event of flashback), packed bed of marbles to smooth flow,

4. Fuel and Air pre-mixing manifold, and

5. Horiba PG-250 5 channel emissions analyzer with quartz enclosure and gas emissions cooling system.

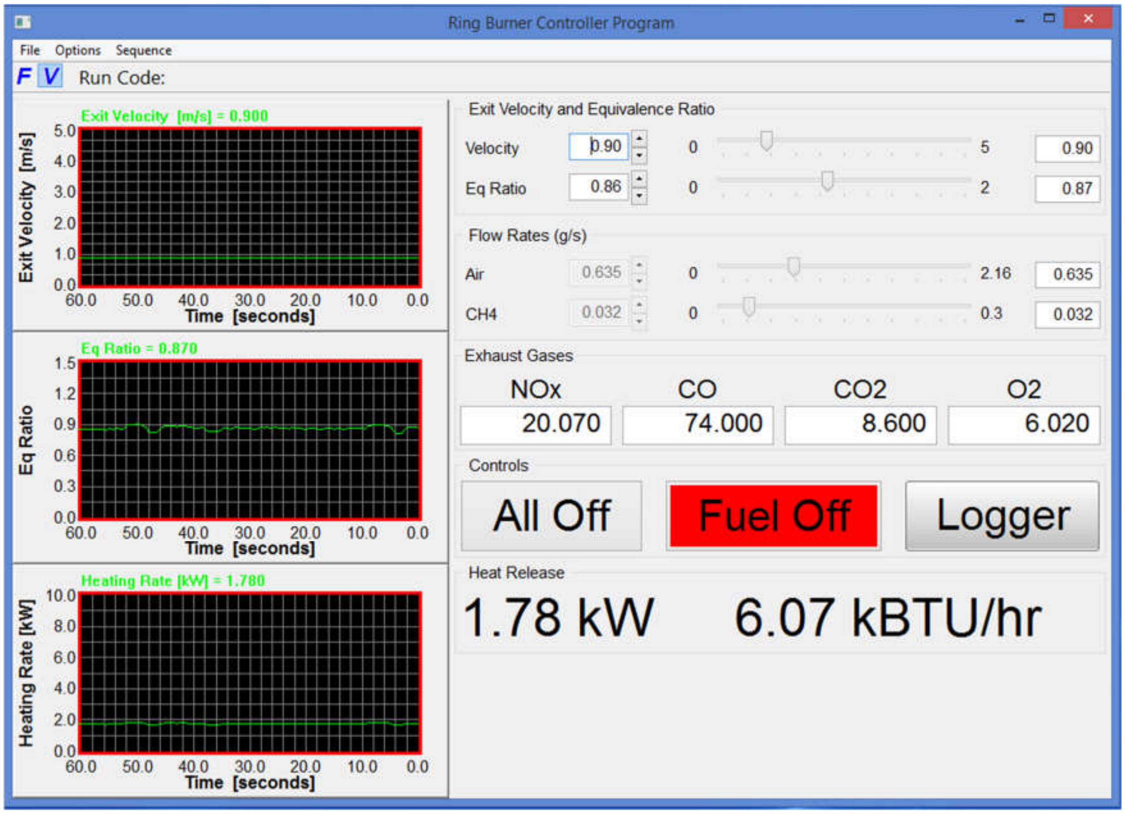


Figure 5: Ring-Stabilizer Burner Controller Program Interface

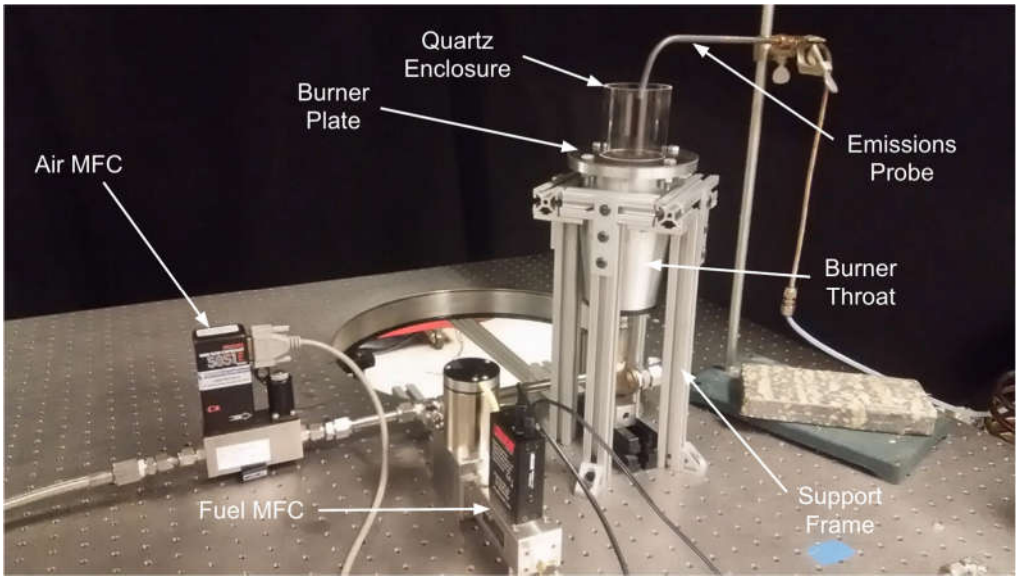


Figure 6: Forced Draft Ring-Stabilizer Experimental Setup

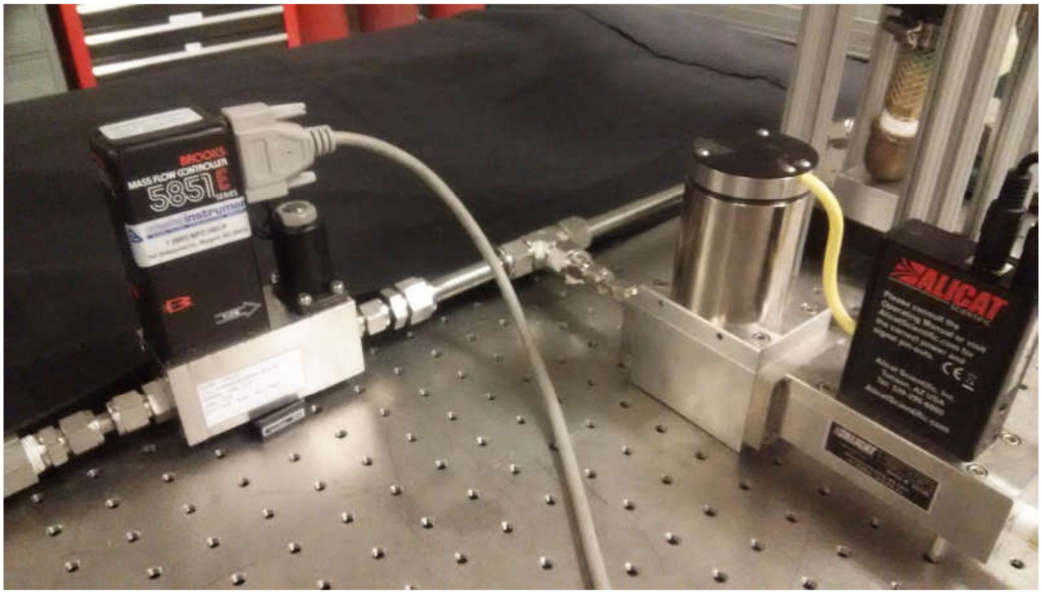


Figure 7: Forced Draft Ring-Stabilizer Air Pre-Mixing Manifold

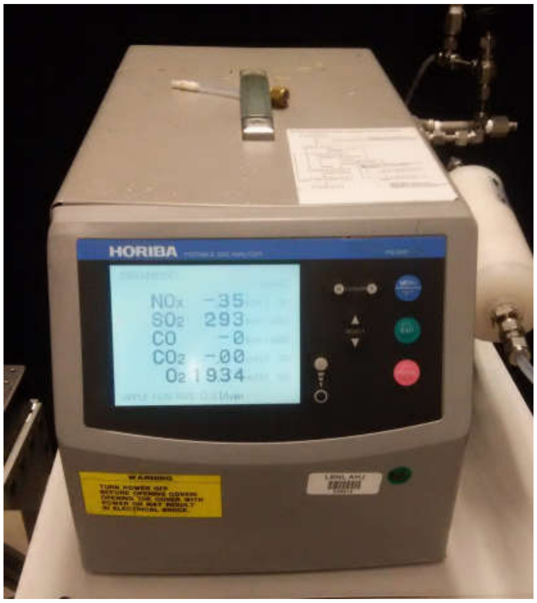


Figure 8: Horiba PG-250 for measuring gas emissions

Mass flow controllers were calibrated and certified prior to use. A new Methane mass flow controller was purchased to enable testing at the relatively low flow rates involved in this study. A custom computer control and data collection program was developed to change the flow of reactants based on desired power and equivalence ratio. The computer program and mass flow controllers also double as a data collection system, allowing the user to track fuel flow, air flow, power output, equivalence ratio and emissions.

2.4.2 Test Protocol

2.4.2.1 Lean Blowoff and Flashback

Lean blowoff describes the physical lifting of a flame above its burner so that the flame is no longer attached to the burner resulting in the flame extinguishing. Lean blowoff occurs at high flow velocity or lean fuel conditions. To test for lean blow off, the burner thermal power output is initially set, based on the range of typical power outputs for conventional gas cookstoves, determined from the vendor survey. The equivalence ratio (and hence power output, much like commercial cooking appliances) is reduced incrementally until the flame no longer attaches to the port. The limiting equivalence ratio and power are recorded. The flow velocity is calculated, based on the power, equivalence ratio and Ring-Stabilizer Burner geometry. This process is repeated for various thermal power outputs in order to generate a curve for a plot of bulk exit velocity vs equivalence ratio. A curve is then generated for each burner plate design. Qualitative notes and pictures are also taken to describe the transition from stable flame to blowoff.

Flashback describes the physical condition in which the flame propogates upstream of its burner, causing undesired combustion that may result in damage or destruction of the burner or other hardware. Flashback occurs at low flow velocity and rich fuel conditions. To test for flashback, an equivalence ratio is set at a known stable level. The power, and therefore flow velocity, is incrementally decreased until the flame flashes back into the burner throat. The limiting equivalence ratio and power are recorded. The flow velocity is calculated, based on the power, equivalence ratio and Ring-Stabilizer Burner geometry. This process is repeated for various thermal power outputs in order to generate a curve for a plot of flow velocity vs equivalence ratio. A curve is then generated for each burner plate design.

2.4.2.2 Emissions

Emissions data are collected using a 5-channel Horiba PG-250 emissions analyzer. A quartz enclosure is placed over the burner port in order to prevent room air mixing and diluting the combustion exhaust stream. The procedure is very similar to that used to test for lean blowoff and flashback. The burner thermal output power is set and equivalence ratio is increased incrementally from the lean blowoff limit. NO_x and CO emissions are recorded at each equivalence ratio set point in order to generate a curve for the selected power. This process is repeated for a range of the typical thermal output powers from the vendor survey. The equivalence ratios are selected based on the fuel lean operating conditions. The results are presented in a plot.

2.4.2.3 Turndown

Turndown can be defined in a variety of ways. One common definition of turndown is the ratio of maximum to minimum energy output a burner can produce, irrespective of other factors such as equivalence ratio. Another definition of turndown ratio takes into account equivalence ratio and is the range of power output for the burner at a given equivalence ratio. This latter definition is used as maintaining a constant equivalence ratio is critical to ensuring low NO_x emissions. For the Ring-Stabilizer Burner, the power output is proportional to the reactant bulk flow burner exit velocity at a fixed equivalence ratio. For a fixed equivalence ratio, the exit velocity, and therefore power, is incrementally increased until lean blowoff occurs. The velocity is then decreased until flashback occurs. The maximum and minimum velocity defines the turndown ratio. This procedure is repeated for various equivalence ratios.

2.4.2.4 Crossover Ignition

The ring-stabilizer ports are configured in a two linear patterns that cross in the middle of the plate. The edge distance between ports is varied from 0.06 inches to 0.25 inches for both plates. To test, an equivalence ratio and power are set, ideally based on settings resulting in ideal parameters from the results of the emissions tests. One port along the edge of the plate is ignited with a hand held torch. The port nearest the torch is ignited and lights off neighboring ports so long as the edge distance between ports is sufficiently small. When the flame no longer propagates to the neighboring ports, the maximum edge distance allowable for ignition is recorded. The procedure is repeated for various equivalence ratios, burner power output, and two different port diameters. The rightmost picture in Figure 9 below shows the final port did not light due to large port gap distance

Figure 9: Crossover Ignition Study.

2.5 Results and Discussion

2.5.1 Lean Blowoff

Lean blowoff testing results of the Ring-Stabilizer Burner are compared to historic data in Figure 10. These data show that scaled down versions of the Ring-Stabilizer Burner have a consistent lean blowoff relationship that is independent of port diameter or number. As the bulk exit velocity (U) from the burner decreases, the equivalence ratio (Φ) at which lean blowoff occurs also decreases. This result is benefitial for the potential to adapt the Ring-Stabilizer Burner from forced to natural draft operation, as bulk exit velocities of natural draft systems are similar to the lower end of the tested forced draft system.

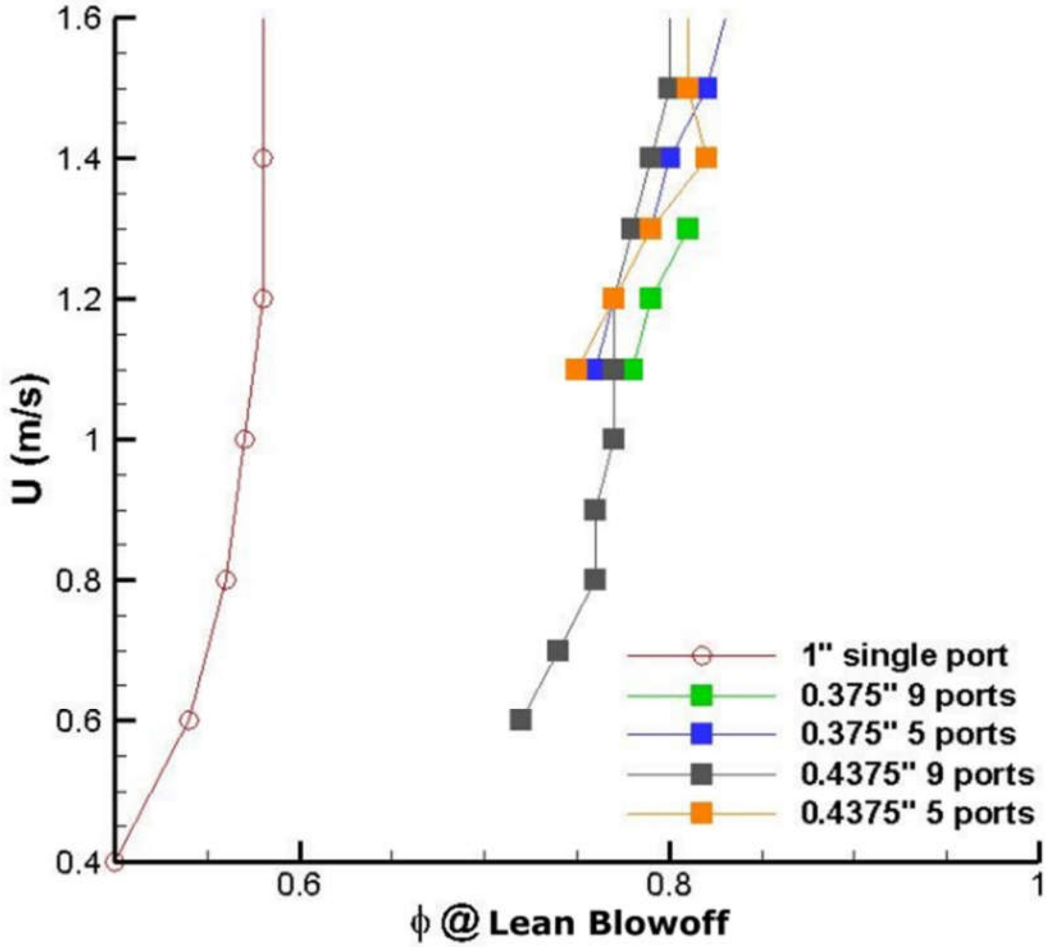


Figure 10: Effect of port diameter (D_P) on lean blowoff

Additionally, a large difference between the lean blowoff limits for the tested scaled down multi-port based ring-stabilizers and the 1-inch single port is seen. This indicates a large potential for further decreases in stable operation with reduced equivalence ratio. Operating with a reduced equivalence ratio will dramatically reduce NO_x emissions as equivalence ratio and NO_x are directly linked through thermal output.

2.5.2 Flashback

Flashback propensity increases as either bulk exit velocity decreases or equivalence ratio increases, as seen in Table 1. The results are very promising for natural draft operation. When in natural draft mode, the lower ranges of bulk exit velocities (0.3 to 0.5 m/s) are potentially possible but we will be operating with significantly lower equivalence ratios than result in flashback. This indicates that while flashback potential should be considered in natural draft operation it is not anticipated to be a limiting factor.

Table 1. Effect of port diameter (D_P) on flashback

0.375” 9 Ports

Equivalence Ratio (Φ)	U (m/s)
0.8	0.4
0.85	0.5
0.9	0.5

0.4375” 9 Ports

Equivalence Ratio (Φ)	U (m/s)
0.8	0.3
0.85	0.4
0.9	0.5

2.5.3 Emissions

Figure 11 shows NO_x and CO emissions, corrected so that values are representative of 3% O_2 in the exhaust stream, for two forced-draft ring-stabilized burners operating across a range of equivalence ratios.

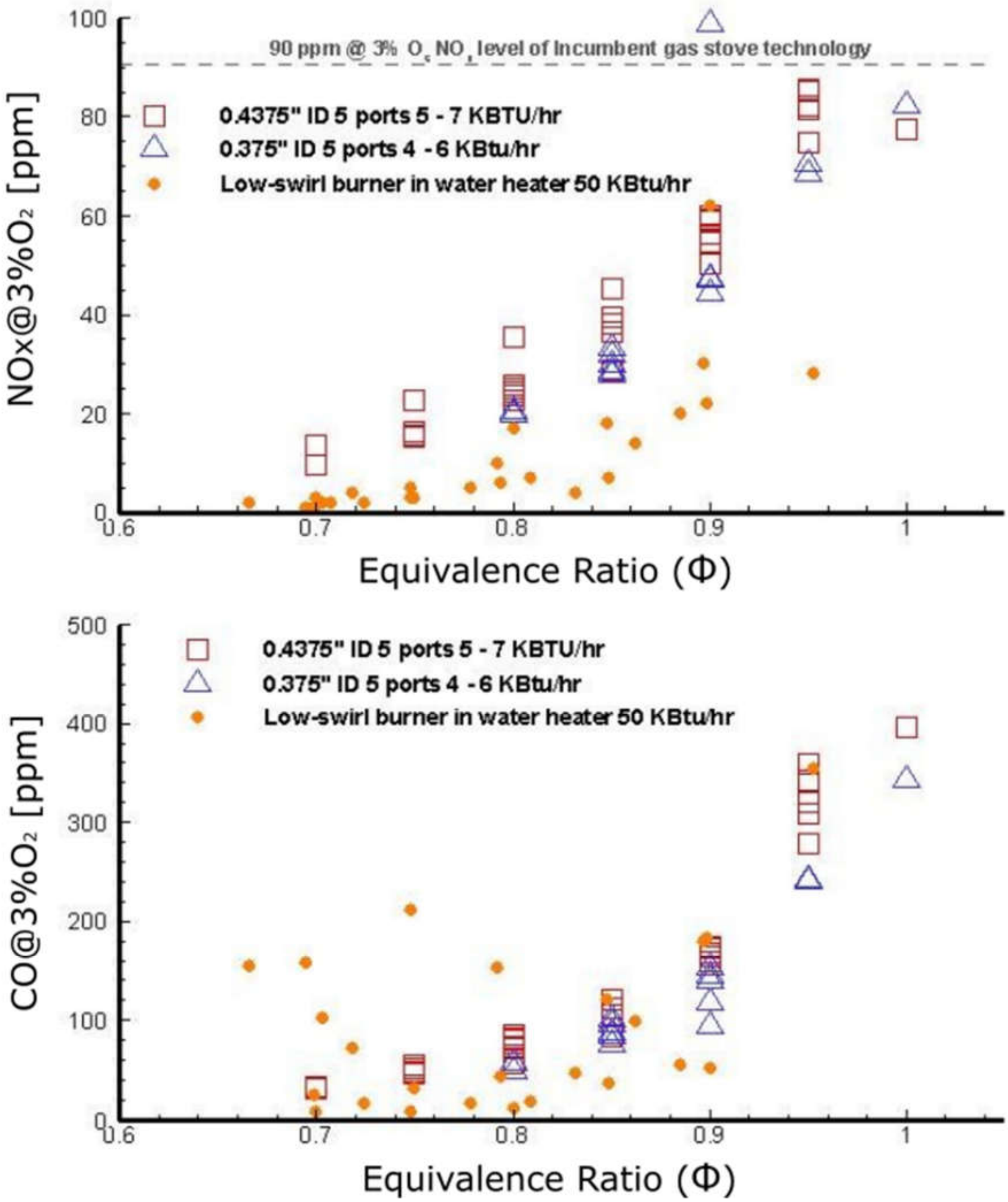


Figure 11: Effect of port diameter (D_P) on CO & NOx emissions.

Additionally, comparative results taken from a forced draft, high flow rate, ultra low emissions low swirl burners are plotted. These results show that the forced-draft reduced scale Ring-Stabilizer Burners are capable of producing lower NO_x emissions than are currently emitted by typical residential cooktops across a wide range of equivalence ratios. The lowest operational equivalence ratios are more than 80% less than the typical cooktop burner, meeting one of the goals of this project. CO emissions are acceptable, below 100ppm, only at the lowest operational equivalence ratios. As shown in the lean blowoff results, the small-scale ring-stabilized burner has the potential to operate with even lower equivalence ratios than those in Figure 11, furthering the possibility of lower CO emissions.

2.5.4 Turndown

The reduced scale burners are capable of between 3:1 and nearly 5:1 turndown. Commercial cooktops are capable of much higher turndown rates. We believe that additional engineering may expand the turndown range.

Table 2. Turndown ratio for test burner plates

0.375" 9 Ports

Equivalence Ratio (Φ)	Turndown Ratio
0.8	3:1
0.85	3.4:1
0.9	4:1

0.4375" 9 Ports

Equivalence Ratio (Φ)	Turndown Ratio
0.8	4.7:1
0.85	4.8:1
0.9	4.6:1

2.5.5 Flame Stability

The reduced scale ring-stabilized burners are capable of producing very stable flames as seen in Figure 12. These stable flames are found widely across the operational range of the burner. However, in some ultra low equivalence ratio cases, the outermost ports are unstable (Figure 12). This issue may be resolved through hexagonal placement of ports rather than linear arrangement. A hexagonal arrangement will allow for nearly ports to maintain combustion through crossover ignition.

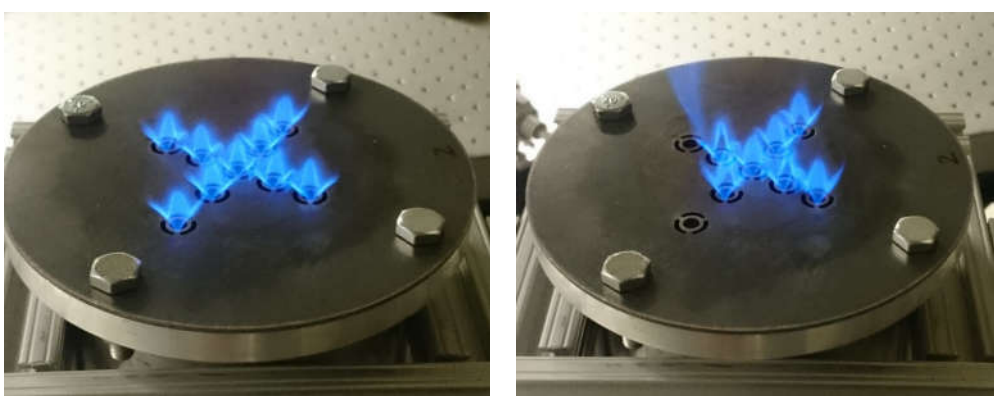


Figure 12: (L) Stable Flames, (R) Unstable Flames

2.5.6 Crossover Ignition

Crossover ignition will be required for multi-port ignition. Results in Table 3 show that ports will need to be less than 0.125 inches apart, an easy geometry to implement that showed no potential for damage to the plate.

Table 3. Maximum allowable distance between ports for light off

0.375" 9 Ports

Equivalence Ratio	Max. Edge Distance (in)
0.8	0.125
0.85	0.125
0.9	0.125

0.4375" 9 Ports

Equivalence Ratio	Max. Edge Distance (in)
0.8	0.125
0.85	0.125
0.9	0.125

2.5.7 Design Selection

The preliminary tests show we need the ability to manufacture ports with smaller gap width due to ful/air leakage from the 0.060 inches minimum gap possible with the water-jet. Reducing the size of the gap and overall port diameter will help address this issue.

3.0 Natural Draft Prototype: Multi-Port Ring-Stabilizer Burner with Venturi

3.1 Introduction

Experiments were conducted to adapt a fuel venturi assembly to the multi-port Ring-Stabilizer Burner designs so the system operates in a natural draft configuration. The venturi is used to induce fuel lean reactants without the need for forced air. This chapter outlines the design process for adapting the multi-port Ring-Stabilizer Burner to natural draft as well as the experimental methodology for characterizing the following characteristics:

- Emissions,
- Turndown,

3.2 Commercially Available Technology

A commercially available fuel venturi assembly was selected based on its thermal output and physical geometry. The venturi burner provides up to 10,000 Btu/hr with a fuel orifice diameter of 0.050”. A fuel control valve varies the thermal output. Calculations were made to determine the thermal output of a burner based on orifice diameter and supply line pressure.

A review of gas burner and venturi design literature suggests that the fuel orifice should be located upstream of the venturi throat at a distance of at least two times the throat diameter. The outlet of the venturi should be located downstream of the throat at a distance of at least 6 times the throat diameter. The selected venturi assembly meets the specified design criteria.

The venturi assembly also has adjustable air shutters, enabling us to test the effect of air gap size on air entrainment. However, as the purpose of the premixing venturi is to maximize air entrainment to the burner the air shutters were left fully open for all testing. An expansion section was added in order to mount the multi-port Ring-Stabilizer Burner plates (see Figures 13 - 15).

Figure 13: Picture of Fisher burner

(Photo credit: http://store.clarksonlab.com/images/products/detail/H5500.jpg)

3.3 Experimental Methodology

3.3.1 Test Stand

A test stand was developed for the natural draft prototype experiments. The test stand consists of:

1. Plumbing for natural gas mass flow meters and pressure gauges to measure thermal power output and pressure upstream of the burner,

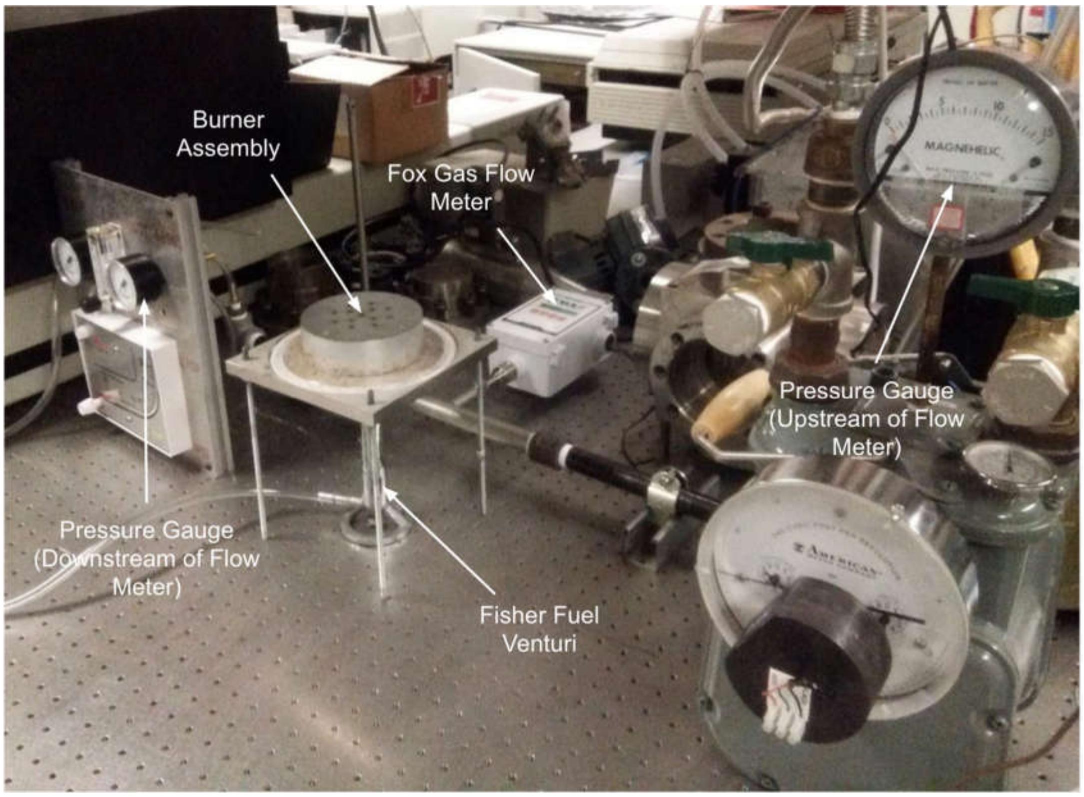


Figure 14: Natural Draft Ring-Stabilizer Experimental Setup

2. Fuel venturi assembly with multi-port Ring-Stabilizer Burner plate mounting including: burner expansion section, turbulence plate, flame arrestor (prevent damage in event of flashback),

Figure 15: Natural Draft Ring-Stabilizer Fuel Venturi Assembly

3. Horiba PG-250 5 channel emissions analyzer with quartz enclosure and gas emissions cooling system.

3.3.2 Test Protocol

3.3.2.1 Emissions

Emissions data are collected using a 5 channel Horiba PG-250 emissions analyzer. A quartz enclosure is placed over the burner port in order to prevent room air mixing and diluting the combustion exhaust stream. The procedure is similar to that used in the previous chapter and measurements taken for commercial state-of-the-art burners. The burner thermal output power is adjusted using the venturi fuel valve. Care is taken to record upstream fuel pressure while testing is conducted as this will be a factor in commercialization. NO_x and CO emissions are recorded at each set point in order to generate a curve for various power levels. This process is repeated for a range of the typical thermal output powers from the vendor survey in the previous chapter. The results are presented in a plot.

3.3.2.2 Turndown

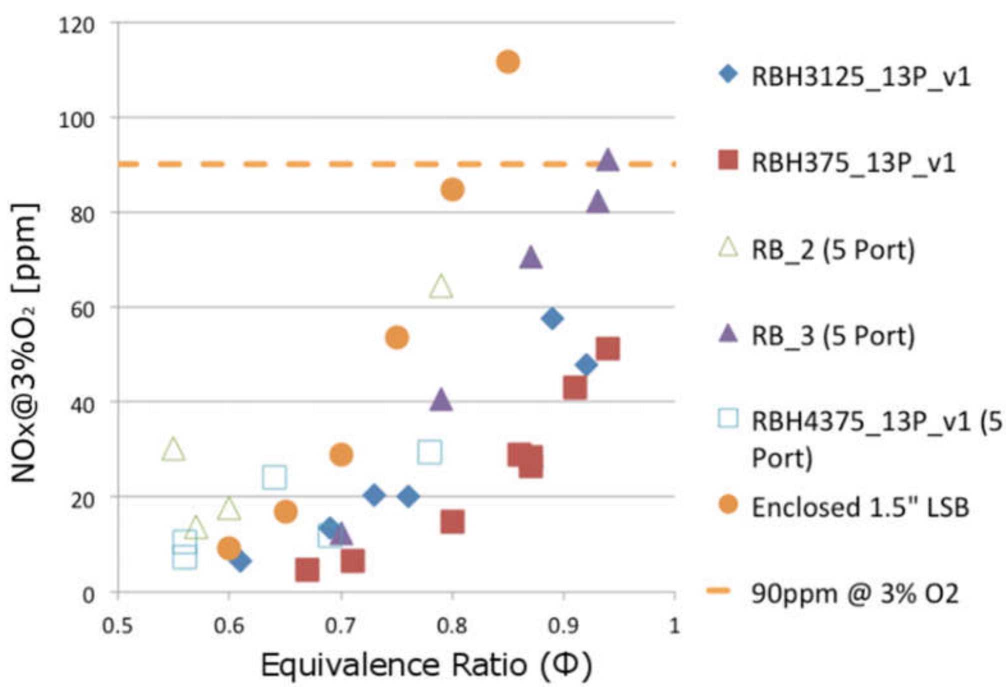
The effect of turndown on air entrainment was tested for the natural draft configuration to determine whether or not a consistent lean stoichiometry can be maintained over a range of fuel flow rates. The testing procedure is the same as with emissions data but flame stability is determined by lean blow off level. Corresponding emissions data are analyzed to determine equivalence ratio ranges for the viable flames.

3.4 Results and Discussion

3.4.1 Emissions

Figure 16 shows corrected NO_x and CO emissions for two natural-draft ring-stabilized burners operating across a range of thermal output levels. Additionally, comparative results taken from the forced draft version of the Ring-Stabilizer Burner are plotted. These results show that the natural-draft reduced scale Ring-Stabilizer Burners are capable of producing low levels of NO_x and CO emissions over a wide range of equivalence ratios similar to their natural draft counterparts. The burners with 13 ports were able to operate with lower emissions than those with 5 ports, possibly due to lower pressure drop increasing air entrainment. This suggests that as burner heads are made with larger surface areas to accommodate realistic cooking spaces emissions will further be reduced.

NO_x emissions are far below the 90ppm level of incumbent technologies. The lowest operational NO_x levels are 80% less than the typical cooktop burners, meeting one of the goals of this project. CO emissions are acceptable only at the lowest operational equivalence ratios. This result is expected as CO formation can be minimized when a stable flame is provided a low carbon content (low equivalence ratio) and is able to completely combustion the fuel.



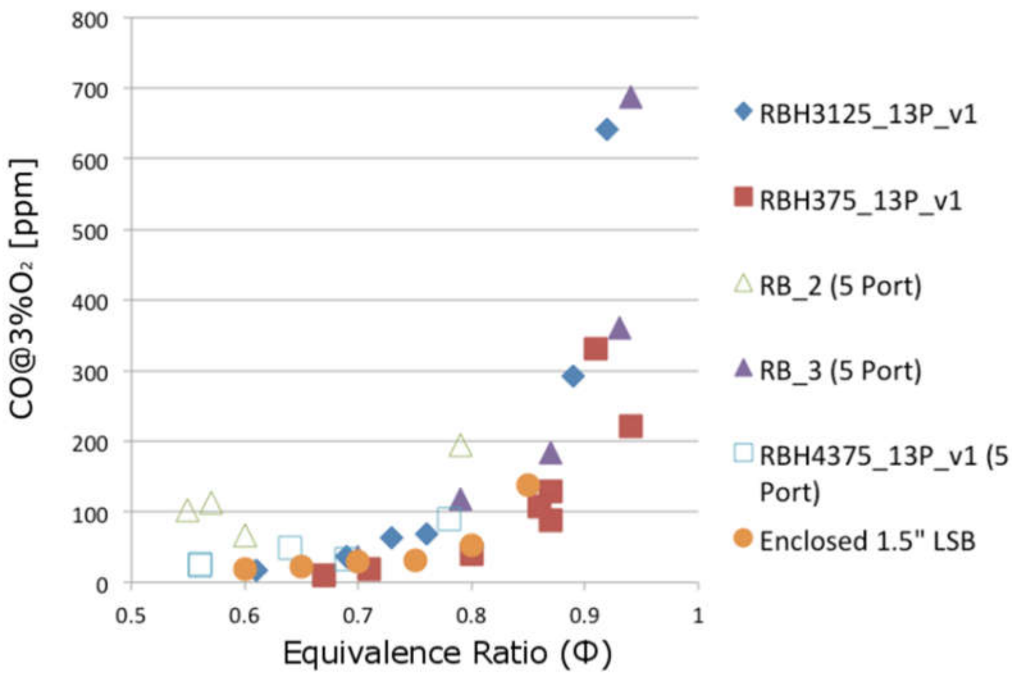


Figure 16: NO_x and CO Emissions from Natural Draft Ring-Stabilizer Burner

3.4.2 Lean Blowout

Lean blowout occurs for all burners between 2.6 and 2.9 KBTU/hr. The burners were designed to operate with a nominal 5 KBTU/hr operation. This would indicate a natural turndown ratio of roughly 2:1. All of the burners can operate with higher levels of heat rate but with poorer emission profiles. Investigation into a venturi that provides a higher rate of turndown is needed. A more effective venturi will allow for greater amounts of fuel variation with lower variability in associated air flow.

Table 4. Turndown ratio for test burner plates

Burner	Heat Output Rate (KBTU/hr) at Lean Blowout
RBH3125_13P_v1	2.9
RBH375_13P_v1	2.8
RB_2 (5 Port)	2.6
RB_3 (5 Port)	2.8
RBH4375_13P_v1 (5 Port)	2.6

3.4.3 Discussion

The Ring-Stabilizer Burner is capable of operating with natural draft operation at target NO_x emission levels. The use of a stock fuel/air mixing venturi provides evidence that a low cost commercial burner system could be developed. However, the natural draft venturi delivers air at a nonlinear relationship to fuel flow. This nonlinearity poses difficulties for the natural draft Ring-Stabilizer Burner to operate with high degree of turndown while maintaining low emissions. A more detailed examination of the fuel/air venturi is needed to maximize heat rate turndown while ensuring low emissions.

4.0 Multi-Port Ring-Stabilizer Burner: Optimization of Clustering Pattern for Larger Thermal Outputs

4.1 Introduction

Clustering pattern of the multi-port Ring-Stabilizer Burner were developed to optimize heat transfer from the burner to an intended heating surface. Knowledge of the port-to-port interactions is needed for scaling and adapting the Ring-Stabilizer Burner to larger thermal outputs and other gas appliances, such as water heaters and small boilers. This chapter outlines the design and experimental process for optimizing the port-clustering pattern in order to develop a scaling strategy for the Ring-Stabilizer Burner.

4.2 Design Methodology

Multiple burner plates were designed to balance the effect of thermal power output, equivalence ratio, plate geometry and fuel type on flashback and lean blowoff. Scaling the traditional Ring-Stabilizer Burner to thermal outputs typical for residential cookstoves presented a manufacturing challenge. The minimum feature width of the waterjet led to gaps that were too large relative to the port diameter, creating a leakage.

Laser-cutting was explored as an alternative manufacturing option. The hope was that it would be capable of producing a smaller minimum feature than the waterjet, thus reducing the gap width between the ring-stabilizer and the outer wall of the port. However, the heat of the laser proved too much for the thin web features, burning through the stabilizing ring and supporting tabs.

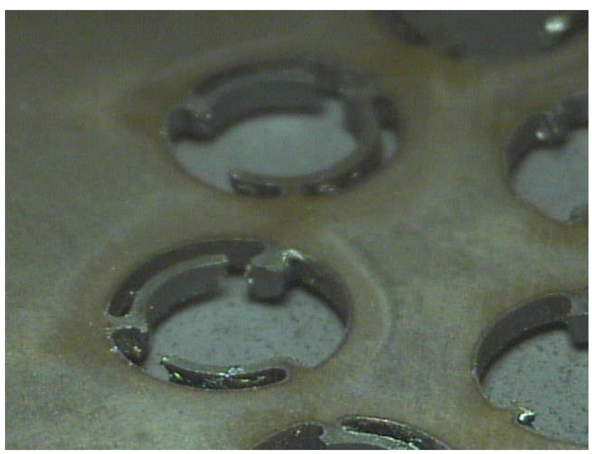


Figure 17. High Heat Output of Laser Melts Thin Features

Instead an alternative design was created which minimized leakage, while enabling continued use of the waterjet:

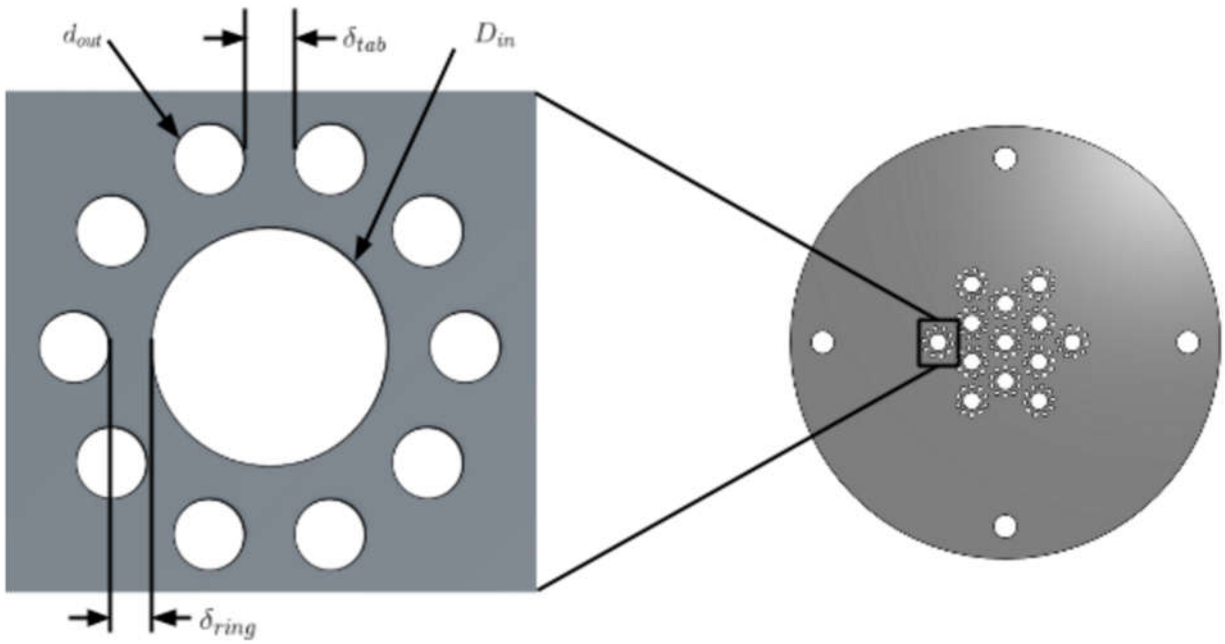


Figure 18. Alternative Design to Minimize Gap Leakage

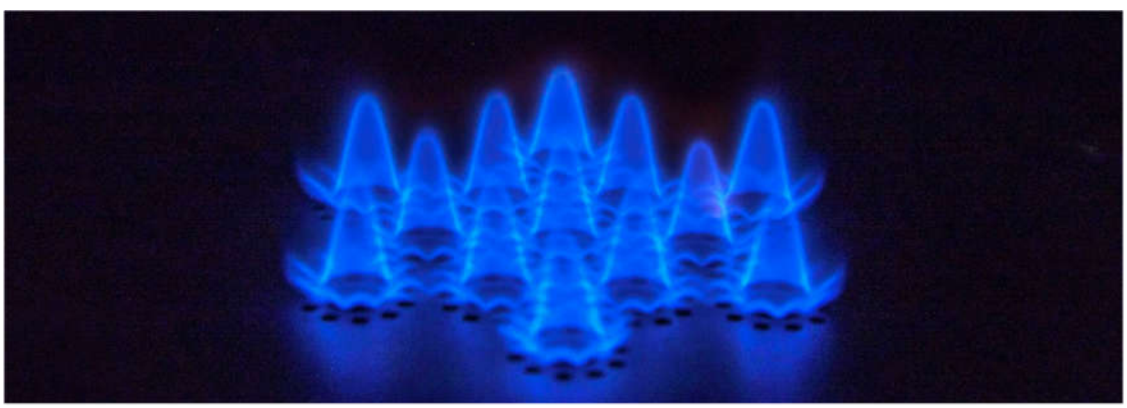


Figure 19. Photograph of Multiple Ring-Stabilier Burner Cluster in Operation

4.3 Experimental Methodology

4.3.1 Crossover Ignition

A crossover ignition study was performed as part of forced-draft testing. For the study, the ring-stabilizer ports are configured in two linear patterns that cross in the middle of the plate. The edge distance between ports is varied from 0.06 inches to 0.25 inches for both plates. To test, an equivalence ratio and power are set, based on settings resulting in ideal parameters from the results of the emissions tests. One port along the edge of the plate is ignited with a hand held torch. The port nearest the torch is ignited and lights off neighboring ports so long as the edge distance between ports is sufficiently small. When the flame no longer propagates to the neighboring ports, the maximum edge distance allowable for ignition is recorded. The procedure is repeated for various equivalence ratios, burner power output, and two different port diameters. The maximum allowable edge distance for ignition was investigated and recorded.

Figure 20: Right Picture Shows Final Port Ignition Failure Due to Large Port Gap DIstance

4.3.2 Turndown

Different port configurations and inner hole diameters, D_{in}, were investigated with the new port geometry defined above in Figure 18. Each clustering pattern was tested to ensure crossover ignition and to determine the effect of the pattern on turndown.

4.4. Results and Discussion

4.4.1 Crossover Ignition

Crossover ignition will be required for multi-port ignition. Crossover ignition tests were also performed as part of forced-draft studies. Results from in Table 5 show that ports will need to be less than 0.125 inches apart, an easy geometry to implement that showed no potential for damage to the plate.

Table 5. Maximum Allowable Distance Between Ports for Light Off

0.375" 9 Ports

Equivalence Ratio	Max. Edge Distance (in)
0.8	0.125
0.85	0.125
0.9	0.125

0.4375" 9 Ports

Equivalence Ratio	Max. Edge Distance (in)
0.8	0.125
0.85	0.125
0.9	0.125

Six new burner plates were tested for crossover ignition. Three of the burner plates testing an ignition "bridge" concept failed preliminary tests and were not tested further. The concept aimed to extend the maximum allowable edge distance between ports by providing an intermediary flame port for crossover ignition.

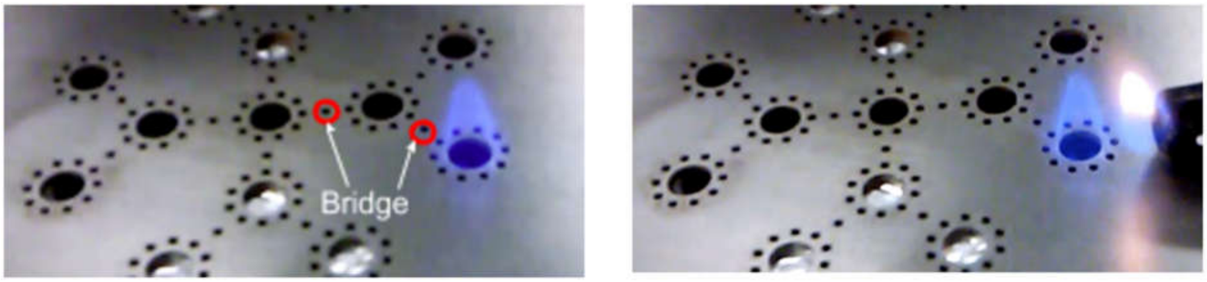
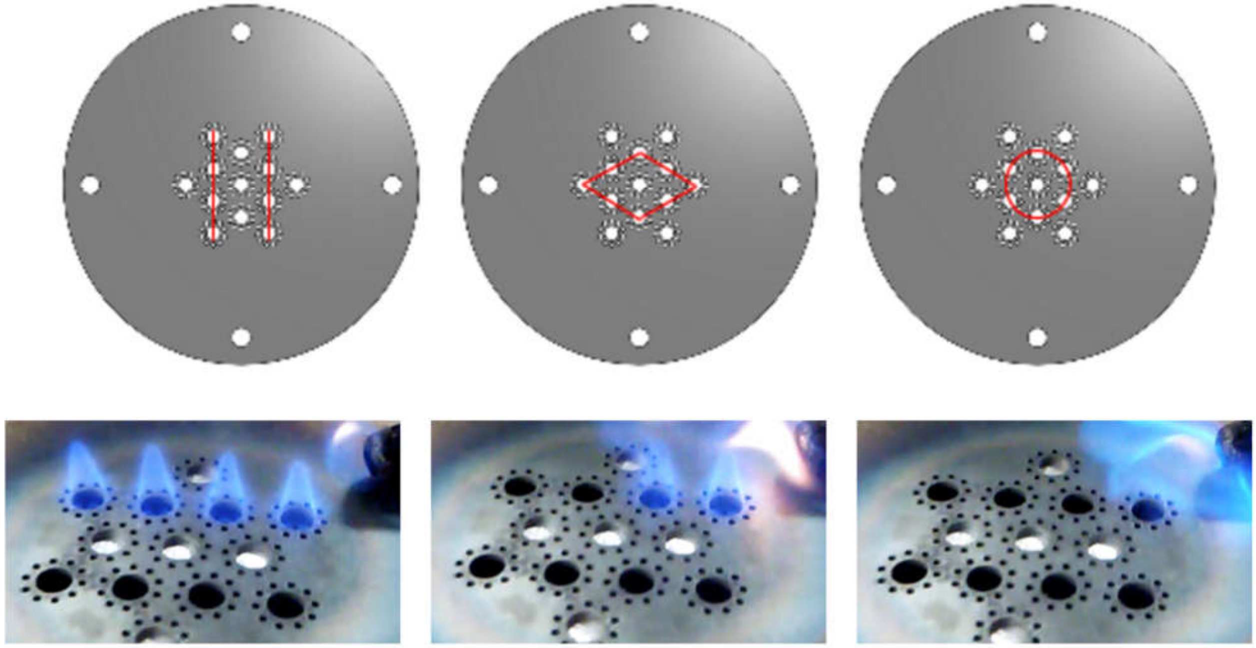


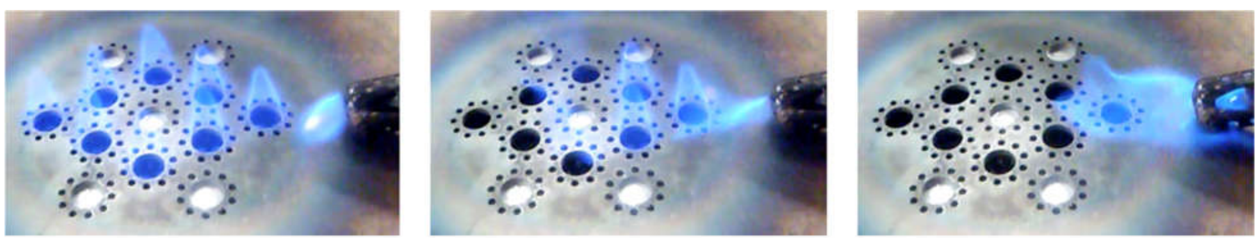
Figure 21. Crossover Failure with Ignition "Bridge" Concept.

For the remaining three plates, the clustering pattern was kept the same and the size of D_{in} was varied from 0.20″ to 0.325″. The number of outer (stabilizing) holes for all ports was kept constant for each plate, as was the ring thickness, δ_{ring}, and the edge distance between ports. The design of each burner plate enables testing of linear, rhombic and circular patterns for all three D_{in}.

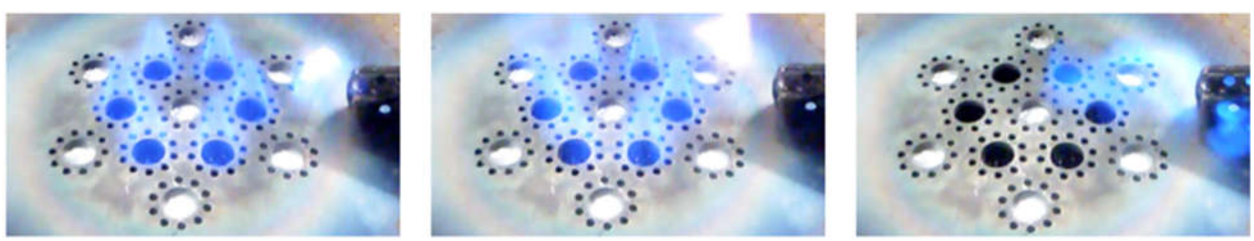
Crossover ignition tests proved successful for each plate. Testing of the three plates showed clustering pattern did not have measurable effect on crossover ignition for the range of power outputs tested, so long as the edge distance did not exceed the maximum allowable distance of 0.125″ previously measured. Three geometries were tested for crossover ignition with the same burner plate: linear, rhombic, and circular. These geometries were constructed by taping select ports shut on the same burner plate. The taped shut ports appear white due to room light reflecting off the tape in Figure 22. The open ports which fual and air can exit appear black.



(a) Linear



(b) Rhombic



(c) Circular

Figure 22. Light-Off Successful Regardless of Clustering Pattern or D_{in}

4.4.2 Turndown

Turndown for the three new plates is the same as for the burners tested previously (approximately 2:1). The limiting factor for turndown is still the performance of the venturi, with the clustering pattern having no measurable effect. The flexibility of the clustering pattern will allow for scaling and adapting the Ring-Stabilizer Burner to other residential and commercial appliances.

4.5. Scaling and Adapting to Other Gas Appliances

As the shape of the clustering patterns tested has little effect on crossover ignition, the clustering pattern should not be the limiting factor when scaling the technology to larger thermal outputs. The flexibility of the pattern is advantageous for adapting to different technologies. Therefore, the range of viable power output per port, dictated by flashback and lean blowoff, and the maximum physical size of the desired burner will be the driving constraints when adapting the multi-port ring-stabilizer to other technologies; this assumes a venturi system can be designed to entrain adequate air to create lean mixtures for any thermal output.

A simplified feasibility analysis was performed for adapting the ring-stabilizer to a residential gas water heater (with tank). A vendor survey was conducted. Typical thermal output for a residential water heater is between 35 and 40 KBTU/hr. The burner head is typically 6 to 8 inches in diameter.

We establish a range of viable thermal power outputs for each port size and the previously collected lean blowoff data. The lower limit is dictated by flashback while the upper limit is dictated by lean blowoff. The surface area (footprint) of each port is also calculated. A design table is then created:

Table 6. Power Output and Footprint for One Ring-Stabilizer Port.

	Power Per Port		
D_{in} (in)	Lower Limit (KBTU/hr)	Upper Limit (KBTU /hr)	Footprint (in^2)
0.2	0.27	0.4	0.240
0.25	0.35	0.55	0.292
0.325	0.51	0.85	0.378

The new water heater burner must be capable of providing 40 KBTU/hr and fit in a footprint of $\pi \quad (8\ in)^2/4\ \approx 50\ in^2$. Using these design constraints, we can test the feasibility of our 3 port sizes.

For the port size of $D_{in} = 0.25\ in$ the power range for this port is 0.35 - 0.55 KBTU/hr per port. Therefore, the number of ports required for a 40 KBTU/hr water heater can range from 73 to 115 ports. The footprint is then calculated for all ports: 21.29 - 33.53 in^2. The replacement multi-port ring burner is capable of providing 40 KBTU /hr while fitting within the current water heater burner footprint. This calculation can be repeated for any port size that has adequate blowoff data. While the port size could be increased to minimize the number of ports, a larger number of ports will allow for better thermal distribution, preventing thermal stresses on the burner body that result from high heat in one concentrated location.

A similar analysis can be performed for any natural gas burner that operates in the upright position. Further testing is required to analyze the effect of burner operating orientation on emissions.

4.6 NO_x Reduction Verification

NO_x emissions of the newly developed natural-draft Ring-Stabilizer Burner were compared to conventional burners. Figure 23 shows corrected NO_x two natural-draft ring-stabilized burners operating across a range of thermal output levels. These results show that the natural-draft reduced scale Ring-Stabilizer Burners are capable of producing low levels of NO_x emissions over a wide range of equivalence ratios similar to their natural draft counterparts. NO_x emissions are far below the 90 ppm level of incumbent technologies. The lowest operational NO_x levels are 80% less than the typical cooktop burners, meeting one of the goals of this project.

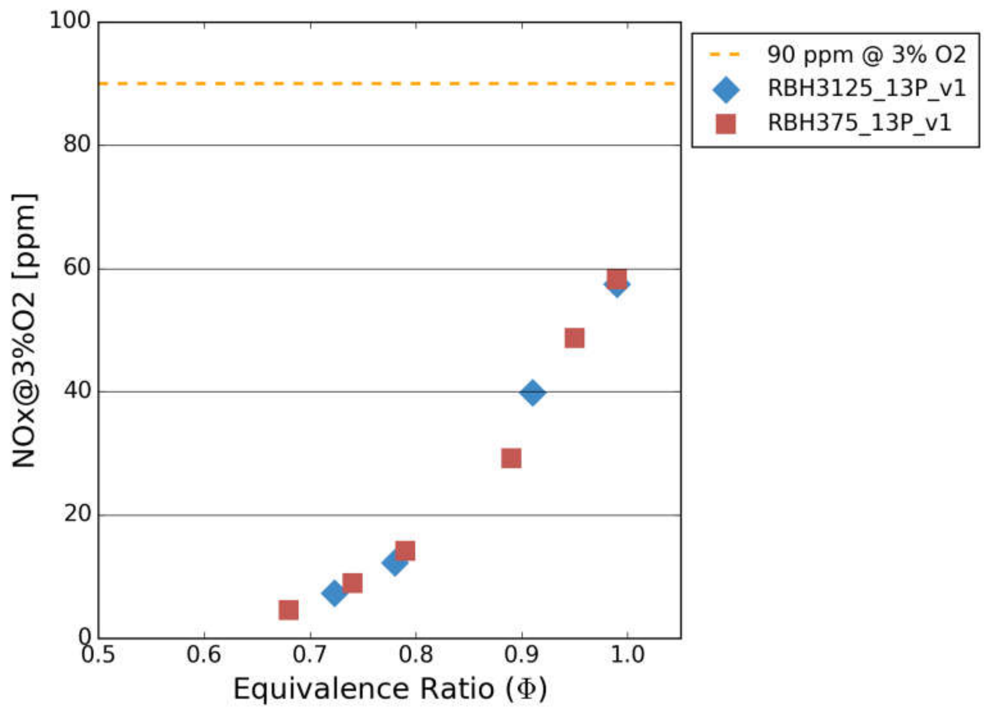


Figure 23: NO_x Emissions from Natural-Draft Ring-Stabilizer Burner

4.6.1 Discussion

The Ring-Stabilizer Burner is capable of operating with natural draft operation at target NO_x emission levels. The use of a stock fuel/air mixing venturi provides evidence that a low cost commercial burner system could be developed. However, the natural draft venturi delivers air at a nonlinear relationship to fuel flow. This nonlinearity poses difficulties for the natural draft Ring-Stabilizer Burner to operate with high degree of turndown while maintaining low emissions. A more detailed examination of the fuel/air venturi is needed to maximize heat rate turndown while ensuring low emissions.

5.0 Conclusions and Next Steps

5.1 Conclusions

This project has proven that significant NO_x emission reudcutions can be made for residential and commercial cooking appliances. The adaptation of the forced-draft to natural-draft Ring-Stabilizer Burner was able to accomplish the objective of this project by reducing NO_x emissions by 80% vs. conventional technology.

5.2 Next Steps

While this result shows promise for the commercialization of low emissions cooking appliances significant efforts are still needed to bring this new technology to market. These efforts will include integrating the new burner technology into a form factor similar to commercial cooking appliances, including the gas delivery train (valve, and plumbing), cooktop cavity, spill tray, and cooking grate. A special focus must be put on integrating an ignition system into the burner assembly as well. Consideration of safety controls to eliminate flashback and flame lift off must be put in places.

Beyond engineering solutions needed to integrate the burner technology, rational for customer acceptance of the new technology must be considered. While low emissions and high thermal efficiency are societal goals that must be achieved, only customer acceptance of the new technology in the competitive market will make such goals obtainable. Efforts must be taken to understand what market drivers will influence customers to adopt this technology as well as what equipment manaufacutres are able and willing to build. These drivers may well not include the societal goals previously identified. Continued development of the new technology must be responsive to cutomer needs to maximize commercialization potential.

Additionally, the ring-stabilizer technology shows promise for alternative applications, including replacement for traditional ribbon burners and other industrial process heating systems. These applications should be evaluated though market studies prior to engineering developments are made to ensure research and development funds are properly leveraged.

GLOSSARY

Term	**Definition**
Natural Draft	The primary combustion air is provided by a fuel venturi (no electric fan needed).
Forced Draft	The primary combustion air is provided by an electric fan or blower.
Lean Blowoff	Flame becomes unattached to port due to lean operation
Flashback	The unwanted intrusion of flame behind the burner port resulting in uncontrolled burning within the premix chamber
Turndown	The range of power output for the burner at each equivalence ratio
Fuel Venturi	A short tube with a constricted throat causing a reduction in pressure that results in air entrainment for premixed burner operation.

REFERENCES

Johnson, Matthew R. and Larry W. Kostiuk (1995) "Lean Burn Technology for Gas Appliances." 15th Canadian Congress of Applied Mechanics, Victoria, BC May 28-June 1 1995.

Johnson, Matthew R., Larry W. Kostiuk, and Robert K. Cheng (1998) "A Ring Stabilizer for Lean Premixed Turbulent Flames." Combustion and Flame, 114:594-596.

Kostiuk, Larry W. and Robert K. Cheng. "Apparatus and method for burning a lean, premixed fuel/air mixture with low NO_x emission" US Patent 5516280, May 14, 1994.

California Energy Commission: California Energy Almanac. "Supply and Demand of Natural Gas in California", n.d., http://www.energy.ca.gov/almanac/naturalgas_data/overview.html