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FINAL PROJECT REPORT

Demonstration of Industrial System with Real-time Response to Fuel Stock Variability

Ultraclean Fuel-switching Industrial Heater to Augment California's Biogas Energy Production

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PREPARED BY:

Robert K. Cheng
Lawrence Berkeley National Laboratory
Vince G. McDonell
Advance Power & Energy Program
University of California, Irvine
Primary Authors

David Weightman
Project Manager
California Energy Commission

Agreement Number: PIR-13-011

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the 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.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

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- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Demonstration of Industrial System with Real-time Response to Fuel Stock Variability is the final report for Contract Number PIR-13-011 conducted by Lawrence Berkeley National Laboratory and the University of California, Irvine. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project sought to demonstrate a low-emissions combustion system capable of switching from biogas, a renewable fuel, to a conventional gaseous fuel, either natural gas or propane, in real time without disrupting the operation of the boiler. This system was tested in a commercial boiler installation at the Chiquita Water Treatment Plant operated by the Santa Margarita Water District. Fuel-switching combustion systems such as this will encourage small to medium buildings, such as hospitals, hotels, and large supermarkets, to use their waste streams to fulfill their energy needs. This technology benefits California by promoting a larger renewable energy portfolio and improving air and water quality. The development involved advancements in burner, fuel sensing, and control technologies. Based on laboratory tests that showed the capability of these technologies to perform real-time fuel switching with ultra-low emissions, a fully functional pre-commercial burner and control system was designed and installed on the boiler. Regrettably, the demonstration could not proceed due to time and administrative constraints coupled with host-site availability. However, results and knowledge gained from developing this demonstration project have clearly shown the technical feasibility of using a real-time fuel-switching system in industrial settings.

Keywords: Biogas, renewable energy, alternate fuels, ultra-low emissions, heating systems

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Introduction

Biogas, also known as anaerobic digester gas, is a fuel derived from organic wastes. Extracting energy from these wastes via biogas production is highly desirable. Because biogas is a carbon-neutral renewable energy source, it does not increase atmospheric carbon dioxide when burned. The production of biogas diverts waste from landfills, which improves water and air quality. In addition, extracting useful energy from waste offsets natural gas consumption and reduces fuel costs for the equipment operator. Remnants of biogas production called biosolids are valuable commercial products that can be sold and used as fertilizer, compost, or landfill cover.

Biogas is generated from the anaerobic digestion or fermentation of biomass (such as organic waste) and used in many of California's large, centralized industrial facilities. These include wastewater treatment plants, landfills, and dairy farms. Biogas use in these large facilities, however, represents only a fraction of the renewable energy potential from waste. According to a 2013 study by the National Renewable Energy Laboratory (LBNL), the methane potential from biomass waste streams nationwide is estimated at 7.9 million metric tons per year. For comparison, in 2013 the United States produced about 30 trillion cubic feet, or about 680 million metric tons of conventional natural gas.

Fourteen percent of biomass waste streams come from food waste, yard waste, paper and cardboard, and other organic waste materials. This has the potential to produce 1.1 million metric tons of methane equivalent. In California, 16.7 million metric tons of organic wastes are disposed of each year at landfills. There is great potential for small- to medium-size facilities such as hotels, supermarkets, large restaurants, hospitals, and wineries to use these wastes on site for energy production in small-scale facilities.

For small and medium-sized facilities, installing and maintaining a chemical digester and combustion equipment involve significant initial capital investments. To obtain a reasonable return on investment, biogas-fueled heat and power systems must operate at high-capacity utilization. However, biogas production is slow and uneven, and the contents and the quality of the biogas are not always consistent. Because of such variations, burning biogas requires specialized combustion equipment that can handle the fluctuation in the energy content of biogas. Moreover, biogas supply is often intermittent, as waste streams are not always consistent, so dedicated biogas combustion equipment cannot be used all the time. Consequently, small- to medium-size industrial enterprises have little financial incentive to invest in biogas systems.

Recognizing that many of these enterprises also rely on natural gas or propane for their heating needs, this project aimed to demonstrate a cost-effective real-time fuel-switching combustion system to encourage installation of biogas systems in California's small- to medium-size facilities. This combustion system enables the operator to maintain a consistent and uninterrupted energy supply by using biogas when it is available on site and switching to or blending biogas with natural gas or propane without interruption when biogas supplies are low or unavailable. The specific project objective was to develop and demonstrate a cost-effective industrial heating system with real-time fuel-switching capability and ultralow emissions at a boiler at the Chiquita Water Reclamation Plant (CWRP) of the Santa Margarita Water Districts of Rancho Santa Margarita in Orange County, California.

In California's metropolitan areas, stationary combustion equipment has to comply with stringent air-quality rules. To meet the low and ultralow emissions targets imposed by these regulations, combustion equipment is finely tuned to a specific fuel and controlled with precision. Fuel-specific burner and precision control schemes are necessary because the low- and ultralow-emission flames are very sensitive to changes in the fuel content and fuel-air ratio. This project sought to develop advanced-burner, fuel-sensing, and combustion-control technologies and adapt them into a pre-commercial unit for demonstrating real-time fuel switching at the boiler at the Chiquita Water Treatment Plant. By developing and demonstrating a pre-commercial real-time fuel-switching system, the project aimed to offer a practical solution to overcome the economic and environmental barriers that impede broader biogas use in small-scale decentralized waste-to-energy facilities.

The technologies being developed evolved from prior combustion research at LBNL and the University of California at Irvine (UCI). The burner technology came from LBNL, where the discovery and development of the patented low-swirl burner led to commercialization of industrial ultralow emissions burners. Many of these are installed in California to meet the most stringent air-quality rules. The fuel-sensing technology detects the changing properties of the fuel stock so that the system can deliver the correct fuel-air-ratio for the lowest NOx emissions. The California Energy Commission supported UCI's development of this technology. To provide the control set points during fuel-switching, flame temperatures for the fuels and fuel mixtures were computed from chemical kinetics and expressed on a fuel-loading map, which comprises the data center of the control system.

The equipment developed with this funding is a combustion system consisting of an advanced burner with a fuel sensor and a fuel control algorithm developed to enable real-time fuel-switching. It was designed as a retrofit to demonstrate that real-time fuel switching can be readily adapted for industrial use and was installed on a steam boiler of 1.99 million British thermal units per hour heat output.

Project Process

The boiler at the CWRP is in a typical industrial setting where steam is produced by boilers for various applications. Biogas fuel is generated on site by large digesters. There are two biogas boilers at the water treatment plant, and both use propane occasionally as a backup fuel. To switch from biogas to propane, a boiler must be shut down completely and restarted. The two boilers are not always operated simultaneously, and the Santa Margarita Water Treatment District offered one of them to be retrofitted with a low-swirl burner and a new control system to demonstrate real-time fuel switching. This capability would be useful when heating demand could be handled by only one boiler.

The initial task of the project was to analyze the configuration of the existing boiler, fuel supply circuit, and control hardware, and guide the engineering developments of the fuel-switching low-swirl burner system. Originally, the goal was to demonstrate fuel switching between natural gas and biogas. However, the research team found that natural gas supply is not readily available at the water treatment plant because of the remote location. As a result, the goal of the project refocused on demonstrating fuel-switching between propane and biogas. To implement the technologies in a pre-commercial demonstration retrofit, including the burner, fuel sensor, and control, the team carried out the developments in two stages.

In the first stage, the team conducted laboratory tests of burner variants using a one-fifth-scale (1/5-scale) prototype. They designed and tested full-scale prototypes in the laboratory, and then on site at the CWRP. They compiled fuel-loading maps from computed flame temperatures and verified the functionality of the maps by installing them in a laboratory computer and using them to perform real-time fuel switching in the 1/5-scale burner prototype. After verifying developments in the laboratory, the research team finalized the engineering designs of the burner and fuel sensor and had them fabricated.

The second stage of the project focused on the control system. Based on information collected at the water treatment plant, the research team selected and procured a suite of electrical and electronic hardware to control the fuel and air supply to the burner. Researchers at LBNL and UCI developed a control scheme to operate the boiler fitted to the low-swirl burner system.

Once analysis and engineering were complete, the final task of the project was preparing for and conducting the demonstration. After constructing the burner, the research team verified its operation before a crew installed it on the boiler at the water treatment plant. At the treatment plant, professional boiler service companies removed the existing burner and replaced it with the low-swirl burner. They also augmented the existing boiler control system with an auxiliary control panel to control fuel switching for the demonstration. The plan was first to verify the operation of the boiler with both propane and biogas, and then demonstrate the fuel switching.

Project Results

The first prototype fuel sensor, which was mounted in the biogas supply line at CWRP, was tested successfully. Knowledge gained from the test led to a design improvement. After this, the team constructed a second prototype with the updated design and verified its operation in the laboratory. Then, they mounted the prototype in the fuel supply circuit of the boiler. The fuel-delivery system of the boiler at CWRP did not require a propane/biogas fuel sensor, but the team developed the basic layout and engineering framework for future applications in which it would be required. The successful results showed the readiness of the speed-of-sound sensor technology for commercial applications.

The team constructed a 1/5-scale prototype of a fully functional low-swirl burner comprised of the swirler, the fuel injector, and a flame quarl, which is a fire resistant channel for a burner in a boiler or furnace. This prototype was then tested in a boiler simulation facility at UCI. These tests produced the first experimental verification of the real-time fuel-switching capability of the low-swirl burner. They verified that the control of flame temperature via a fuel-air ratio allowed fuel switching without interruption.

Based on the findings from the 1/5-scale low-swirl burner tests, the project team fabricated a full-scale low-swirl burner for the boiler. The research team designed this low-swirl burner as a "package" for ease of retrofitting the boiler. The burner head, which included the swirler and fuel injector, along with the air blower, fuel-controllers, and other plumbing hardware, were mounted on a rolling skid. Operation of the low-swirl burner package was verified by firing into a cylindrical enclosure that simulated the geometry of the boiler combustion chamber. The results showed that the low-swirl burner package supported stable flames at full and partial loads. The burner achieved ultralow emissions of less than 10 parts per million oxides of nitrogen, corrected to 3 percent oxygen, which was the target level.

The control system, which is the brain of the fuel-switching low-swirl burner, was made up of commercially available control hardware and software for boilers. It was closer to a commercial product than expected in the original plan. The control system consisted of two main parts: first, the "legacy" control system for the boiler, which was kept mostly intact, and second, an auxiliary control system, which operated simultaneously with the legacy controls. Except for changing out a few components, this control system required minimum alterations to the fuel delivery circuits of the boiler. Because commercial equipment was used, the final control system could be operated by a trained and licensed boiler professional. This made it a pre-commercial prototype. The system showed that combustion heaters with real-time fuel switching could be realized cost-effectively without using specialized equipment.

Regrettably, the project did not reach the goal of demonstration in a commercial boiler. The low-swirl burner system and related controls were installed in one of the boilers at CWRP, but various time, administrative, and host-site constraints restricted the time available. There was not enough time to make required changes to the low-swirl burner light-off mechanism, so the boiler could not be started and lit. Despite this setback, the tasks successfully performed yielded a wealth of knowledge and significant insights. They provide the technological foundation and basic engineering framework for launching the real-time fuel-switching in commercial waste-to-energy systems.

Knowledge or Market Transfer

The project team drafted a knowledge transfer plan for information dissemination. This technology transfer plan included mechanisms such as web seminars, presentations and papers for technical meetings, technical reports, and fact sheets. Since the project was not demonstrated in a commercial boiler, these knowledge transfer activities were not completed.

Benefits to California

The main benefit of this project to California is to increase the state's renewable energy portfolio by offering a practical and cost-effective system to encourage small- to medium-size facilities to use their waste streams to fulfill their energy needs. Broader use of waste-to-energy systems will divert waste from landfills to improve water and air quality and lower the energy cost of operations by avoiding the cost of purchased fuel gases.

The technological achievements of this project contribute to California’s leadership in the advancement of renewable energy systems, which in turn supports the state’s mandate of carbon neutrality by 2045. The two technologies developed for the fuel-switching burner system, which are a fuel sensor to provide feedback on fuel constituency and a fuel-flexible burner that maintained stable flames with ultra-low emissions, are ready for commercialization in a wide range of gas heating systems.

CHAPTER 1: California's Biogas Energy Potential

Biogas, also known as anaerobic digester gas (ADG), is a fuel derived from organic wastes. It is a carbon-neutral, renewable energy source that is generated and used in many of California's large centralized industrial facilities such as wastewater treatment plants, landfills, and dairy farms. However, small- to medium-size facilities such as hotels, supermarkets, large restaurants, hospitals, and wineries have yet to exploit their biogas waste-to-energy potential in small-scale decentralized facilities. The main impediments to on-site usage of biogas are the intermittent availability and variations in the biogas constituency. This project sought to develop and demonstrate a cost-effective pre-commercial phase industrial heating system with real-time fuel-switching capability (that is, switching from biogas to natural gas or biogas to propane during continuous operation) and ultralow emissions. This system provides a practical technology solution to overcome the economic and environmental barriers that impede broader biogas use in small-scale decentralized waste-to-energy plants. The equipment demonstrated is a combustion system consisting of an advanced lean premixed burner with a fuel sensor and a fuel control protocol installed in a typical steam boiler of 1.99 million British thermal units per hour (MMBtu/hr) heat output. The combustion system is designed as a retrofit to demonstrate that real-time fuel switching can be readily adapted to industrial settings.

The first two sections of this chapter present an overview of biogas and the current use in California. The following two sections explain how real-time fuel-switching combustion systems can expand the use of biogas and the technical challenges to develop an advanced and cost-effective heater with real-time fuel-switching capability. The last section summarizes the results of a recent analysis performed at the Lawrence Berkeley National Laboratory (LBNL) on California's biogas energy potential and the economic barriers to using biogas at small-scale decentralized facilities.

Biogas Production and Potential

Biogas is produced by anaerobic digestion or fermentation of biomass (such as organic waste) commonly found at factories, agricultural sites, and water treatment plants. Examples include food wastes, animal manure, and wastewater. In the United States, especially in California, large industrial-scale anaerobic digestion systems are becoming increasingly common at large facilities such as wastewater treatment plants and dairy farms. Biogas use in these large facilities, however, represents only a fraction of the renewable energy potential from wastes. According to a 2013 study by LBNL, the methane potential from biomass waste streams nationwide is estimated at 7.9 million metric tons per year. For comparison, in 2013 the United States produced about 30 trillion cubic feet of natural gas. At 0.05 pounds per cubic foot, this represents about 680 million metric tons.

Fourteen percent of the biomass waste streams come from food waste, yard waste, paper and cardboard, and other organic waste materials and has the potential to produce 1.1 million metric tons of methane equivalent. In California, 16.7 million metric tons of organic wastes are generated annually and disposed of at landfills (CARB, 2013). Extracting energy from these waste streams is highly desirable for many environmental and economic reasons. First, diverting waste from landfills improves water and air quality. Wastes left in landfills to decompose generate leachate, a highly corrosive toxic liquid and methane that is a greenhouse gas air pollutant. Leachate can contaminate underground water aquifers if landfill liners are breached, while methane in the atmosphere has a higher heat trapping potency, thus is a stronger greenhouse gas than carbon dioxide produced by combustion of the biogas derived from the waste. More significant, extracting useful energy from wastes offsets natural gas consumption and reduces fuel costs for the equipment operator. Remnants of biogas production, called biosolids, are valuable commercial products that can be used as fertilizer, compost, or landfill cover.

To broaden the use of biogas in California, the project goal is to demonstrate an industrial heating system that will enable small- to medium-size industrial, agricultural, and water treatment enterprises to take full advantage of the associated potential biogas energy supply instead of sending the waste streams to landfills, which results in the uncontrolled release of methane to the atmosphere. The system is designed to address concerns regarding biogas supply (that is, inconsistencies of biogas quality and availability), the operational effect of biogas on the performance, the reliability of the equipment, and the limited return on investment of biogas equipment. These are the barriers that prevent small to medium facilities from realizing the biogas potential.

For small- to medium-size industrial enterprises, installing and maintaining a chemical digester (to convert biological waste to biogas) and combustion equipment (for generating heat or power) involve significant initial capital investments (Anderson and Therkelsen, 2016). To obtain a reasonable return on investment, biogas-fueled heat and power systems must operate at high capacity use. However, biological waste degradation and the subsequent generation of biogas is a slow and uneven process. Because of this, biogas properties that are indicators of quality as a potential fuel source vary based on several factors, such as digester influent, bacterial health, and operational practices. In most cases, burning biogas, which has variable and inconsistent energy contents, requires dedicated and specialized (thus more complex and costly) combustion equipment. Of additional importance, biogas supply is often intermittent in the case of small generators; thus, dedicated biogas combustion equipment cannot be productive all the time. Consequently, small- to medium-size industrial enterprises have little financial incentive to invest in biogas systems. Recognizing that these enterprises also rely on natural gas or propane for heating, this project demonstrates a cost-effective real-time fuel-switching combustion system to enable the operator to maintain consistent energy supply by using biogas when it is available on site and by switching to or blending biogas with natural gas or propane when biogas supply is low or unavailable.

Biogas Properties and Current Biogas Combustion Equipment

Biogas is a low-Btu (British thermal unit) fuel composed of 50 percent to 75 percent methane (Table 1). In comparison, typical natural gas has more than 95 percent methane. Also shown in Table 1 are other constituents of biogas consisting of mostly inert gases such as carbon dioxide (CO_2) and nitrogen (N_2). These inert gases act as diluents that lower the energy content of biogas per-unit volume, as inert gas percentages increase fuel combustion quality decreases. To make biogas compatible with natural gas, the research team must use a purification process to remove CO_2 and other inert constituencies. The product is biomethane, which can be injected into natural gas lines. However, the capital and operating costs of purifying biogas into biomethane are significant. Therefore, biomethane conversion is practiced only at large waste facilities such as landfills, livestock operations, and water treatment plants. The practice is not economically feasible for small- to medium-size enterprises that generate intermittent and small volume waste streams.

Table 1: Typical Compositions of Biogas

Compound	Formula	Percent Composition (%)
Methane	CH_4	50–75
Carbon dioxide	CO_2	25–50
Nitrogen	N_2	0–10
Hydrogen	H_2	0–1
Hydrogen sulfide	H_2S	0–3
Oxygen	O_2	0–0.5

State-of-the-art industrial combustion systems in California, many of them steam boilers, are designed to achieve high efficiency and ultralow emissions within a wide range of operating conditions. To attain these performance goals, these systems are finely tuned to the combustion characteristics of a singular fuel stock, such as pipeline quality natural gas, propane, or a specific biogas (Richards et al., 2001). Accomplishing these performance goals is not trivial and can be challenging, even for natural gas. The many burner technologies for natural gas systems (for example, surface-stabilized, forced internal-recirculation, trapped vortex burner, rich-quench-lean burner, and others) that have been developed, demonstrated, and commercialized in the last 30 years are testaments to the scale and challenges. To add fuel flexibility as a design parameter, a more complex multi-stage burner (that is, one nozzle head containing a primary, secondary, or even a tertiary burning zone) is deemed by many industrial experts to be the only viable option.

The combustion properties of propane are close to those of natural gas. Consequently, combustion equipment with dual-fuel natural gas/propane capability is the most commonly available commercial product that is labeled as "fuel-flexible." Manufacturers promote and market products that can use either natural gas or propane because a burner and associated control that have been designed for one fuel can support stable combustion when burning the other. Even so, these systems cannot switch between fuels in real time because the fuel and air valves need to be adjusted or switched. Because most industrial processes require the combustion equipment to operate continuously without interruption, fuel switching is rarely practiced because of the requirement to shut down and undergo air purging before the equipment can be restarted.

From an energy efficiency standpoint, an important characteristic for a piece of combustion equipment is maintaining a consistent heat or power output, which is controlled by adjusting the volumetric flow rate of a given fuel. Because each fuel has a characteristic heating value (expressed in terms of Btu/ft^3) the fuel flow rates to produce a desired heat output would be different for different fuels. In addition, gas densities measured in kilograms/cubic meter for various fuels are not the same. These differences in heating values and density mean that the fuel delivery system, called the fuel injectors, must be tuned for a particular fuel. To provide combustion engineers a means to estimate the similarity or differences of various gaseous fuels, the Wobbe Index (heating value normalized by the square root of the specific gravity) is used as an indicator of the compatibility. If the Wobbe indices of two fuels are within 5 percent, it would mean that a piece of combustion equipment designed for one fuel can operate on the other without changeover of the fuel injection valve, fuel injection nozzle, burner settings, and system controls.

Though the Wobbe Index is useful as a guide, it is not an indicator for the chemical reactivity of different fuels, which dictates basic combustion properties such as flame speed, flame temperature, and flammability limits. These combustion properties are critical parameters for designing burners that produce stable flames with high efficiencies and low emissions. The differences in flame properties often lead to situations where the Wobbe indices of two gaseous fuels are matched, yet there are issues concerning emissions, flame stability, and flame position that affect system performance (McDonell et al., 2013). To address these flame-related issues, the burner technology (that is, the method to produce a stable flame using a mechanical flame holder, a chemical approach such as a catalyst, and aerodynamic approaches using high-swirl, low-swirl, recirculation, and vortices) are central to achieving fuel-switching capability. Almost all equipment that had been designed for natural gas or propane cannot be easily switched to burn biogas or vice versa without changing out the hardware. Fuel flexibility, in particular switching from burning pipeline natural gas or propane to low-Btu biogas, cannot be accommodated without service interruption (that is, equipment shutdown and restart) or compromising one or all the performance metrics or both.

Promotes Biogas Use in California by Demonstrating a Fuel-switching Industrial Combustion System

Biogas-only combustion systems are specialized equipment and thus have limited market appeal. The installation of a biogas combustion system often comes at a premium. This cost premium is prohibitive for small- to medium-size enterprises to use their waste streams that tend to be moderate in volume and intermittent in supply. Moreover, the dedicated stand-alone biogas system can be supplemental only to the fossil fuel-based combustion equipment, which has consistent fuel supply as the baseload energy producer. To make biogas usage more attractive to these enterprises, combustion systems that can be used as a baseload energy provider with real-time biogas/natural gas/propane fuel-switching capability should be shown to be reliable, efficient, clean, and cost-effective. Then they would have a broader appeal and impact. This system will enable the operator to use biogas when it is available and switch to natural gas or propane (by blending biogas with natural gas) without interrupting production when biogas fuel quality or quantity is unable to meet output demand.

Commercially available real-time fuel-switching systems will expand the renewable biogas market, accelerating the replacement of natural gas with biogas in California. This project sought to demonstrate a cost-effective and ultralow emissions pre-commercial industrial system with real-time biogas/natural gas/propane fuel-switching capability and provide a technology solution to overcome the economic and environmental barriers to increased biogas usage in California. The demonstration provides the evidence to equipment manufacturers that such a fuel-switching system is not only technically feasible, but also cost effective.

Technical Challenges to a Real-time Fuel-switching Combustion System

To meet stringent air-quality rules in California, stationary combustion equipment in industrial settings must operate in premixed mode in which combustion takes place in a stream of thoroughly mixed fuel and air. To control the emissions of oxides of nitrogen (NOx), key pollutants contributing to smog formation, the air-to-fuel ratio of the mixture is set to fuel lean, meaning more air than is needed to oxidize, or burn, all available fuel. Because NOx formation is very sensitive to the fuel-air-ratio (through an exponential relationship to the flame temperature), precise controls for the fuel air delivery system are necessary. The operation of a single-fuel industrial lean premixed combustion system is set at a fixed fuel-air-ratio and monitored by measuring the leftover oxygen (O_2) concentration in the exhaust stream. The fuel-air ratio set point, in terms of the flow rates for air and fuel, is determined from chemical kinetics computations of the flame process for a particular fuel to target a flame temperature of less than 2,800°F, below which NOx emissions can be reduced. Due to the complexity of combustion chemistry, the fuel-air-ratio settings are not the same for different fuels. Therefore, it is necessary that a real-time fuel-switching system use a fuel sensor that can provide information on the fuel contents so that fuel and air-handling systems can deliver the right fuel-air-ratio for stable, efficient, and clean operation throughout the desired fuel space (that is, the range of fuels to be encountered).

When a different fuel is used in a gas burner, the tendency is for the flame to become unstable and to incite noise, vibration, and flashback. These tendencies have been well documented in combustion scientific and technical literature. These effects are manifestations of the differences in the flame properties such as flame speed and the flow dynamics associated with combustion heat release. Flow turbulence, which occurs naturally within the burner and inside the combustion chamber, amplifies these flame effects even further. Consequently, a well-designed fuel-flexible burner system needs the capability to address these combustion aerodynamic effects while maintaining an efficient and clean stable lean premixed flame. As discussed earlier, to maintain a stable lean premixed turbulent flame, a key design element in the burner system is a robust flame-holding mechanism, which helps maintain continual combustion. During fuel switching, the additional requirement is that the flame-holding mechanism can withstand the transient effects such as fluctuations in fuel and airflow rates and changes in flame sizes, when switching from one fuel to another.

As discussed above, the fuel and flame properties of natural gas and propane are close. However, the corresponding properties for biogas vary significantly depending on the compositions of the biogas. Due to the presence of inert gases in biogas, the associated energy content is lower than natural gas and propane. To produce the same amount of energy out of biogas or natural gas, the flow rate (flow volume) of the biogas needs to be higher than that of natural gas or propane. Therefore, the capabilities of the fuel and air-handling equipment—namely the air-blower, fuel control valve, the fuel injector, fuel-air mixing device, and control—need to be expanded to accommodate a wider range of fuels.

The control of a real-time fuel-switching industrial heating system requires scientific information on the combustion properties of the various fuels to be used as input for the control set points. Moreover, the control protocol (the steps taken to switch from one fuel to the other) must be designed to address possible transient effects. During fuel transition, the two fuel streams will be mixed. When transitioning from biogas, a weak fuel, to natural gas, a more robust fuel, the control systems must be programmed such that the flame, burning both fuels, would not become too rich (more fuel in the reactants) to cause flashback. In reverse, that is, transitioning from natural gas to biogas, the task of the control is to avoid flameout due to the mixture being too lean. During the transition, the flame position may change. If changes occur too rapidly, the risk of generating noise and vibration becomes very likely. Therefore, enabling real-time fuel switching requires a system that offers synchronous operation of the fuel and air supply systems, the fuel sensor, and the burner by a control system and protocol that is based on fundamental combustion knowledge.

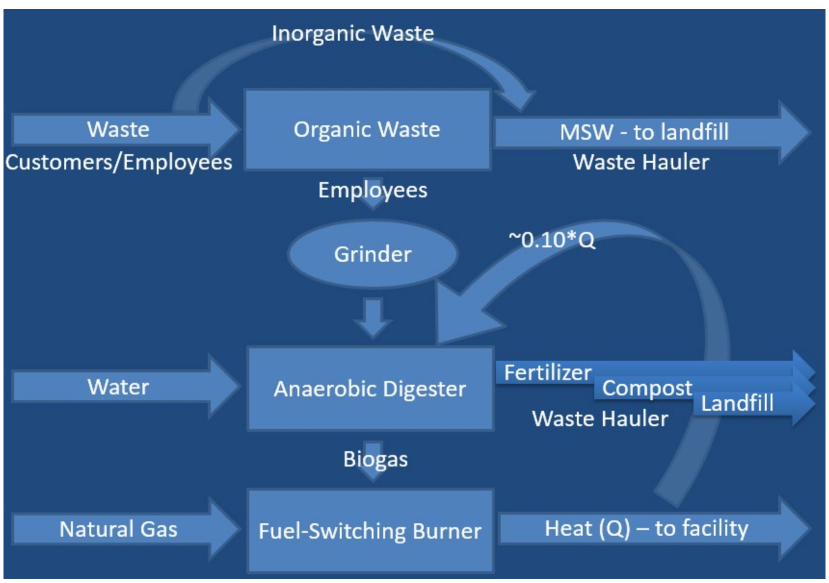
Technological, Economic, and Environmental Analysis of Decentralized Waste-to-Energy System

To evaluate the costs and benefits of distributed waste-to-energy systems that will be made feasible by a fuel-switching combustion system, researchers at LBNL analyzed the development of these systems for commercial facilities such as restaurants, large supermarkets, hotels, and hospitals that have moderate (75 to 750 pounds per day), but predictable organic waste streams. The study was motivated by the fact that most biogas-to-energy studies and analyses had been on centralized large facilities.

In surveying the biogas energy potential in the United States and particularly California, the LBNL study finds that while progress has certainly been made with implementing anaerobic digestion at wastewater treatment plants and farms, there remains significant untapped potential. According to the U.S. Environmental Protection Agency, the potential exists for an additional 400 MW of biogas-based electricity generation capacity and nearly 30,000 MMBtu/day of thermal energy at wastewater treatment plants alone (ERG and RDC, 2011). Waste-to energy potential for smaller waste generators remains largely untapped. Another example is the 3.3 million metric tons of dry biomass and 1.7 million metric tons of food waste that California sends to landfills each year that have the combined potential to generate 134 megawatts (MW) of electricity (Matteson and Jenkins, 2007). To exploit these waste energies, collecting a community's food waste from restaurants, supermarkets, and hospitals and processing them in large-scale centralized anaerobic digestion plants have been considered. However, according to an estimate by the National Energy Research Laboratory analysis (NREL, 2013), the predicted net present value of a centralized anaerobic digester for food waste in St. Bernard, Louisiana, showed a loss of $6.7 million, meaning that lifetime system revenue will be insufficient to overcome capital, operational, and maintenance costs inhibited by low energy and landfill tipping prices. The high capital costs were associated with large-scale digesters and transportation costs of water-laden organic wastes. By decentralizing the digestion process and allowing smaller facilities to produce their own biogas, some of these challenges can be avoided.

The framework for the LBNL analysis was a conceptual ecosystem of a small-scale decentralized waste-to-energy system depicted in Figure 1. The first step in the process is to separate the waste stream into inorganic wastes for disposal and organic wastes for processing by a grinder and then feed to the anaerobic digester to produce biogas. The biogas is then delivered to the fuel-switching burner to produce heat for on-site use. About 10 percent of the total heat produced by the burner is diverted to operate the anaerobic digester. The fuel-switching burner enables the system to use biogas for normal operation and switch to natural gas or propane for backup without the need to shut down and restart the heater. Remnants from the anaerobic digester can be used as fertilizer and compost, with a portion sent to the landfill.

Figure 1: Conceptual Ecosystem of a Decentralized Waste-to-Energy System



Since the objective of this project was to develop a fuel-switching combustion system, the LBNL analysis focused on the current technologies for and availability of small-scale anaerobic digesters with capacity to process 75 to 750 pounds of organic waste per day, typical of the volume produced by hotels, hospitals, and large restaurants. The first finding of the study was that digesters of these capacities are not readily available commercially. Though this finding may appear to impede the development of decentralized waste-to-energy systems, it can also be an opportunity. To meet the fuel requirement of the combustion equipment, much of the current technologies for anaerobic digesters are devoted to fine tuning the equipment to produce biogas within a well-defined and narrow range of compositions. Fuel cleanup is also a major development effort. However, by using a fuel-switching burner and a fuel sensor that accepts a broad range of fuel types and fuel compositions, the requirement for the digester to produce biogas whose properties fall within a narrow band of specific compositions will not be necessary. Consequently, the performance requirements of the digester can be relaxed, allowing for flexible and broad designer possibilities to economize and optimize the digester and the burner in a well-matched system.

To maximize the yield of biogas from wastes, developing an anaerobic digester, regardless of size, must consider a host of issues pertaining to the biological, chemical, and physical properties of the waste stream. For a small-scale digester, optimizing the design to handle the variations in the waste stream properties such as the pH levels, moisture content, ratio of the volatile solids to total solids, carbon-to-nitrogen ratio, and ammonia concentration is most often more challenging than in the associated large-scale counterpart. To increase methane production from waste, almost all studies have shown the effectiveness of increasing the digester process temperature. A higher digester temperature, however, will increase the concentration of ammonia in the biogas. The toxicity of ammonia will inhibit the digester process. In surveying the literature for large digester development, the LBNL study compiled and reported a list of ideal conditions that address the issue of balancing yield of methane and lowering ammonia production. In addition, the study also found that co-digestion of feedstock (for example, mixing food waste with green waste) is an effective approach for increasing methane yield. These findings indicate that the fuel-agnostic property of the combustion system developed for this project can be exploited to offset some challenges for the digester.

The LBNL study also included the investigation of air emissions, waste containment, and permit requirements for implementing distributed waste-to-energy systems in California. Anaerobic digestion systems are regulated in the same way as composting facilities that require notifications to the California Department of Resources Recycling and Recovery (Cal Recycle) for each new digester and proposed size. An annual digestate sampling from each digester is also required. For the remainder of the system, it would be necessary to acquire a conditional land use permit from the appropriate county, a water discharge requirement from the regional water quality control board, and an authority to construct permit from the local air pollution control district. Although the permitting process may vary significantly among regions, the navigation of regulation will not preclude feasibility because of the small-scale nature of the system and past experiences with digestion systems at dairy farms.

Although the anaerobic digestion of waste to produce biogas is beneficial in many ways, the cost analysis performed at LBNL showed that there are numerous barriers to overcome before small-scale digestion systems can become widespread. The most obvious and impactful costs are the capital expenditures associated with the procurement and installation of the digester and combustion system. High capital costs have to this point deterred the adoption of standard biogas systems at the average dairy farm and many other facilities. There are also operational and labor costs associated with the maintenance, permitting, and testing of the system, which, although not as substantial as the initial capital expenditures, must be taken into account in a detailed economic analysis. Moreover, costs regarding issues such as space requirements, fire protection, and employee training that vary depending on location and type of system have been identified but deemed difficult to quantify by the LBNL researchers.

While the installation costs of this system may at first seem daunting, revenue opportunities exist that include natural gas savings, reduction of tipping costs at landfills and composting centers, creation of carbon credits for use in a cap-and-trade program, and the ability to sell digestate as fertilizer or compost. In addition, there are societal benefits associated with revenue generation, including the reduction of greenhouse gas emissions, improved air and water quality, reduced odor when compared to traditional waste storage, and improved public relations.

The economic viability study conducted at LBNL showed that after considering revenue from natural gas offset, landfill avoidance, carbon credit generation, and the sale of digestate, an average restaurant could expect an annual revenue of between $4,000 and $5,500, corresponding to a natural gas offset of between 41 percent and 57 percent. In the past, high capital costs for anaerobic digesters and biogas combustion equipment together with low energy prices have limited the production and use of biogas in the United States. It is anticipated, however, that the fuel-switching low-swirl burner (LSB) will significantly lower capital costs by decreasing the number of burners and boilers each facility must install and maintain. Assuming a system cost of $40,000, the simple payback period at a restaurant would be between 7 and 10 years, without including installation, permitting, or operation costs. As with other economies of scale, these costs would be expected to decrease as the systems become more widespread.

The LBNL report concluded that the investigation was cursory and provided necessary but not sufficient proof for the feasibility of small-scale waste-to-energy systems. Determination of system feasibility would require deeper studies with detailed mass and energy balances, in-depth economic analyses, and life-cycle comparisons of alternate organic waste disposal options. However, there is no compelling reason to suggest that on-site biogas use via a fuel-switching LSB is unattainable.

CHAPTER 2: Enabling Technologies for Demonstrating Real-time Fuel-switching

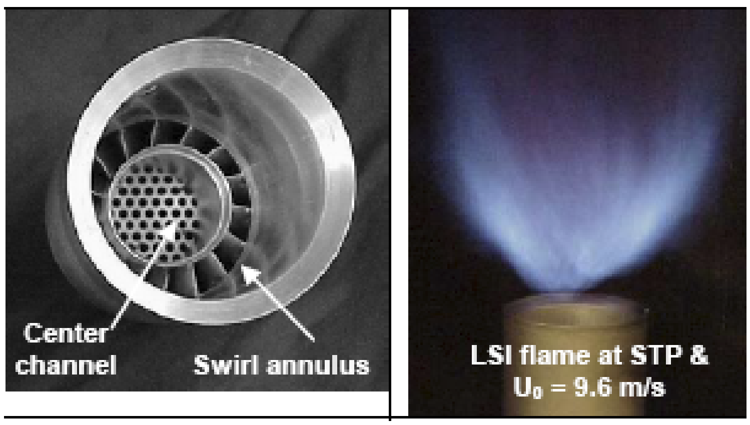
The previous chapter discussed the technical challenges of developing a cost-effective fuel-switchable combustion system that delivers performance, in particular, ultralow emissions targets of significance to California. The characteristics of such a system must have an engineering design for the combustion nozzle, also known as the burner assembly. The engineering design also needs to support stable burning of lean-premixed turbulent flames (to ensure ultra-low emissions) under all operating conditions without significant flame shift (which affects heat transfer efficiency) or being prone to flame blow-off, flashback, instability, and combustion dynamics (which compromise performances such as turndown, safe operation, and reliability). Furthermore, the fuel/air delivery system must function synchronously with the burner assembly to sense and detect the changing properties of the fuel stock (in other words. constituents of the fuel). The system must then control and supply the right amount of fully premixed fuel and air at a ratio (which varies with fuel constituents) for the burner to produce maximum efficiency, high flame stability, and ultralow emissions at all operating points. The approach of this project was to address the first challenge by using the LSB technology developed by LBNL. The second challenge was addressed by integrating the speed-of-sound fuel sensor developed at UCI into the control system. The scientific principles of these technologies are detailed below. These principles are followed by a short description of the control protocol that has been developed to enable fuel switching.

Low-swirl Burner

The LSB operates using an aerodynamic flame stabilization mechanism that exploits the principle of turbulent displacement flame speed, a fundamental property of premixed turbulent combustion. The LSB hardware is relatively simple with no moving parts (Figure 2, left.) It is engineered to produce a divergent flow (that is, a flow that spreads out) of fuel/air reactants where the flame suspends and burns freely (Figure 2, right). As elaborated in this report, laboratory studies and analyses published in archival journals showed that the fuel-agnostic characteristic of the LSB is due to the invariant nature of the divergent flow structure (known as self-similarity in mathematics) and linear dependency of the turbulent displacement flame speed on turbulence intensity. The critical characteristic that allows fuel switching is the effect associated with changing fuel stock (except for fuels with very high percentage of hydrogen), manifested in variations in the laminar flame speed, which become exceedingly small at typical flow velocities of an industrial system.

A patented swirler (Figure 2, left) is the heart of the LSB for generating a divergent flow (Cheng and Littlejohn, 2007; Cheng and Littlejohn, 2008; Cheng et al., 2009; Littlejohn et al., 2010; Smith et al., 2010). The function of the swirler is opposite the associated counterparts in conventional high-swirl burners, where the swirler is engineered to produce a recirculating flow. The LSB swirler suppresses recirculation by splitting the stream of fuel/air reactants into two passages and then recombining them. The main portion of the fuel/air reactants passes through the outer swirl annulus and the rest though the center channel. The guide vanes in the swirl annulus impart swirl to the outer flow, while the inner flow passes the center channel (covered by a perforated plate as shown) and remains unswirled. The two streams recombine and interact in a nozzle tube downstream of the swirler before discharging into the combustion chamber. When the recombined stream enters the combustion chamber, it expands radially (outward or diverge in fluid mechanics term) due to the angular momentum of the swirling motion. As a consequence of flow divergence, the velocity in the nonswirling central flow region decelerates. The decelerating flow allows the premixed turbulent flame to self-propel and settles at a position where the local flow velocity is equal and opposite to the turbulent flame speed. A "floating flame" (Figure 2, right) is a characteristic feature of the LSB when it fires into the open.

Figure 2: Photographs of the LSB Swirler and Flame



From laboratory studies, the research team developed scaling rules for adapting the LSB to different sizes and heat release capacities. The basic parameter is the swirl number, *S*, which is proportional to the divergence rate of the LSB flow field.

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

In Equation (1), α is the swirl vane angle, $m=m_c/m_s$ is the ratio of the flows through the center channel, m_c, and the swirl annulus, m_s. $R=R_c/R_b$ is the ratio of the radii of the center channel, R_c, and the LSB nozzle, R_B. The two parameters α and R on the right hand side of Equation (1) are fixed by the swirler geometry. The remaining parameter, *m*, is the means to tune the LSB to the targeted swirl number range. This tuning is accomplished by changing the blockage ratio of the perforated plate that covers the center channel. The perforated plate creates the appropriate pressure drop to achieve the proper flow splits, *m*. An additional function of the perforated plate is to control the turbulence intensity.

For natural gas, the guidelines are $0.4 < S < 0.55$, $0.5 < R < 0.8$, $37^o < \alpha < 45^o$ with a nozzle tube of $2R_B$ to $3R_b$ in length. These guidelines were applied to Maxon's commercial LSB products of 1"< R_b < 11", as well as LSBs for water heaters and steam and hot water boilers. For gas turbines, the design rules are similar. The LSB for Solar Turbine Taurus 70 engine and for a microturbine were 1″ < R_b < 1.25″. A larger R_b = 2″ LSB was also developed and evaluated at the facility of a major manufacturer of utility-size gas turbines. Once the burner nozzle was configured, the LSB can operate over a wide range of load, offering up to 60:1 turndown.

Figure 3: The LSB Flame Remains Stationary During a 5:1 Turndown

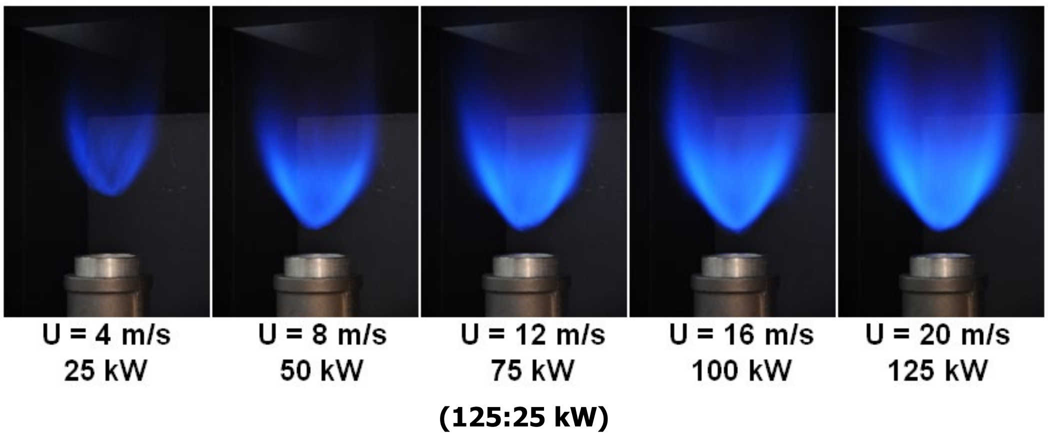
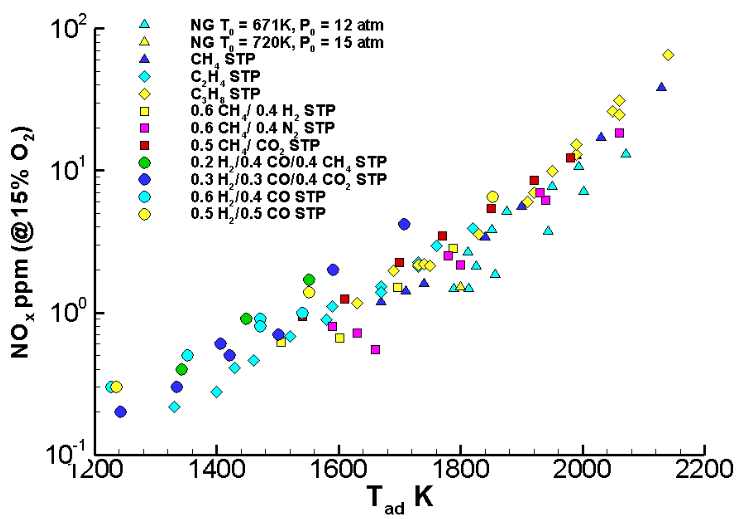


Figure 3 shows photographs of the LSB flame within a 5:1 turndown. As can be seen, the lifted flame remains at the same position throughout turndown. This attribute is important for the LSB to maintain consistent and optimum heat transfer at different load points. For fuel-flexible operation, laboratory studies show that the LSB configured for natural gas can support stable combustion of all hydrocarbons and diluted hydrocarbons (Littlejohn et al., 2010). The only exception is high-hydrogen fuel (that is, fuels containing more than 50 percent hydrogen by volume). In a study conducted at Georgia Institute of Technology (Littlejohn et al., 2010), the fuel-switching capability of a small R_b = 0.5″ LSB was verified under well-controlled laboratory settings at standard atmospheric conditions as well as simulated microturbine operating conditions. The NO_x emissions for a range of fuels including 0.5 CH_4 to 0.5 CO_2 typical of biogases are shown in Figure 4.

Figure 4: NOx Emissions of LSB Showing Log-linear Dependency on Adiabatic Flame Temperature



These data clearly show a log-linear dependency of LSB NO_x emissions with the adiabatic flame temperature T_{ad} but not on the type of fuel. The implication is that LSB NO_x emissions can be controlled conveniently by adjusting the fuel-air ratio of different fuels to a desired T_{ad}.

To expand the scientific foundation for LSB developments, the LBNL researchers developed an analytical model to explain how the LSB flame responds to load change and variations in the fuel compositions. The model describes the coupling between the divergent flow produced by the LSB nozzle and the turbulent displacement flame speed, $S_{T,LD}$. By using a laser-based particle image velocimetry (PIV) technique to measure the mean velocities and turbulence in the LSB flame, it has been shown that the nearfield of the divergent flow is self-similar, which means that the normalized flow distribution is invariant regardless of the flow velocity. Two parameters can then be invoked to characterize self-similarity of the divergent flow field: the virtual origin of the divergent flow, x_0, and the nondimensional axial aerodynamic stretch rate, a_x. The turbulent flame characteristics can be expressed in terms of the turbulent displacement flame speed, $S_{T,LD}$, and the position of the flame, x_f. Analysis of $S_{T,LD}$ for natural gas, hydrocarbon, and hydrogen flames shows that they increase linearly with turbulent fluctuation, u'. The model (Equation [2]) is basically an equation for the axial velocity at x_f. It shows that the self-similarity of the divergent flow field and a linear turbulent flame speed correlation with turbulence enables the LSB flame to remain stationary through a wide range of velocities and fuel-air equivalence ratios, ϕ.

$$1 - \frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_{T,LD}}{U_0} = \frac{S_L}{U_o} + \frac{K\,u'}{U_0} \qquad (2)$$

The two terms on the far right-hand side simply state that $S_{T,LD}$ increases linearly with turbulence fluctuation, u', at a slope of K above the baseline value of the laminar flame speed, S_L. This slope is an empirical value determined from experiments. The first term of the right-hand side tends to a small value at typical gas turbine bulk flow velocity U_0 of > 10 meters per second (m/s) because the laminar flame speeds of lean hydrocarbon and hydrogen fuels are on the order of 0.2 to 1 m/s. The second term on the right-hand side is the turbulent intensity, u'/U_0. This term is constant in accordance with the behavior of near isotropic turbulence produced by the perforated plate at the center core of the LSB. On the left-hand side, self-similarity means that the normalized axial aerodynamic divergence rate, $a_x = dU/dx/U$, in the second term is constant. The consequence is the flame position $x_f - x_0$, reaching an asymptotic value at large U_0. Therefore, when S_L is held constant for a given fuel at a given fuel air ratio, the flame does not change its position with load when $U_0 > S_L$. The asymptotic behavior was confirmed by visual observations in industrial burners and in gas turbines.

This analysis explains why the LSB nozzle can be used for different fuel stocks. In a recent parametric study, the authors showed that the LSB nozzle design is forgiving. The variations in the number of guide vanes, vane shapes, and vane angles do not affect the overall performance. Moreover, the LSB has lower low drag than typical high-swirl burners. This feature can be exploited to lower the parasitic energy such as the electric power of the air blower. These features will be incorporated to enhance the LSB nozzle for the demonstration unit. Therefore, the LSB technology is mature, beyond the proof-of-concept stage, and ready for real-time fuel-switching demonstration.

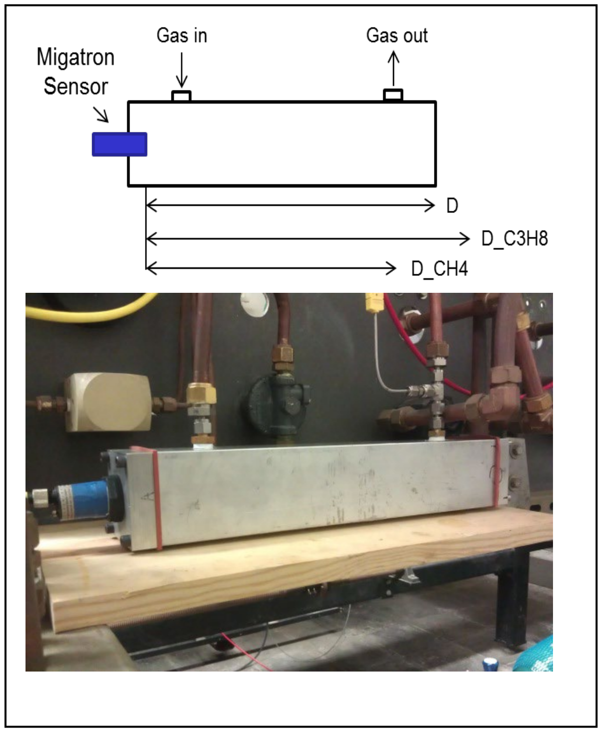
Fuel Identification and Properties: Speed-of-Sound Sensor

The UCI-developed fuel sensor quantifies the molecular weight of the fuel stream by measuring the associated speed of sound using low-cost piezoelectric transducers. By assuming the fuel mixture follows the ideal gas law, the density of the fuel mixture can be calculated. Since the fuel density varies with the ratio of the key fuel components—for example, methane, CO_2, and N_2—measuring fuel density provides the data to quantify fuel composition. As illustrated in the schematics in Figure 5, the information on the fuel composition provides the feedback to control the fuel-air ratio according to a set of control algorithms to maintain the same flame temperature in the boiler/combustor. The control algorithm developed for the fuelstock used in this project consists of the adiabatic flame temperature expressed in a phase space with the fuel components and air as the parameters. Calculation of this phase space requires the use of software that uses a set of basic chemical kinetic reaction rate coefficients for natural gas and biogases (e.g., CHEMKIN premixed module).

The most common way to measure fuel composition in a pipeline is to use a gas chromatograph, but these devices are generally expensive, have a large footprint, have low sample frequency, and require a considerable amount of regular maintenance and calibrations. A novel approach of estimating composition is to measure the speed of the sound of the fuel source. Determining the composition of a binary gas (such as methane and carbon dioxide) is straightforward and was demonstrated by UCI (Jordan et al., 2013) using a prototype sensor that is the basis for the sensor to be developed for the proposed effort.

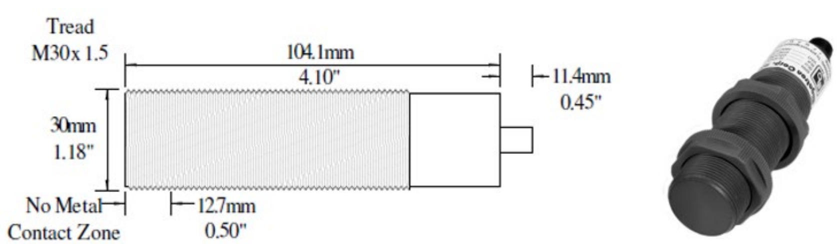
The schematic of the fuel composition sensor developed for measuring fuel Wobbe Index for California Energy Commission Contract 500-10-048 (POEF02-V10) is shown in Figure 5 (Jordan, 2013a). The device is a carefully engineered acoustic chamber in which all or part of the fuel gas passes through. An acoustic generator/receiver mounted in the acoustics chamber is the only electronic instrument.

Figure 5: Speed-of-Sound Fuel-sensor Schematics (Top) and Hardware (Bottom)



The fuel sensor shown in Figure 5 was fitted with an intrinsically safe ultrasonic sensor made by Migatron (Figure 6). This sensor was designed to measure the distance from the sensor to a nearby object by emitting and receiving ultrasonic sound waves. For a fixed medium, such as air, the speed at which a sound wave can propagate is known and can easily be modeled. By recording the time delay between emitting a pulse and receiving the reflected signal, the distance of an object can be calculated using basic kinematic formulas (distance = speed*time). Now when the object is fixed (in this case a wall at the end of a tube) and the medium is varied, the time between emitting and receiving a pulse will fluctuate. Rearranging the speed of the sound wave can be measured for an unknown medium. Since every substance has a corresponding speed of sound, it is easy to correlate the results to a single or binary mixture of gases.

Figure 6: Schematics (Left) and Hardware (Right) of Migatron RPS-409A-IS Intrinsically Safe Ultrasonic



Once the speed of sound C of the gas can be estimated, it can be correlated to the Wobbe number and carbon-to-hydrogen ratio by plotting against C^2/T, where T is the absolute temperature in the chamber.

While the measured time varies for a fixed object with a fluctuating medium, the output of the Migatron sensor is only the apparent distance if the medium was air. In other words, the sensor thinks the object is moving while really it is still stationary, and it is the medium that is changing. Therefore, the following equation was derived to relate the various apparent distances to the speed of sound of an unknown gas:

$$C_{gass} = \frac{D}{D_{gas}} * C_{air} \qquad (3)$$

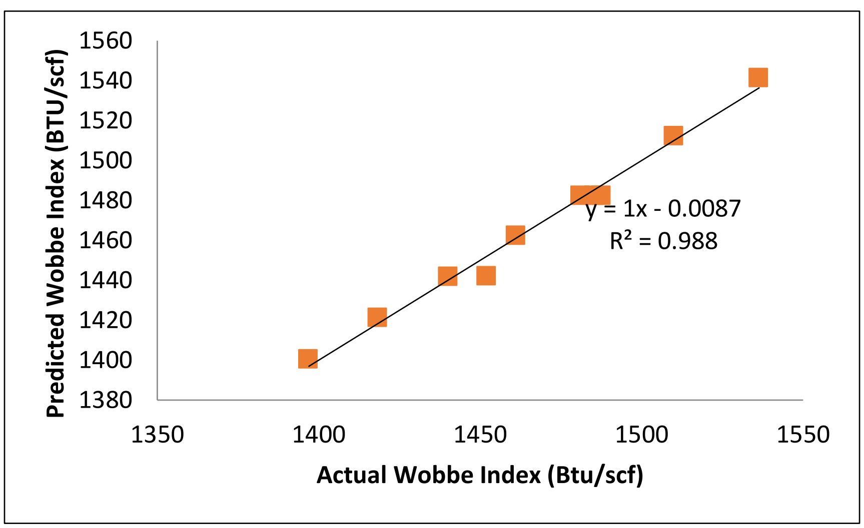
where C_{gas} and C_{air} are the speed of sounds in the gas and air, respectively. D_{gas} is the apparent distance of the wall, and D is the actual distance of the wall. For example, if methane was the medium, the apparent distance D_CH4 would be less than the actual distance D due to the lower density of methane (higher speed of sound), as seen in Figure 5. For the sensor to work properly, it needs a flat reflective surface. For this reason, a 3" x 3" x 14" rectangular aluminum tube was constructed, which can be seen as a schematic and actually implemented in Figure 5.

To account for fluctuation in the temperature of the working fluid, while relating the speed of sound to the medium properties, the following proportionality was derived using basic ideal gas laws.

$$\frac{C_{gass}^2}{T} \propto \frac{\gamma}{MW} \qquad (4)$$

In Equation (4) γ is the specific heat ratio, MW is the molecular weight, and T is the absolute temperature in Kelvin. The above equation states the speed of sound squared divided by the temperature is proportional to the physical properties of a gas. This solution can also be extended to relate the speed of sound to the C/H ratio (mole) and Wobbe number. Tests of the Migatron sensor were conducted, and relations between the speed of sound and the C/H ratio, as well as the Wobbe Index, are shown in Figure 7. As shown, the sensor is able to accurately indicate the fuel Wobbe Index to within 0.5 percent.

Figure 7: Predicted vs Actual Wobbe Index (HHV Basis)



For the mixtures planned to be investigated, the Wobbe numbers are both linearly related to the term C^2/T. The Migatron sensor has proven to be accurate to within 2 percent of the actual speed of sound and 0.5 percent accurate in determining the Wobbe number and C/H ratio for this range of mixtures.

For this project with biogas (that is, methane and carbon dioxide), the same principle can be applied. Some work suggested that such a sensor with large amounts of diluents may cause unreliable results (Lueptow and Phillips, 1994). As a result, additional sensors are proposed to expand the capability of the existing sensor. By adding either a thermal conductivity sensor or a CO_2 sensor to the existing speed of sound sensor or both, additional details regarding the biogas mixture can be resolved, including the presence of additional species. From the speed of sound, thermal conductivity, and CO_2 sensor, a set of nonlinear equations results can be solved to accurately estimate the Wobbe Index and mole fuel-air ratio for a wide variety of biogas mixtures. These additions will make the sensor more generally applicable for a wide range of fuels.

Thus, for this project, the plan was to implement this basic approach but with an ultrasonic sensor in a pulse/echo mode, a CO_2 sensor, and two thermal conductivity sensors.

A sensor with a Migatron worked well for the natural gas and mixtures of natural gas with propane and ethane blends. The research team noticed that when pure methane was used, the sensor went into a standby/saturation mode. This same result was seen for mixtures of natural gas and CO_2 that contain higher than 15 percent CO_2 by volume. This situation can be overcome with a redesign of the acoustic cavity or procurement of an ultrasonic sensor with an acoustic "beam" tailored for CO_2. When the working fluid undergoes a change in density, the beam width could also fluctuate, thus the chamber can be adapted to account for this. In the current design, the added reflections from the walls from the expanded beam trigger the standby/saturation mode. To counteract this problem, the inside wall distance must be increased (example: use a vessel that is 5″ x 5″ x 14″ instead of 3″ x 3″ x 14″). Alternatively, the length of the vessel could be producing acoustic nodes based on dynamics of a moving gas in a tube (example: pipe organ). These acoustic nodes could be fluctuating based on the different densities. Increasing the length of the vessel might shift the nodes, but the added length will face issues with beam width. Shortening the vessel would decrease wall reflection problems, but if the vessel is too short, the sensor could quickly leave the associated sensible region (4″ to 40″ sensible distance). For mixtures with fast speeds of sounds, the appeared distance might fall below the sensor threshold.

If neither solution solves the problem with the current Migatron sensor, then the next step would be to purchase a different ultrasonic sensor. There are various ultrasonic sensors with narrow beams and moderate sensor ranges available for $30 and $150. The planned CO_2 sensor to be added is available for $100 to $750. The planned thermal conductivity sensors are available at a cost of $50 to $100. Hence, even with the added sensors, the cost of the fuel composition sensor will still be less than $1,000. If this device is optimized for cost and quantity volumes considered, a cost on the order of $200 is expected, which is nominal considering the cost of a typical 2 MMBtu/hr boiler system.

Control System Protocol

Developments to increase the flexibility of the fuel/air delivery system and related control were significant to maintaining a smooth transition from one fuel to the other during fuel switching. The hardware of the system consists of the fuel and air controllers, the fuel injectors, and the fuel/air premixer. Due to the differences in basic properties and combustion characteristics of various fuels, the fuel/air delivery system has to respond to fuel stock variation by delivering a homogeneous mixture of fuel and air at appropriate proportions prescribed by a fuel-loading map. The fuel-loading map is obtained from computations of the combustion chemistry for the different fuels at a range of fuel-air ratios. To maintain system efficiency and low emissions, the control curve for the system will follow the contour of constant combustion temperature on the fuel-loading map to set the fuel-air ratio. For a system switching between natural gas and biogas, the fuel-loading map is two-dimensional. The map is two-dimensional because the active ingredient for both fuels is methane, such that the two parameters of the fuel-loading map are the fuel-air-ratio and the ratio of methane to carbon dioxide, which are the main diluents in biogas. For a system switching between propane and biogas, as it is being performed for this project, the fuel-loading map is three dimensional because of the addition of a third parameter, which is the ratio of the propane to methane.

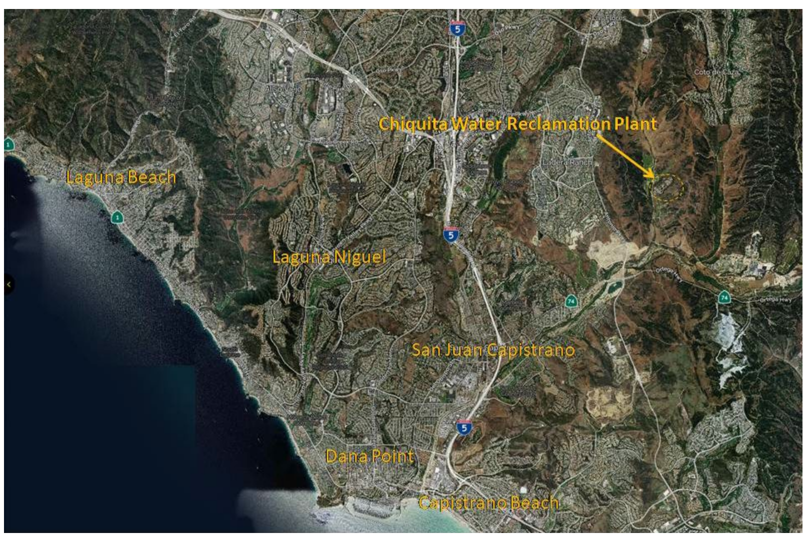
The control module is the brain of the system with software that controls the flame sensor, fuel sensor, ignitor, and air and fuel valves for all functions, including light off, shutdown, load change, and adjustment of the fuel-air ratio for different fuel stocks. For fuel switching, the control system uses data from the fuel sensor as feedback to respond to fuel change. The control algorithm developed for the fuel stock to be used in this project consists of the fuel-loading maps based on the calculated adiabatic flame temperature for the fuels at a range of fuel-air ratios expressed in two-dimensional (for biogas/natural) or three dimensional (for biogas/propane) phase space with the fuel components and fuel-air ratio as parameters. Calculation of these fuel-loading maps involves software that uses a set of basic chemical kinetic reaction rate coefficients for methane, propane, and biogases.

CHAPTER 3: Demonstration Equipment, Scope of Work, Demonstration Plan, and Metrics

Demonstration Site

To demonstrate fuel switching in a real-world industrial setting, the research team developed an advanced combustion system that embodies the technologies presented in Chapter 2. This system was designed as a retrofit for a steam boiler of 1.99 MMBtu/hr installed at the CWRP of the Santa Margarita Water District in Orange County. The plant is in the city of Rancho Santa Margarita (Figure 8) and treats wastewater generated by the district's 62,674-acre service area. CWRP is a leader in technologies that treat and recycle wastewater for irrigation. The facility has an anaerobic digester that produces biogas from collected sewer water. The biogas is used on site to generate electricity from a microturbine and steam from two boilers for heating the anaerobic digester. The demonstration for this project took place in one of these boilers.

Figure 8: Location of the Chiquita Water Reclamation Plant for the Demonstration



Boilers for Real-time Fuel-switching Demonstration

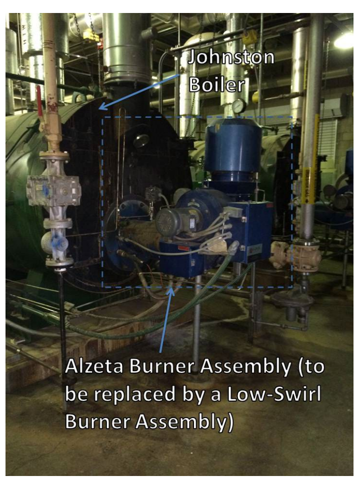
Overview of the CWRP Boilers

The two boilers at CWRP are identical four-pass 2.3 MMBtu/hr heat output steam boilers manufactured by Johnston Boiler (Figure 9). They are typical of those used in a wide range of industries, including agriculture, manufacturing, and food processing. A common feature of these industrial boilers is that they are designed to accept different types of burners to meet customer needs and local air quality regulations. Burners in these boilers require regular inspection, service, and ultimate replacement because they generate heat and, therefore, receive intense thermal stresses that lead to degradation.

Figure 9: The Two Johnston Boilers at CWRP

The two Johnston boilers at CWRP were fitted with surface-stabilized burners manufactured by Alzeta Corporation (Figure 10). Though the Alzeta burners are rated at 2 MMBtu/hr, they were operated at 1.99 MMBtu/hr at CWRP. The boilers were installed side-by-side (Figure 9), and each had a separate control panel for independent operation. The Alzeta burners were designed to operate on biogas as a principal fuel and propane as an occasional backup. The two fuels are supplied to these boilers via separate control valves, actuators, switches, and shutoffs. The two fuel systems were engineered for independent operations. Switching from one fuel to the other requires a purging cycle that necessitates a complete shutdown of the boiler. After shutdown, the start-up sequence begins with a one-minute air purge prior to flame light-off (the sequence of events leading to initiating combustion in a boiler). The equipment developed for the demonstration is a combustion system with a fuel-switching low-swirl burner and associated control. As mentioned above, almost all commercial boilers are designed to accept different burners; therefore, the low-swirl burner consisting of the burner nozzle, fuel injector, fuel controllers and air blower, is a retrofit for the Johnston boiler. The basic configuration that can be readily scaled and adapted to boiler systems of different sizes and capacities is, in essence, a generic retrofit.

Figure 10: Alzeta Burner Installed at CWRP Boilers

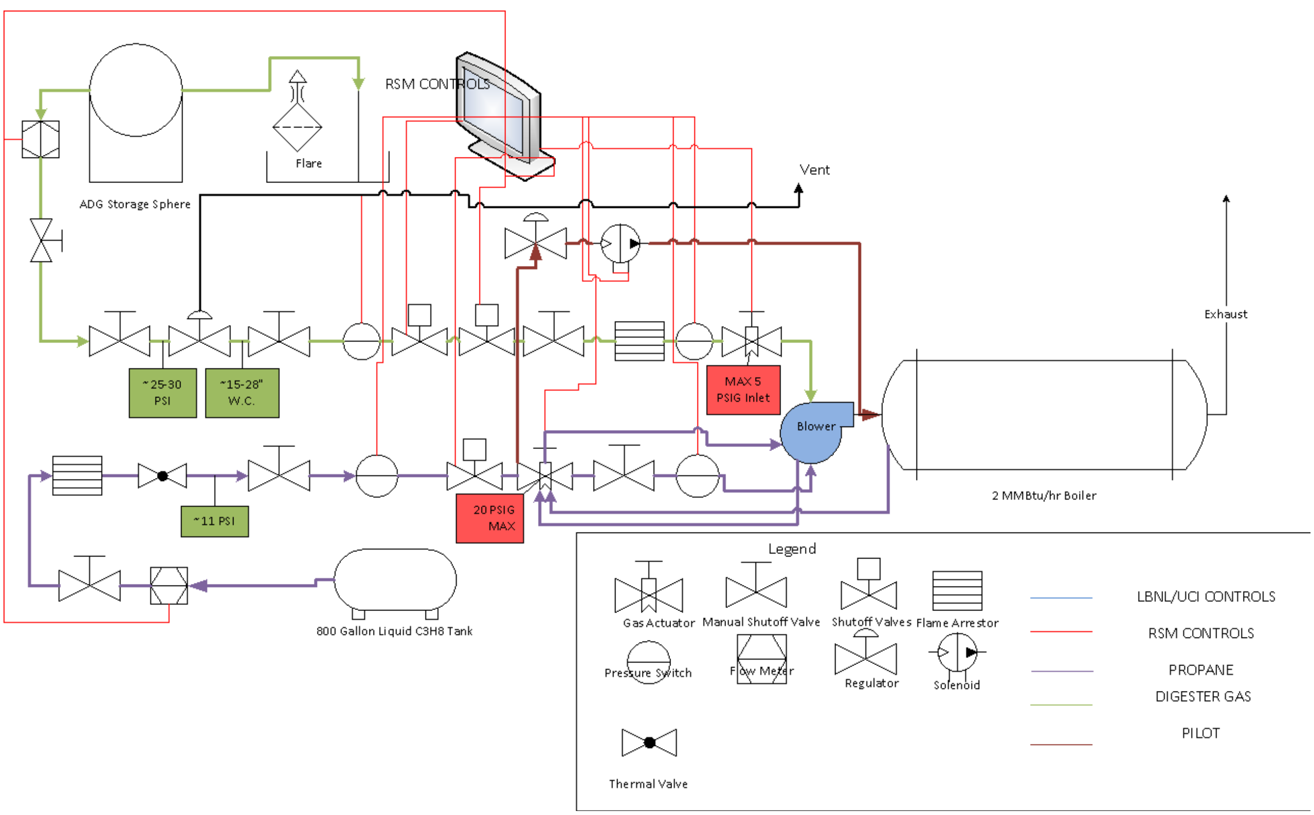


System and Control of the Existing CWRP Boiler

To develop the low-swirl burner system, the research team first established the design specifications by documenting the dimensions of the boiler, engineering specifications for the fuel supply systems, and the normal operating conditions and procedure (with the Alzeta burner) for the boiler systems at CWRP. Information collected through examination of the manufacturer's engineering documents, inspection of the interior of the boiler, and observation of the normal start-up and shutdown cycles of the boilers for biogas and propane was used to determine the size of the low-swirl burner nozzle and the approach for a modified fuel supply circuit and control system for enabling real-time fuel switching demonstration.

The schematics for the fuel circuits and control for the boiler at CWRP are in Figure 11. Each boiler uses two fuel supply circuits. One is for the biogas produced on site and the other for propane supplied from an 800-gallon storage tank. The boiler normally operates on biogas typically of about 40 percent CO_2 and 60 percent CH_4. Propane is used occasionally as backup. Each fuel is supplied to the Alzeta burner through separate plumbing systems, each with dedicated actuators, switches, and valves for control and shutoff. As the two fuel lines are engineered for separate operations, switching from one fuel to the other requires a purging cycle that necessitates a complete shutdown of the boiler. After shutdown, the air purge and start-up sequence for biogas or propane typically lasts about a minute. This duration provides a realistic time-scale criterion for the fuel-switching sensing and control protocol.

Figure 11: Schematics of the Two Separate Fuel Lines for the Alzeta Burner and Control Components of the Johnson Boiler at CWRP



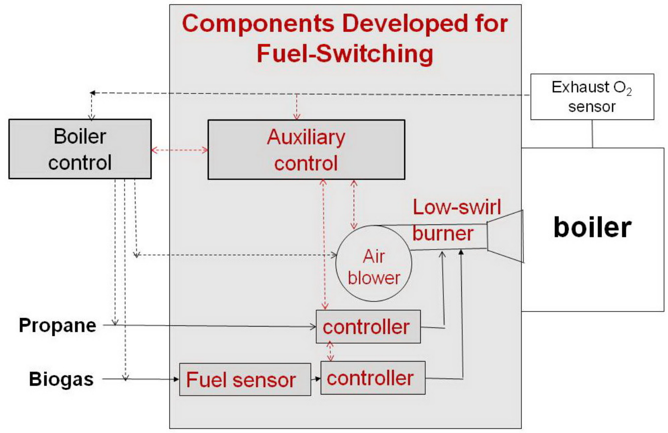
System Design for Fuel-switching Demonstration

From the information on operation and control of the boilers, the research team identified some issues regarding the approach to modify one of these units with a low-swirl burner for real-time fuel switching. The biogas and propane were delivered to the Alzeta burner at different pressures. The biogas had a delivery pressure of 15” to 18” water column, whereas the propane has a delivery pressure of 11 pounds per square inch (psi). The large difference in the fuel delivery pressures was not amenable to the research team’s original idea, which was to blend the two fuels before supplying to the low-swirl burner. The reason was that the propane fuel lines and control valves would have to be significantly modified to deliver the two fuels at similar pressures. Moreover, the fuel and air controller for the boilers, which were enhanced for the two separate fuel lines, did not have adequate precisions needed for controlling the transitional set points during fuel switching. A more precise control of the air supply was also needed to avoid veering off the ultralow emissions target during fuel switching. To minimize the high cost involved in redesigning, procuring, and installing a new fuel control system, the research team decided to design the fuel delivery circuit of the low-swirl burner to use much of the components of the existing biogas and propane supplies. The fuel supplies lines were augmented by electronic flow controllers and an auxiliary control system with the algorithm for fuel-switching operation. The auxiliary control system, fabricated and installed by a boiler controls subcontractor, operates in parallel with the existing boiler controls to ensure that the existing boiler control and the auxiliary controls work synchronously.

Because the demonstration equipment is a temporary installation and needed to be removed to restore the boiler to the “as-found” condition, the fuel supply circuit and controls for the low-swirl burner used much of pipes and valves for the Alzeta burner. The fuel sensor was installed in the biogas supply line to detect variations in the constituency. Electronic flow controllers connected to an auxiliary control system were added to the biogas and propane fuel lines. Much of the boiler controls remained unchanged and were used for boiler start-up and shutdown. During fuel switching, the algorithm of the auxiliary control used feedbacks from the fuel controller and other sensors to transition in part or fully to another fuel stepwise that maintained flame stability, not exceeding desired pollutant emission levels without after treatment technologies and ensuring operability through desired turndown ability on either fuel of 2 MMBtu/hr heat capacity.

Figure 12 shows the schematics of the system for demonstrating real-time fuel switching at the CWRP boiler. Shown in red are the new components and feedback paths. The new components were the low-swirl burner that includes the burner nozzle, a flame quarl, and a fuel injector. A variable-speed air blower supplied airflow to the low-swirl burner, and electronic flow controllers supplied the fuels. The fuel sensor was connected to the biogas supply line to monitor the variation in fuel composition. The auxiliary control systems communicated with the existing boiler control systems and used feedback information from the air blower and fuel flow controllers for real-time fuel switching.

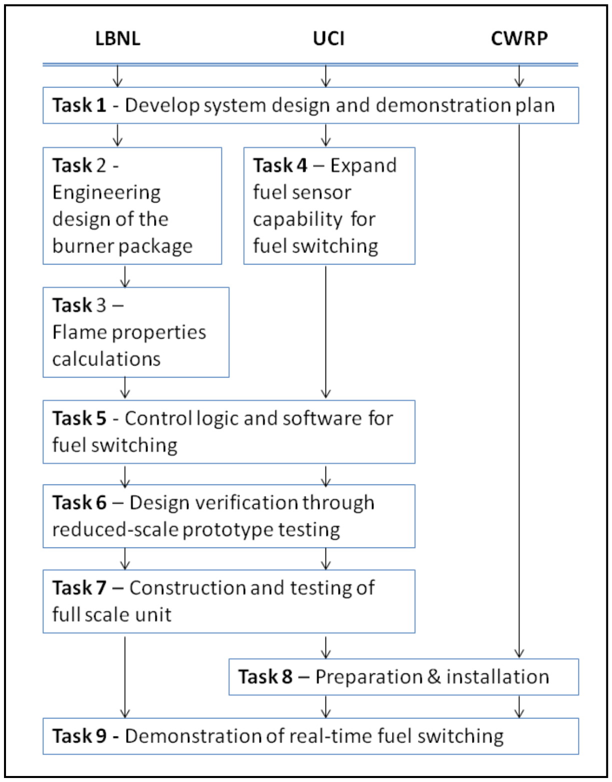
Figure 12: Schematics of the System for Real-time Fuel switching Demonstration



Scope of Work

Figure 13 shows the scope of work and technical tasks for this project. The first task was an investigation of the engineering details of the boiler at CWRP and related operation. The research team used the results of this investigation (reported in the second section of this chapter) to develop the overall design of the fuel-switching burner system as reported in the section above. The team developed the two technologies, the low-swirl burner (Task 2) and the fuel sensor (Task 4), in parallel. The low-burner development involved laboratory experiments to evaluate and compare the performances of various designs. The fuel sensor development involved laboratory tests and then was installed on site at CWRP to verify performance. As the brain for the fuel-switching low-swirl burner system, the auxiliary control for the boiler used scientific data on the flame properties of biogas and propane flames that were obtained through chemical kinetic calculations (Task 3). These flame properties provided the foundation for the control logic to maintain flame stability during fuel switching. Refinement of the system that consisted of the low-swirl burner, the fuel sensor, and the control logic was performed in the laboratory using a reduced 1/5-scale burner prototype (Task 5). The reduced-scale burner allowed for verification of the performances of the system at conditions that extended beyond the range of conditions for typical boiler. The purpose was to gain scientific and technical insights for broader adaptation of the technology to enable fuel switching in other heating and power systems.

Figure 13: Project Tasks and Scope of Work



Completion of laboratory verification for the 1/5-scale low-swirl burner design led to finalizing the design of the full-scale burner and selecting the electronic hardware for fuel and air control. The operation of the low-swirl burner with the associated electronic controllers was verified at UCI (Task 8). The research team performed these verifications using typical laboratory algorithms. In parallel, the auxiliary control system, with information from the chemical kinetic calculations, were developed in cooperation with a commercial boiler control company (Task 8). The boiler company was also responsible for installing the full-scale LSB in the boiler and integrating the auxiliary control system hardware and software with the boiler control (Task 9).

Demonstration Plan and Metrics

In general, the proposed demonstration followed these steps:

1. Installation of the new burner, fuel sensor, fuel controllers, and auxiliary control system to existing hardware to enable real-time fuel-switching between biogas and propane.
2. Operation of the system without flame to verify the integrity of the auxiliary control hardware and software and compatibility with the original boiler control.
3. Operation with biogas and propane at full load and partial load to obtain baseline performance of the low-swirl burner and compare the performance with that of the Alzeta burner.

4. Based on the results from step 2, choosing an appropriate condition to conduct the fuel-switching test.
5. Adjustment of the system, if necessary, to promote fuel-switching operation
6. Repetition of fuel-variation tests at random intervals to assess system response and long-term operational durability.
7. Third-party measurement and verification of fuel-switching capability and performance.
8. Removal of new hardware and controller and reinstallation of original burner to restore boiler and operation to "as-found" condition.

The metrics being measured or monitored for the real-time fuel-switching demonstration were flame stability, emissions, and turndown for biogas and propane operation, and fuel switching.

CHAPTER 4: Hardware and Software Developments

This chapter details the developments of the enabling technologies for the real-time fuel-switching demonstration. The research team conducted these developments at the research laboratories of LBNL and UCI. The first section describes the development of the fuel-loading map, which is the combustion data needed for the fuel-switching control protocol as well as for the designs of the low-swirl burner and the fuel sensor. The second section describes the development of the low-swirl burner and related fuel injector by laboratory tests of a 1/5-scale prototype. The third section reports on the development and testing of the fuel sensor to detect the variability in the composition of the biogas. The fourth section addresses the development of the control logic for fuel-switching demonstration in the CWRP boilers.

Fuel-switching Control

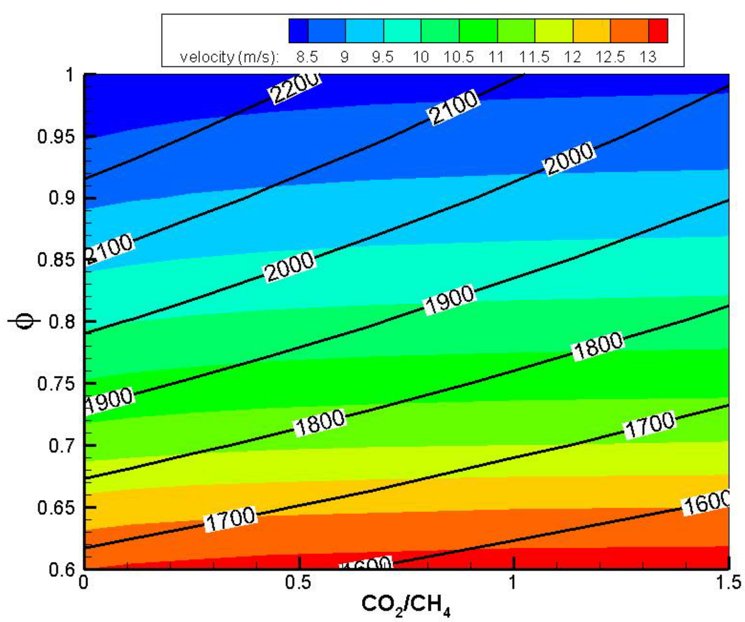
The important performance metric of a commercial and industrial heater is to deliver the specific amount of heat to the process while maintaining low emissions and system efficiency. From a control standpoint, the process variables of a fuel-flexible combustion system are: (1) the process temperature, which is proportional to the adiabatic flame temperature, T_{ad}; and (2) the energy output, which depends on the heating value and the flow rate of the fuel. When fuel type or fuel composition changes, the fuel flow rate needs to be changed to achieve the same heat output. The air flow rates also need to be adjusted to maintain the same flame temperature. In combustion science, the adiabatic flame temperature, T_{ad}, is expressed in terms of the equivalence ratio, ϕ, which can be interpreted as an indicator of the whether the fuel-air mixture is fuel-rich or fuel-lean. Fuel-rich is indicated by $\phi > 1$ meaning that the amount of air in the fuel-air mixture is insufficient to oxidize the fuel. Fuel-lean, indicated by ϕ <1, is the opposite in that the amount of air is more than is needed to oxidize the fuel. As discussed in Chapter 1, contemporary low-emissions combustion systems utilize fuel-lean premixed combustion to control NO_x emissions. The underlying principle is to use the extra air as a diluent to lower the adiabatic flame temperature, T_{ad}, of the flame to impede the oxidation of nitrogen in air. Consequently, the control strategy for the fuel-switching system is to maintain the same adiabatic temperature when burning different fuels by setting the equivalence ratio and air and fuel flow rate according to a fuel loading map calculated from chemical kinetics.

Fuel-loading Maps

Because biogas consists mainly of CO_2 and CH_4, and natural gas is over 95 percent CH_4, the fuel loading map for the biogas/natural gas system (Figure 14) is presented here to illustrate various aspects of fuel-switching that impact the operation of the combustion system. The fuel-loading map is a phase space for the adiabatic flame temperature, T_{ad}, (expressed in contours in Figure 14) expressed in terms of ϕ and the biogas fuel composition represented by the ratio of CO_2/CH_4 in its composition. The T_{ad} results were compiled from CHEMKIN calculations using the Premixed Flame modules and GRI 3.0 reaction mechanism. The colored background of Figure 14 displays the contours of bulk flow velocities, U_0, through the nozzle of a hypothetical LSB of 4” diameter with heat output of 200 kW operating under standard atmospheric conditions. In additional to T_{ad}, other computed parameters computed are the laminar flame speed (s_L), the Wobbe index (see Chapter 1), and the mass and volumetric flow rates of the fuel and air for the hypothetical system.

The range of conditions computed for the fuel loading maps are $0 < CO_2/CH_4 < 1.5$ and $0.6 < \phi < 1$. As seen in Table 1 of Chapter 1, typical biogas has between 50 percent to 75 percent CH_4 which corresponds to $0.33 < CO_2/CH_4 < 1$. The range of equivalence ratio are for stoichiometry ($\phi = 1$) to fuel lean ($\phi < 1$). For a natural gas combustion system, which corresponds to the conditions on the left axis of $CO_2/CH_4 = 0$, it can be seen that by lowering ϕ from 1 to 0.67 reduces the adiabatic flame temperature from over 2200 kelvin (K) to 1800K. Due to the complexity of the chemical reactions, the relationship between ϕ and T_{ad} is not linear. Most often, natural gas combustion systems are set at a fixed fuel-air ratio for NO_x control. Because of the design of the burner and the interaction between the flame and the combustion chamber affect NO_x emissions, setting the fuel-air ratio base on T_{ad} is a starting point. In-situ adjustment of the fuel-air ratio is necessary to achieve the emissions goal. Data calculated for natural gas also show other impacts of operating at lean conditions. The bulk flow velocities (color background) computed for a hypothetical system show that increasing the air flow to lower the flame temperature (while maintaining a constant heat output) corresponds to up to 50 percent increase in the bulk flow velocity through the burner nozzle. This increase in flow velocity and weakening of the flame (due to air dilution with lowered fuel air ratio) encapsulates the technical challenges in lean premixed burner design. As discussed in Chapter 2, the unique aerodynamic flame stabilization mechanism of the low-swirl burner has shown to be well-suited to overcome these challenges.

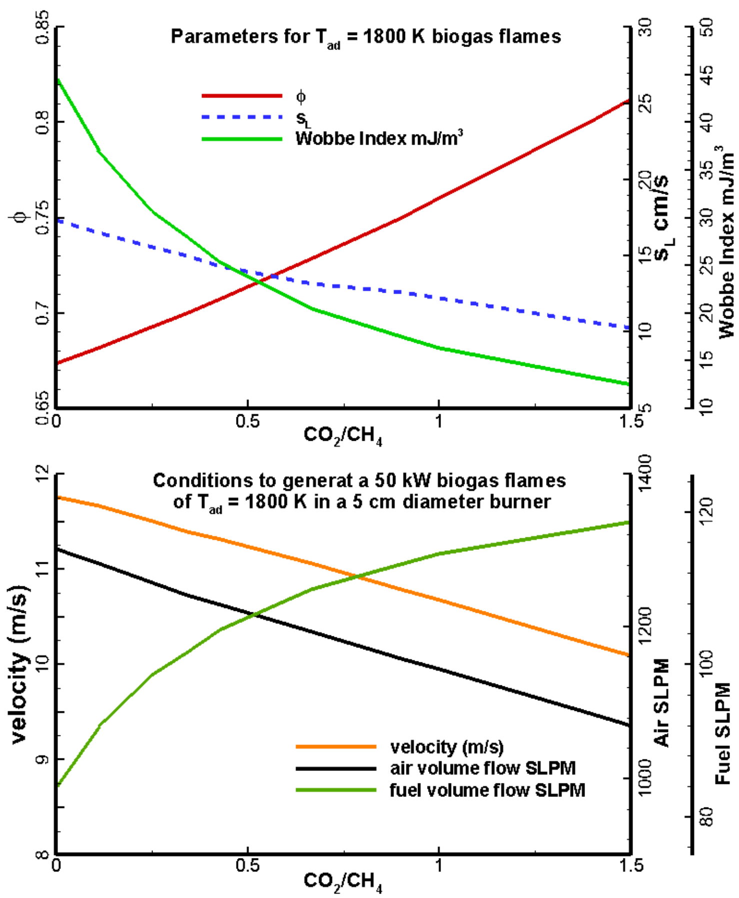
Figure 14: Fuel-loading Map for Biogas/Natural Gas System



Based on Contours of Adiabatic Flame Temperature (in degrees Kelvin) Computed for Premixed Laminar Flames of Blended CO_2/CH_4 Fuels

For a system that switches between biogas and natural gas, the fuel loading map of Figure 14 serve as the lookup-table to set ϕ when the fuel components change. During fuel-switching, the goal is to maintain a constant T_{ad} for NO_x control and process efficiency. The control protocol extracts information from this fuel loading map as follows. If the boiler is operating with pure CH_4 (i.e., natural gas) at T_{ad} = 1800K, the equivalence ratio ϕ of the reactants will be set at 0.675. When the fuel content changes to CO_2/CH_4 = 1, then the equivalence ratio ϕ of the reactants needs to increase to about ϕ = 0.75 to maintain the same thermal efficiency and emission levels. During the switch over from biogas to natural gas (or the reverse), the set points can be extracted from the data along the T_{ad} = 1800K contour. The combustion parameters for these intermediate set points are shown in Figure 15. The T_{ad} = 1800K contour is chosen as an example because of its relevance to attaining ultra-low emissions in lean premixed combustion heaters. This flame temperature is often considered as the upper most allowable for NO_x control. At T_{ad} > 1800K, NO_x emissions would be above the limits being implemented in urban areas worldwide.

Figure 15: Combustion and Flow Properties on the T_{ad} = 1800K Contour from the Fuel-loading Map of Figure 14



The upper plot of Figure 15 shows ϕ, the laminar flame speed, S_L, and the Wobbe index. Most notable from this plot is a significant variation in the Wobbe index when switching from natural gas (CO_2/CH_4 = 0) to biogas of CO_2/CH_4 = 1. As discussed in Chapter 1, the Wobbe index is a parameter to estimate the feasibility of a fuel injector to accept different fuels (delivered at the same pressure drop) without hardware modification or change in the fuel pressure. Normally, fuels within a range of Wobbe index of ± 5 percent are considered interchangeable, i.e., no modification or adjustment required. As shown in Figure 15, the variation in Wobbe index between the natural gas and biogases can be more than ±20 percent. This indicates that the fuel pressure requirement for natural gas and biogas would be different if the same fuel injector is used.

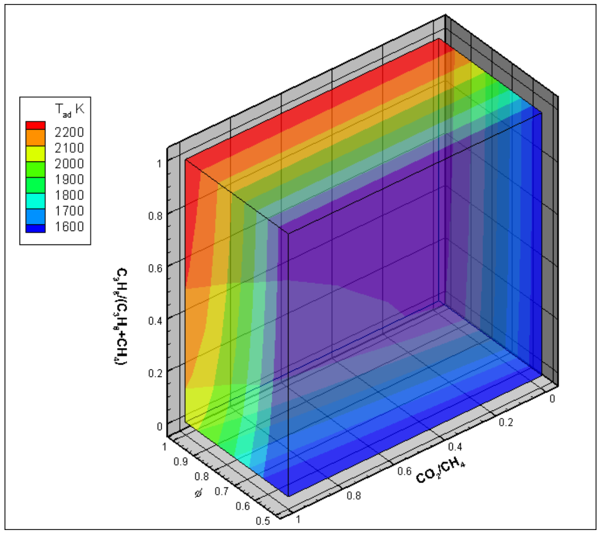
The bottom plot of Figure 15 shows the variations in flow rates during fuel-switching. It is seen that to produce the same amount of heat release the biogas flow rate must be more than 50 percent above the flow rate of natural gas. For a fuel injector with a fixed number of injection orifices fuel injection velocity will increase accordingly. Concurrently, the amount of air for burning biogas is reduced because CO_4 in the biogas serves as a diluent that helps to lower the flame temperature. Air reduction results in a lower bulk flow velocity through the burner nozzles. The increase in fuel injection velocity and the decrease in air velocity will affect the mixing process between fuel and air. The changes in thermal dynamics and flow conditions during fuel-switching illustrate the complexity of the processes and the potential engineering challenges for the design of the combustion system.

The addition of propane, C_3H_8, as the third component means that the fuel-loading map for the propane-biogas system is more complex than the one for biogas and natural-gas. An additional parameter is required to represent the three major fuel constituents, i.e., C_3H_8, CH_4, and CO_2. In addition to the ratio of CO_2/CH_4 used in the biogas/natural gas system described above, the ratio of propane to methane $C_3H_8/C_3H_8+CH_4$ is invoked. The two parameters appear in the general equation (Equation (5)) for the propane/biogas–air system where air is approximated by $(O_2 + 3.762N_2)$.

$$\boldsymbol{w}C_3H_8 + (1-\boldsymbol{w})\,CH_4 + (1-\boldsymbol{w})\boldsymbol{z}\,CO_2 + \lambda\,(2 + 3\boldsymbol{w})(O_2 + 3.762\,N_2) =$$
$$(1+2\boldsymbol{w}+\boldsymbol{z}-\boldsymbol{wz})\,CO_2 + 2(\boldsymbol{w}+1)\,H_2O + (2+3\boldsymbol{w})(\lambda-1)O_2 + 3.762\,\lambda\,(2+3\boldsymbol{w})\,N_2 \qquad (5)$$

In Equation (5), $\boldsymbol{z} = CO_2/CH_4$ is the ratio of carbon dioxide to methane in the fuel stream. In the current system with capability to switch between biogas and propane, this ratio represents the property of the biogas. The other parameter $\boldsymbol{w} = C_3H_8/(C_3H_8+CH_4)$, quantifies the ratio of propane to methane which the burner experiences during fuel-switching when a fuel stream consisting of biogas and propane are delivered to the burner. The last parameter $\lambda = 1/\phi$ is known as the air number. The fuel loading map is thus a three dimensional phase space for the adiabatic flame temperatures, T_{ad} at various values of $\boldsymbol{w}$, $\boldsymbol{z}$, and ϕ (Figure 16). As can be seen, the constant T_{ad} contours are surfaces in the 3D phase space. This fuel loading map will be the look-up-table for the control system to set the conditions, i.e., fuel and air flow rates, to maintain a constant temperature in the boiler based on the fuel compositions, reported in terms of the values of $\boldsymbol{w}$ and $\boldsymbol{z}$, from the fuel sensor.

Figure 16: Fuel-loading Map for the Propane-biogas System



Fuel Sensor Development

As seen in the previous section, the controls for real-time fuel-switching require information on the compositions of the fuel. The role of the fuel sensor is to provide this information by sampling the values of $\boldsymbol{z}$ = CO_2/CH_4 or $\boldsymbol{w}$ = $C_3H_8/C_3H_8+CH_4$). As discussed in Chapter 2, the fuel sensor developed at UCI uses airborne sound properties to interrogate the fuel (Jordan et al., 2013). The advantage in using an acoustic gas sensor is its fast response, robustness, and low cost at the expense of sensitivity (Lueptow & Philips, 1994). The fuel sensor developed for this project evolved from an earlier development to detect the variability in the composition of natural gas. Since natural gas has more than 70 percent hydrocarbons, chiefly methane, the development for biogas involved redesigning the hardware to detect the variation in the lower methane contents (50 percent to 75 percent) in biogas. The work was conducted at the laboratory of UCI as well as in-situ verification at CWRP. The basic concept for a fuel sensor to sample the ratio between CH_4 and C_3H_8 was also developed. Due to the fact that the C_3H_8 and biogas lines at CWRP have very different pressures such that they are supplied separately into the LSB, the system cannot accommodate a CH_4 or C_3H_8 fuel sensor and was thus not built.

Technical Background for the Biogas Fuel Sensor

The speed of sound through a gas mixture is dictated by its molecular weight and the gas temperature. This relationship is given as

$$c^2 = \frac{\sum_{i=1}^{N} y_i c_{p_i}}{\sum_{i=1}^{N} y_i c_{v_i}} \frac{RT}{\sum_{i=1}^{N} y_i M_i} \qquad (6)$$

where c is the speed of sound of the gas mixture, y is the mass fraction of a gas component, c_p and c_v are the specific heat at constant pressure and constant volume respectively for gas component i. R here is the universal gas constant (8314.5 joule per mole kelvin), T is the temperature of the gas, and M is the molecular weight for the gas component. N represents the number of gas components in the gas mixture. Since biogas approximates a binary mixture, N for biogas is 2. The basic function of the fuel sensor is to detect the changes in the speed of sound when sending an acoustic signal through a chamber filled with the biogas.

The speed of sound is also dependent on the frequency of the acoustic signal sent out by an ultrasonic transducer. Equation (7) is Equation (6) expressed in terms of the frequency ω (Lambert, 1977):

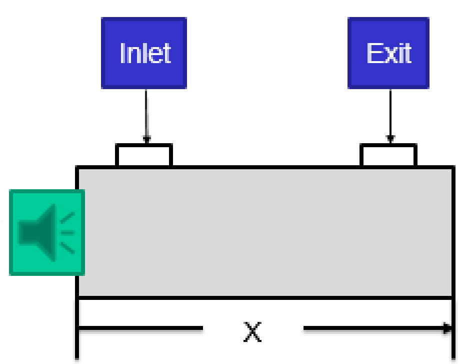
$$c^2 = \frac{RT}{M}[1 + \frac{R\left(c_{v_0} + c_{v_\infty}\omega^2\beta^2\right)}{c_{v_0}^2 + c_{v_\infty}^2\omega^2\beta^2} \qquad (7)$$

Equation (7) contains two specific heats at constant volume due to what is known as a dispersion zone. In this zone the speed of sound for a gas mixture can have two different values due to a difference in the specific heat c_{v_0} before the dispersion zone and the specific heat c_{v_∞}after the dispersion zone. Consequently, the fuel sensor must avoid operating within the dispersion zone.

Acoustic attenuation refers to the loss of acoustic energy. Its occurrence in a fuel sensor will lead to erroneous data. This phenomenon is caused by the forward and backward motion of gas molecules as the sound wave travels through the gaseous medium. This forward and backward motion leads to molecules colliding and the energy exchanges during these collisions can lead to acoustic energy loss. Acoustic attenuation differs drastically depending on the frequency of the transducer and gas composition. In pure CO_2, the attenuation of an acoustic signal is much greater than in pure methane. Therefore, the challenge in the development of a biogas fuel sensor is to identify the acoustic attenuation frequency ranges for CO_2 and CH_4 and choose a transducer frequency range outside of these ranges.

Figure 17 shows the schematics of the fuel sensor which consists of an acoustic chamber with an inlet and outlet for the fuel and an ultrasonic distance sensor is mounted on one of the long ends of the chamber. The distance sensor is designed to measure the distance of an object by detecting the time for the sound signal to reflect back. When mounted inside the chamber, the distance sensor will report back the distance x if the chamber is filled with air. If the chamber is filled with methane which has a different molecular weight than air, it will report a distance that is not x. The difference in the distances is due to the change in the speed of sound from which the molecular weight, and thus the fuel composition, can be inferred.

Figure 17: Schematics of the Speed of Sound Fuel Sensor



As distance sensors are designed to detect distances by sending a sound signal through air, to use them as a fuel sensor, calibration of the distance sensor in air is the necessary first step by using:

$$2d_{air} = c_{air} * t \qquad (8)$$

Here c_{air} is the speed of sound in air, t is the transit time of ultrasonic wave, and d_{air} is the measured distance. Since c_{air} is dependent on temperature, a thermistor was used to account for the changes in temperature, T_C (in degree Celsius) such that:

$$c_{air} = 331.5 + (0.6 * T_c) \qquad (9)$$

Because the distance between the PING)))™ sensor and the end wall is fixed, the speed of sound of a different gas filling the chamber can be determined from the temperature, the calibrated distance (d_{air}) in air, and the transit time of the sound wave, i.e.

$$c_{gas} = \frac{2d_{air}}{t} \qquad (10)$$

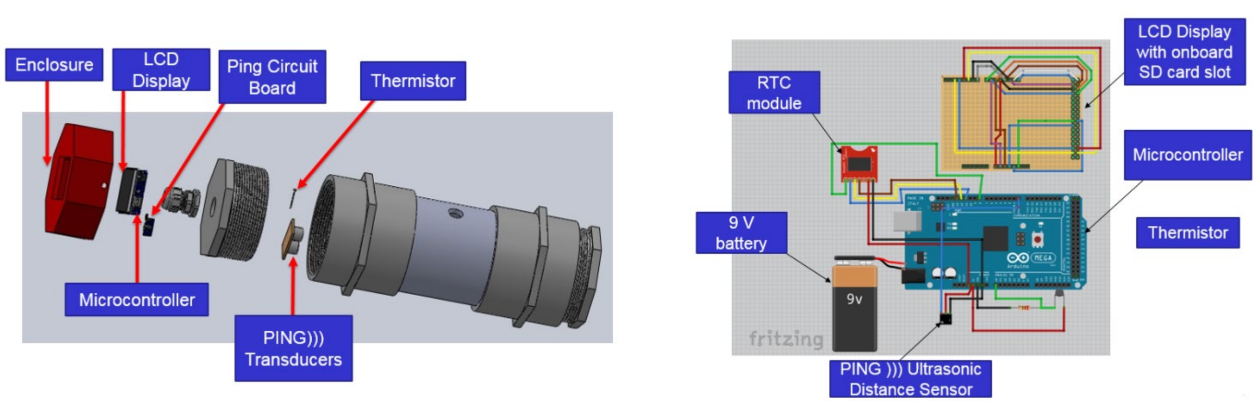
The molecular weight of the gas can then be calculated from Equation (6).

Biogas Fuel Sensor: First Prototype

The first fuel-sensor prototype uses a commercial ultrasonic distance sensor PING)))™. This sensor operates at frequency of 40 thousand Hertz (kHz) which is away from the acoustic attenuation peaks of CO_2 and CH_4. The detection range of the sensor is 0.787" (2cm) to 118.11" (3 m) meaning that the chamber length (x in Figure 17) can be made within this size range.

The components and electronics for the first biogas fuel sensor prototype are shown in Figure 18. The acoustics chamber for the prototype was constructed of a polyvinyl chloride (PVC) pipe and the electronics are fitted inside a 3D printed enclosure. Included in the electronic assembly was a real-time clock to time-stamp of the data and a liquid-crystal display (LCD) touch-screen display with an onboard SD card slot to record data from the sensor.

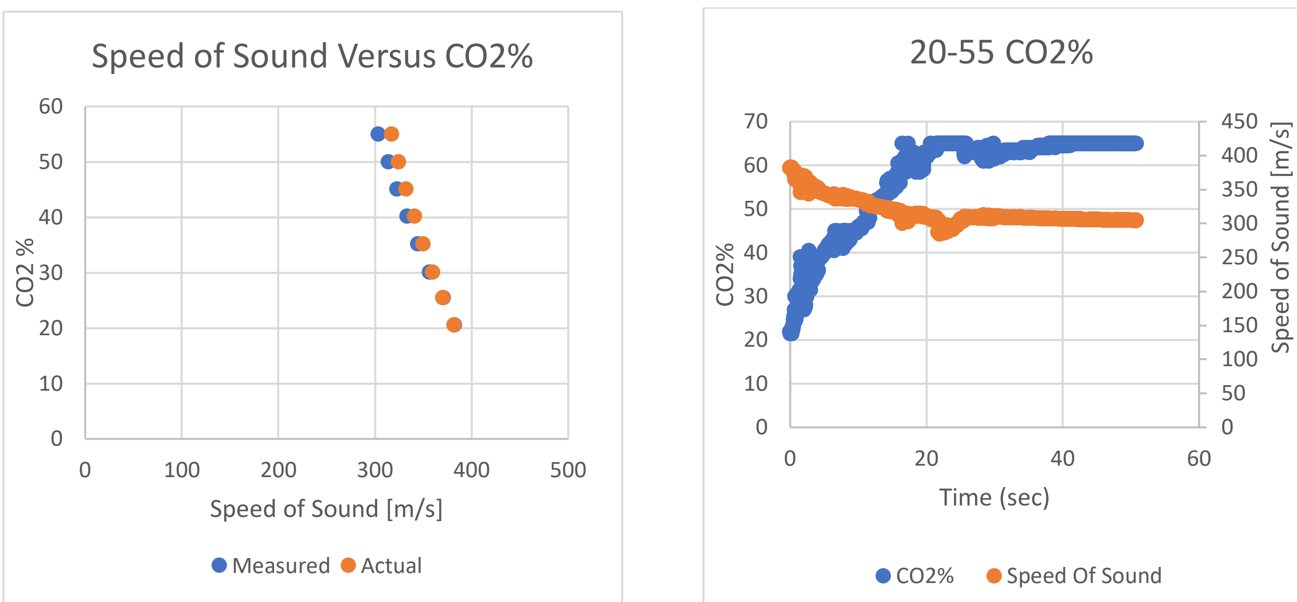
Figure 18: Components (left) and Electronics (right) of the First Prototype Acoustic Sensor for Biogas



Tests of First Prototype Biogas Sensor

The laboratory tests were performed by operating the fuel sensor using mixtures of CO_2/CH_4 of known proportions to determine its accuracy, response time, and stability. The speed of sound results plotted in Figure 19 illustrate good agreement only at CO_2 < 25 percent. Deviation from actual value increases above 30 percent CO_2. The response of the system is seen from the results plotted in the right of Figure 19. Here, the gas composition in the chamber was varied from 20 percent to 55 percent CO_2 within 20 seconds. At the beginning of the test, the sensor reports back a reading of 20 percent CO_2 which is consistent with the actual composition. When the fuel composition changed to 55 percent CO_2 the sensor reports 62.5 percent CO_2 corresponding to an error of approximately 13 percent. This error margin may not be acceptable for an industrial system.

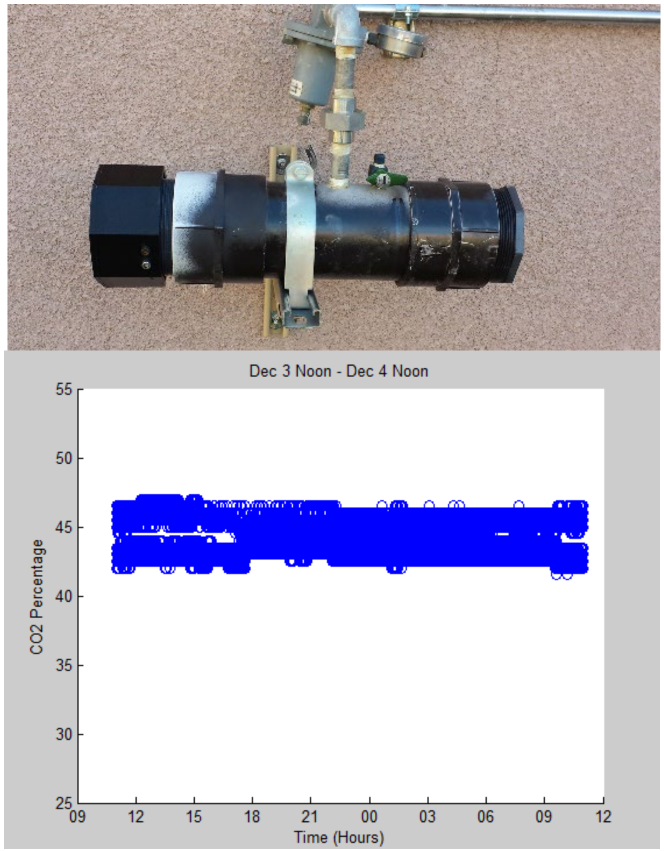
Figure 19: Results of Laboratory Testing of the First Fuel-sensor Prototype



Speed of Sound as a Function of CO_2 Percentage (left).
Sensor Response to CO_2 Percentage Change (right).

Further evaluation of the first fuel sensor prototype was conducted at CWRP where it was connected to a biogas fuel line used for a micro turbine for generating electricity (Figure 20 top). For these tests, the sensor was installed at a point in the biogas line where the pressure was 10 psi. At CWRP, the CO_2 concentration in this biogas is monitored and thus provides a basis for evaluating the accuracy of the first prototype biogas sensor. Figure 20 bottom is a plot of the data obtained for a 24-hour period showing the CO_2 concentration varied from 42.5 percent to 47 percent CO_2. The range of variation is consistent with the CWRP values. However, there are occasions during which the first prototype reported data that showed significant jitter with the CO_2 concentration fluctuating abruptly between 25 percent to 45 percent. One cause for the observed erratic output was the changing fuel pressure which resulted in slight deformation of the PVC pipe acoustic chamber. Deformation of the chamber affects the alignment of the distance sensor and thus the erroneous data. The test's results from the first prototype indicated that the distance sensor can be used in an industrial setting for sensing the biogas variations over a long period. However, a rigid construction of the acoustic chamber and a sensor with a more secured mounting were necessary to improve its performance.

Figure 20: First Prototype Biogas Sensor with PING)))[TM]



Installed at CWRP (top) and CO_2 Percentage of Biogas Fuel at CWRP Over a 24-hour Period (bottom)

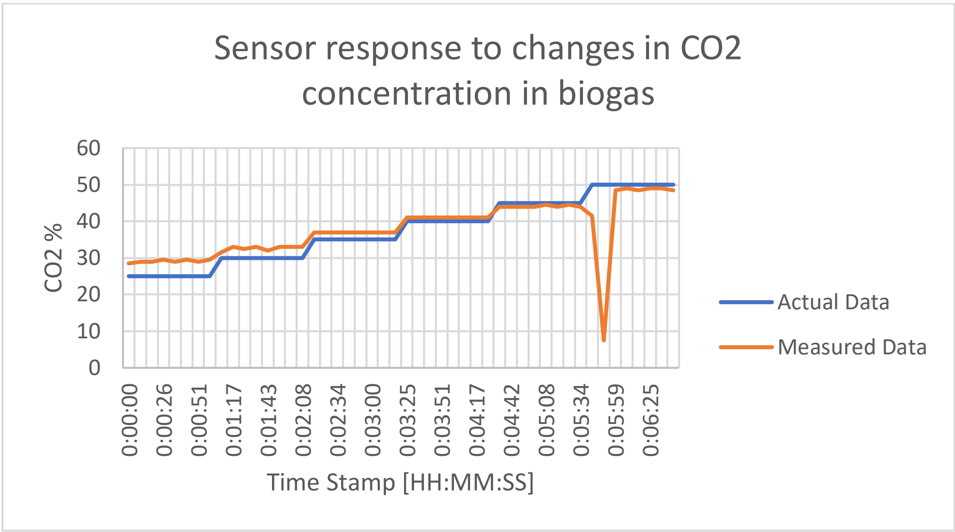
Biogas Fuel Sensor: Second Prototype

The design of the second prototype addressed the deficiencies found in the first prototype. A different sensor MB7380 model from Maxbotix Sensors was chosen. This sensor operated at a frequency of 42 kHz and as a threaded end for secured and rigid mounting. The acoustic chassis was constructed with aluminum with the end plates mounted with gaskets to ensure tight hermetic seal. The electronics for the first prototype were retained and a temperature sensor (1/8" type K thermocouple) was added.

Test of Second Prototype

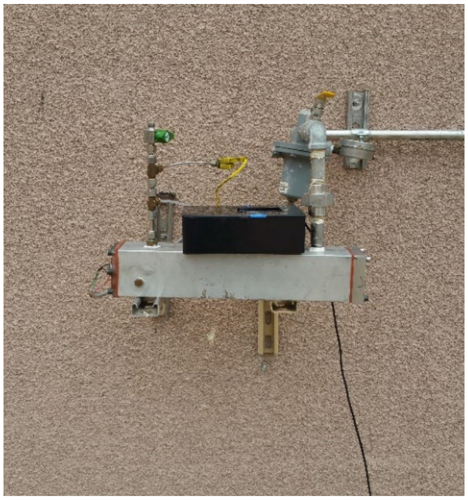
As with the first prototype, laboratory testing was conducted for the second prototype. Figure 21 shows that its performance in terms of following the change in CO_2 concentration in the biogas was much improved. For the biogas produced at CWRP fuel (i.e., between 42 percent to 47 percent CO_2) the uncertainty was 2.5 percent. However, the accuracies of the second prototype fuel sensor decrease for biogases having CO_2 concentration below 35 percent. The degradation in performance in this fuel range compared to the first prototype was due to the Maxbotix MB7380 Sensors having a minimum detection distance of 1.811″ (3 cm) that is higher than the 0.787″ (2cm) minimum detection distance of the PING)))™ sensor installed in the first prototype. Consequently, biogas having a higher speed-of-sound (i.e., low CO_2) corresponds to the lower limit of operation for the Maxbotix MB7380 Sensors where the uncertainties are large.

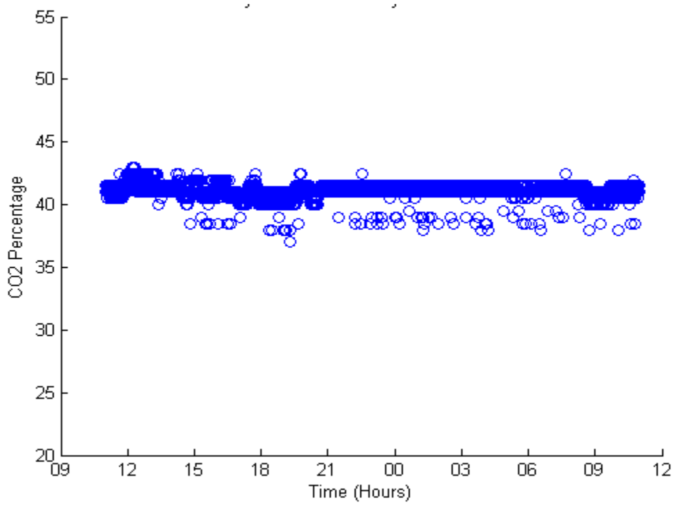
Figure 21: Response of the Second Fuel-sensor Prototype to Changes in Biogas Compositions



The second prototype fuel sensor was also installed at CWRP (Figure 22) where it was tested for two weeks. As seen in the data plotted in Figure 22, the performance of the second prototype was very satisfactory with stable operation shown over a period of 24 hours. Data obtained during several other days in the test period are consistent with the data shown in Figure 22.

Figure 22: Second Prototype Fuel Sensor at CWRP and Biogas Composition Over a 24-hour Period





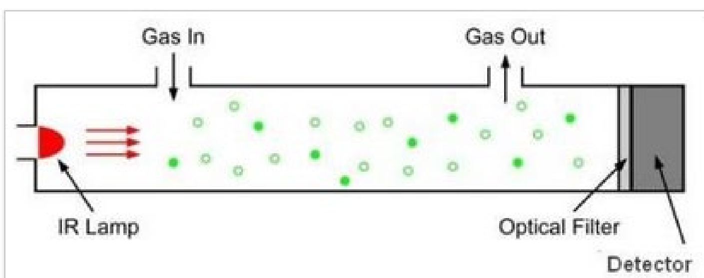
Conceptual Design for a Propane-biogas Fuel Sensor

As discussed above, the LSB system to be installed at the CWRP has biogas and propane delivered through separate fuel lines because of the difference in the fuel pressures. This situation precludes the need for a fuel sensor that could determine the concentrations of CH_4, CO_2, and C_2H_8. In an effort to extend the fuel sensor technology to enable fuel switching for industries where biogas and propane gas are available, the conceptual design for a fuel sensor for ternary mixtures i.e., biogas (CO_2 and CH_4) and, propane (C_3H_8) was pursued.

The basic concept of the biogas/propane fuel sensor is to include a sensor for direct measurement of the CO_2 concentration alongside the speed-of-sound sensor for determination of the molecular weight. CO_2 sensors operating on NDIR (Non-Dispersive Infrared) principle are available commercially. To evaluate this concept a CO_2Meter (COZIR Wide Range 100% CO_2 Sensor) was procured. This CO_2 sensor is affordable (about $100), has very low power requirement, and is sufficiently robust to detecting CO_2 fractions between 0 percent to 100 percent.

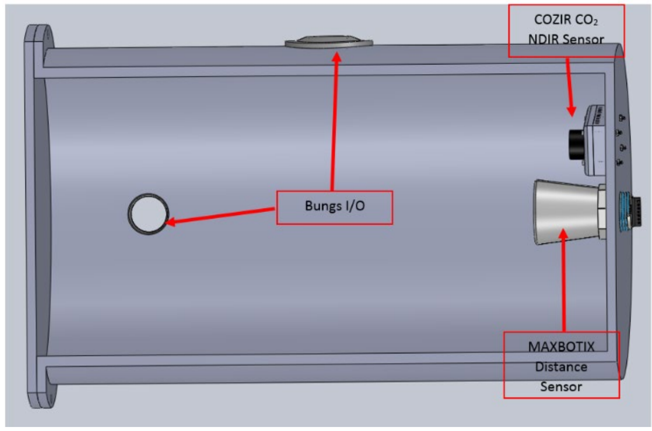
The basic concept of NDIR technology is shown in Figure 23. It involves an infrared (IR) light source and a detector mounted at the either ends of a gas sample chamber. The wavelength of the IR light source is tuned to the absorption frequency of CO_2 gas molecules. In front of the detector is an optical filter that transmits only light at the wavelengths of the IR source. Because CO_2 absorbs light at the specific IR frequency, its presence in the gas sample will attenuate the light level seen by the detector. Thus, the attenuation of the detector signal can be calibrated for different concentrations of CO_2 in the gas sample.

Figure 23: NDIR CO_2 Sensor Schematic



The conceptual design for a biogas/propane fuel sensor is shown schematically in Figure 24. It incorporates the MB7380 Ultrasonic Distance Sensor and the COZIR Wide Range CO_2 Sensor. There are two ports for the fuel to flow in and out with CO_2 sensor mounted in an enclosure isolated from other electronic components and the steel chassis. The ID of the chassis is 8.5″ (21.59 cm) to reduce the interference from the wall of the chambers to the ultrasonic pulse sent out by the MB7380 sensor. The distance between the sensor and the end of the steel frame is approximately 16″ (40.64 cm) which provided ample space for the MB7380 sensing distance limits.

Figure 24: Cross Section of the Conceptual Biogas-propane Fuel Sensor



Fully Functioning Biogas Fuel Sensor for CWRP

Results from testing the second prototype biogas fuel sensor with a MB7380 ultrasonic distance detector from Maxbotix Sensors shows it is appropriate to use during the demonstration at CWRP. This unit was installed on the biogas line of the LSB. However, it is important to note that this sensor does not have the capability to be adapted to a biogas/natural-gas system. This is due to an increase in uncertainties as the CO_2 concentration decreases. However, our demonstration shows that the fuel sensor is robust and well-suited for industrial installations. The knowledge gained from the prototype developments can be used to redesign the dimension of the fuel sensor chamber and the selection of an ultrasonic distance detector to enable high precision throughout the range (i.e., 0 percent to 60 percent CO_2) required for a biogas/natural gas fuel sensor.

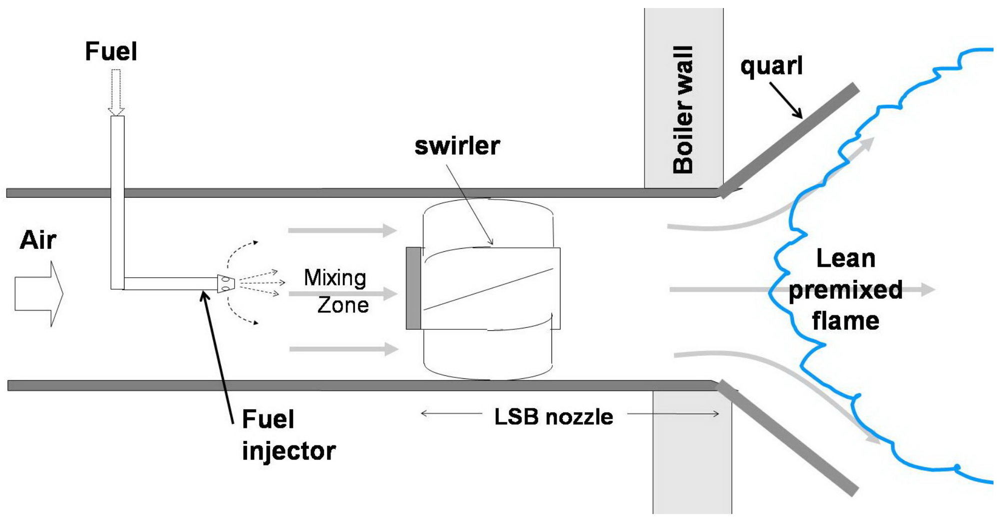
Low-swirl Burner

Sizing the low-swirl burner for the boiler was dictated by the maximum heat output of 1.99 MMBtu/hr boiler. Scaling the LSB to this output capacity was based on the constant bulk flow velocity criterion (Cheng et al, 2002). In addition, other performance and physical aspects of the boiler such as the turndown range (i.e., the ratio between the highest to the lowest heat output of the system) and the interior dimensions of the boiler were factors to consider relating to burner sizing. These parameters determine the maximum allowable size of the burner and thus the range of flow velocities through the burner nozzle, the size of the flame, and the pressure requirement for the air blower to drive the combustion process.

Based on the engineering rules established for the LSB, the optimum burner size for the Johnston boiler is 5" diameter. The size is in accordance with the guideline for having a ratio of 1:3 between the radiuses of the LSB and the combustion chamber. When operating a 5" LSB at a full load of 1.99 MMBtu/hr with a 1:5 turndown, the bulk flow velocities with propane or biogas flames are all above the minimum bulk flow velocity of 10 m/s.

The main components of the LSB installed in the boiler at CWRP are shown schematically in Figure 25. The heart of the LSB is its nozzle (labeled in Figure 25) consisting of a swirler mounted in a cylindrical pipe at a distance recessed from the exit where the LSB nozzle connects with a flame quarl. By supplying a fuel-air premixture to the LSB nozzle, its main function is to generate lifted stable lean flame downstream of the exit. The developmental efforts were focused on the features of the swirler and the length of the cylindrical pipe. The flame quarl is a conical shaped flame guide whose function is to guide a smooth transition of the flow from the LSB nozzle exit into the combustion chamber. Another function of the quarl is to mitigate, vibration, noise, and instabilities generated by the interaction of the LSB flame with the internal flow within the boiler combustion chamber. Upstream of the swirler is a fuel injector that discharges fuel into the air stream supplied by an air blower. As discussed earlier, the design of the fuel injection, its size, and its location must be optimized to ensure even mixing irrespective of the fuel volume due to the differences in the fuel volumes of biogas and propane.

Figure 25: Schematics of the LSB Prototype for the Johnston Boiler at CWRP

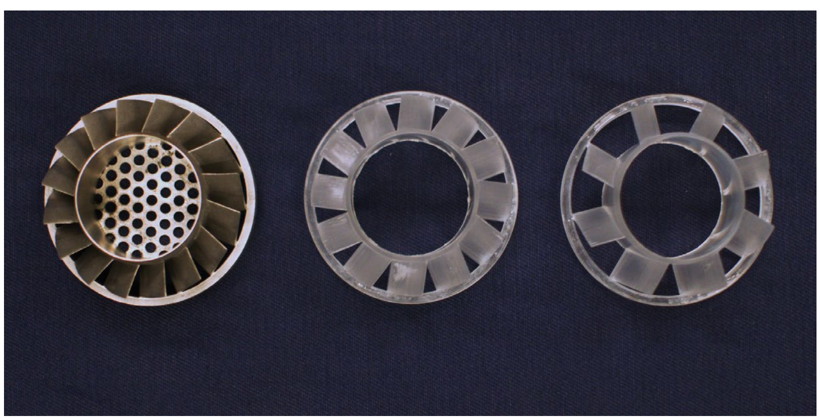


Development of the LSB started by laboratory tests using a 1/5-scale prototype to evaluate and optimize the designs for the LSB nozzle, the fuel injector and flame quarl. Testing at 1/5 scale in a laboratory setting allowed for simulating the fuel-switching process in a well-controlled manner to gain insights on stability during transition as well as baseline information on the response time of the flame to fuel changes. The initial developments were performed at LBNL with the experimental conditions simulating one-quarter to three-quarter loads of the CWRP boiler. A fully functional 1/5-scale prototype (i.e., LSB nozzle and a fuel injector) was evaluated at UCI at simulated full load conditions. The design of the full-scale LSB was based on the results from these tests and an engineering guideline was developed and included at the end of this section.

The 1/5-scale prototype LSB nozzle with a diameter of 2.25″ corresponds to a full-sale burner of 5″ diameter. The first part to develop was the swirler which was based on a review of the LSB swirler database available at LBNL. By comparing the performances of various configurations in terms of fuel-flexible capability, pressure drop, and ease of manufacturing, the final design was a swirler with thin constant-radius curved vanes that had been developed for gas turbines. Though the curved vanes swirler is more complex to manufacture than the flat vane swirler in commercial LSBs, the main benefit is its proven fuel-flexible capability. Another benefit is that the aerodynamically shaped curve vane produces lower drag than flat vanes and thus requires lower operating air pressure for reducing the parasitic energy of the system, thus improving system efficiency. With this basic configuration, the next task was to determine the optimum number of vanes. Fewer vanes incur lower cost of manufacturing. Additionally, the number of swirl vanes (assuming the blade profile remains unchanged) also affects the aerodynamic drag of the swirler. In a boiler system, using fewer numbers of vanes could further reduce the parasitic energy.

The swirler, originally developed for gas turbines, has 16 constant radius thin curved vanes (first one on the left in Figure 26). It is made from laser sintered 3D printing using cobalt chromium alloy so it can withstand the elevated pressure and temperature environment in gas turbines. Because much about the operation and flowfield characteristics of this swirler is known. This swirler, named CV37-16, was used as a baseline. The swirl vane angle, α, and center channel ratio, *R*, (parameters in Equation (1) in Chapter 2) are respectively 37^o and 0.6. Two variants of the baseline CV37-16 with 12 vanes (CV37-12) and 8 vanes (CV37-8) were configured and fabricated (Figure 26 center and right). The only difference between the three variations is the number of vanes. All other dimensions are the same. The two newer swirlers were fabricated from resin by laser 3D printing. These swirlers are fully functional because the laboratory LSB flame does not touch any part of the burner. All the swirlers were fabricated with an open center channel (see photos of CV37-12 and CV-8 in Figure 26) so that the swirl number can be varied by attaching different perforated plates to the center channel. To start, the 40 percent open perforated plate used with CV37-16 (shown in Figure 26) was mounted to CV37-12 and CV37-8 to investigate if this plate would work with the two swirlers with fewer vanes.

Figure 26: The Three Swirlers Used in the 1/5-Scale LSB Prototype Development

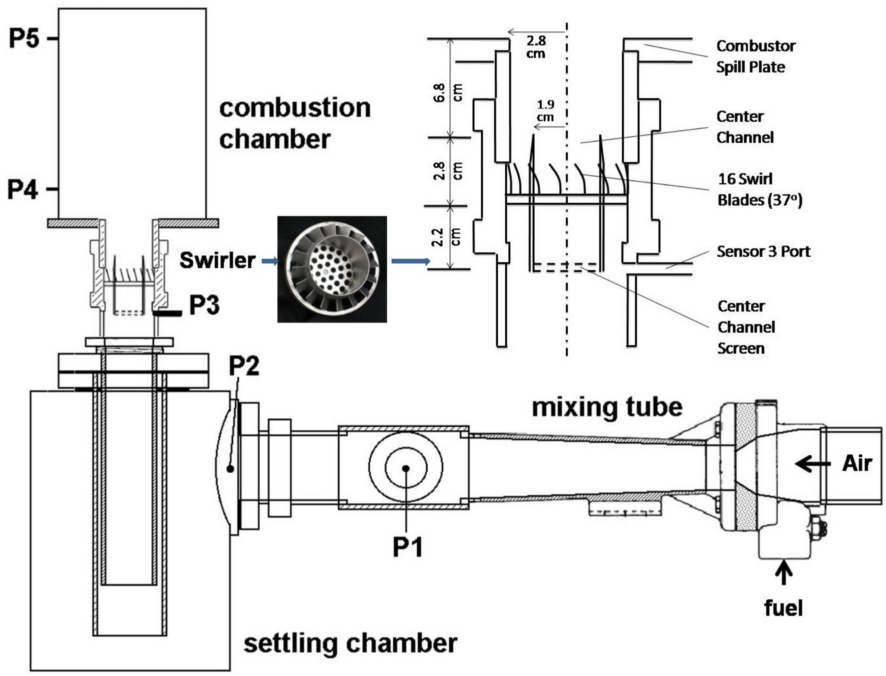


The Baseline 16 Vane Swirler on the Left (CV37-16) is Shown Fitted with the 40 Percent Open Perforated Plate. The Perforated Plate was Found to be Suitable for Operating with the 12 (CV37-12 Center) and 8 (CV37-8 Right) Vane Swirlers.

The laboratory setup comparing the performances of the three swirlers at LBNL is shown schematically in Figure 27. The configuration was used for fundamental studies on lean premixed turbulent combustion. In these tests, gaseous fuel and air are blended far upstream. The reactants then enter a settling chamber to supply a uniform flow to the inner tube that feeds the LSB. Flow and mixture conditions of this setup can be considered as well-mixed and near ideal. By evaluating the LSB swirlers in this configuration, a set of baseline data were obtained for evaluating the performance of the boiler burner prototype. Also shown in Figure

27 is a cross-section view of the LSB nozzle. The recess distance for the prototype was 6.5 cm (2.7") which is within the $2R_B$ to $3R_b$ range of our design guideline. The exit of the nozzle tube discharges into the open (see Figure 2) or into a quartz cylinder that simulates the enclosure of a combustion chamber.

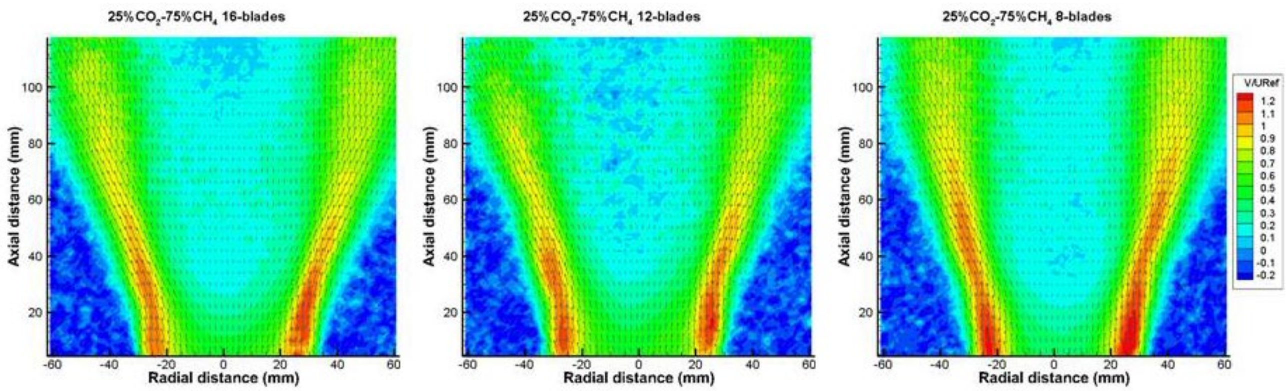
Figure 27: Schematics of the Burner Evaluation Station at LBNL



The three swirlers, fitted with the 40 percent perforated plate, were evaluated at identical mixture and flow conditions. The first tests involved firing the LST nozzle into the open to compare global flame features such as blowoff limit, flame lift-off height, and flame stability characteristics. The flow velocities for the tests, ranging from 6 m/s to 15 m/s, correspond to 30 percent to 75 percent load of the full-size boiler burner. Fuels tested include laboratory grade CH_4 and simulated biogases of 25%CO_2/75%CH_4 and 50%CO_2/50%CH_4. The results show that CV37-16, CV37-12, and CV37-8, fitted with the 40 percent open perforated plate are operable with CH_4 and simulated biogases. More importantly there were no significant differences in the lean-blowoff limits, flame lift-off heights, and flame stability behaviors of the flames generated by the three swirlers. Therefore, reducing the number of vanes in had no observable effects.

To further characterize the flame produced by the three swirlers, the laser-based particle image velocimetry (PIV) system measured and compared the open flame flowfields. PIV captures in 2D the instantaneous velocity distribution upstream and downstream of the LSB flame. This laser diagnostics method has been a standard tool for LSB research, and the PIV data was instrumental in supporting the development of the analytic model of Equation (2). For each of the three swirlers, PIV experiments were performed on flames burning CH_4, 25%CO_2/75%CH_4 and 50%CO_2/50%CH_4 at equivalence ratios corresponding to an adiabatic flame temperature of 1800K (see section 6 for more details). Compared in Figure 28 are the 2D mean velocity fields of the 25%CO_2/75%CH_4 flames produced by the three swirlers. Also shown in the background are color contours of the magnitudes of the velocity vectors. The three plots show that there are no significant differences in the overall features (i.e., spatial distribution and directions) of the velocity vectors. However, the background color contours show a slight decrease in flow divergence as the number of vanes is reduced. This is indicated by a slight decrease in the flow spreading angle between the right and left high velocity regions illustrated in orange and red. The central low velocity regions (light blue) suggest an upstream shift in the weak recirculation region that usually formed downstream of the flame.

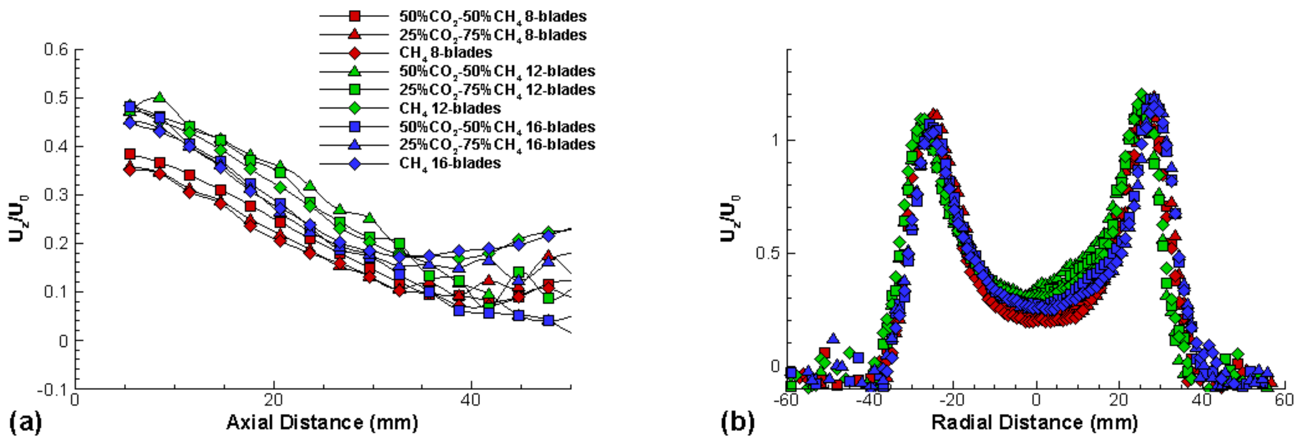
Figure 28: Mean Velocity Vectors Measured in the Flowfields of Premixed 25%CO_2/75%CH_4



Air Flames at ϕ = 0.68 Produced by LSB Using Three Swirlers with 16, 12, and 8 Curved Vanes.

To investigate the subtle differences between the flame flowfields of the three swirlers, the profiles of the normalized mean axial velocity, U_z/U_0 in the near field regions of the nine flames (below axial distance of 50 mm) are compared in Figure 29. The U_z/U_0 profiles of Figure 29 (a), obtained on the center line of the flowfields, show linear decreases from the origin (i.e., at the nozzle exit) up to the flame front (at about 35 mm). This linear decrease, quantifiable by the parameter a_x discussed in Section 2, is the important feature of the LSB flowfield. Self-similarity is shown by the profiles measured for each swirler (plotted in the same color) for the three different fuels collapsing into consistent trends. The only observable difference between the profiles for the three swirlers is that the magnitudes of U_z/U_0 from SV37-8 are lower than those from the other two. The radial profiles of U_z/U_o obtained at an axial distance of 15 mm are compared in Figure 29 (b). Here, all the profiles collapse onto the same trend. The two high velocity regions are seen flanking the low velocity region at the center.

Figure 29: Nearfield Normalized Axial Velocity Profiles Obtained for 25%CO_2 /75%CH_4

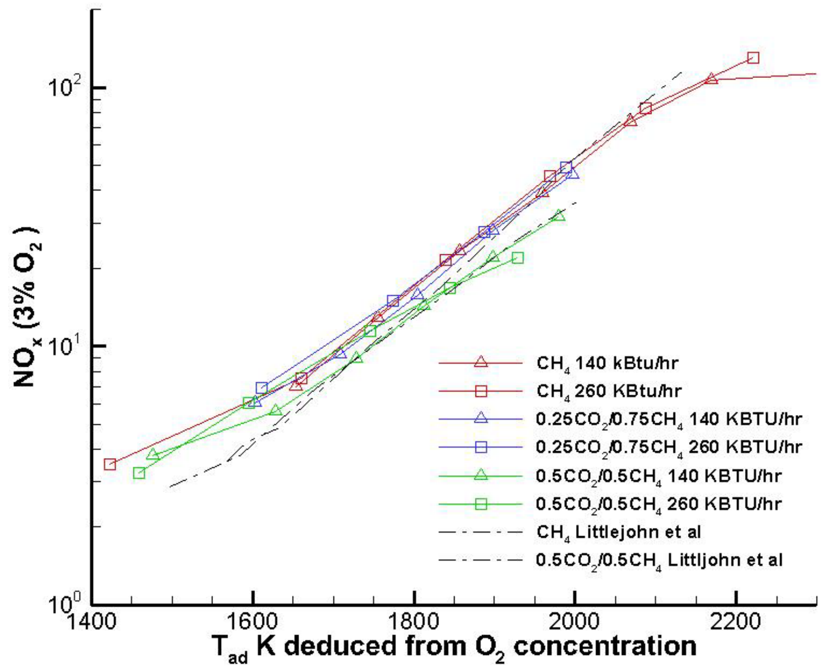


Air Flames at ϕ = 0.68 Produced by LSB Using Three Swirlers with 16, 12, and 8 Curved Vanes.

From the PIV results, it was clear that there is no fundamental difference between the flame flowfields produced by the three swirlers. The small variations, i.e., the reduction in the flow divergence angle and lowering of U_z/U_0 in CV37-8 are symptoms of a change in the swirl number due to the fact that we used the same perforated plate for all three swirlers. To verify, the swirl numbers were determined using a standard procedure that involves measuring the drag coefficients of the swirl annulus and the perforated plates to calculate the parameter, *m*, in Equation (1). The results show that the swirl numbers *S* for CV37-16, CV37-12 and CV37-8 are respectively 0.47, 0.48 and 0.5. These swirl numbers are well within the targeted operating range of LSB.

The next set of experiments was to verify that the NO_x emission of the LSB is dependent primarily on the adiabatic flame temperature T_{ad}. These experiments were conducted using three fuels (pure CH_4, 0.25CO_2/0.75CH_4, and 0.5CO_2/0.5CH_4) that correspond to high quality natural gas and two biogases. The conditions at 140 and 260 kBtu/hr simulate the boiler burner at 30 percent and 60 percent loads. As can be seen, in Figure 30, NO_x emissions collapse to a log-linear trend. This indicates the feasibility of controlling the NO_x emissions of the boiler by setting the fuel-air equivalence ratio according to the fuel loading T_{ad} maps of Figure 15.

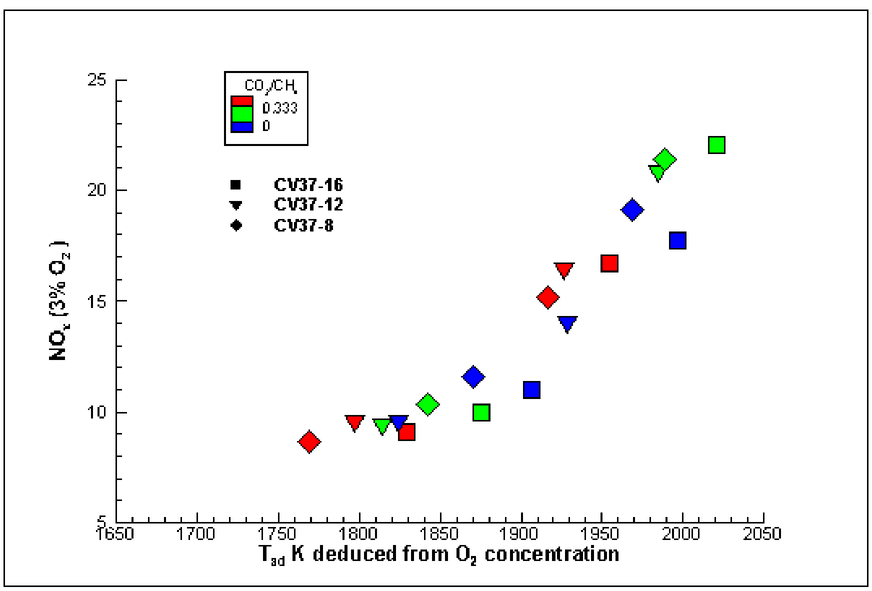
Figure 30: NOx Emissions of LSB with the Baseline Swirler Operating with Simulated Biogas



Littlejohn & Cheng, (2007)

To demonstrate real-time fuel-switching, the fuel-loading map was incorporated into the laboratory control software to change the CO_2 concentration in the fuel and set the equivalence ratios corresponding to T_{ad} = 1750K. These experiments showed that the flame remains stable during fuel-switching and confirmed the real-time fuel-switching capability of the LSB nozzle.

Figure 31: NOx Emissions from the LSB Fitted with the Three Swirlers of Figure 26



Under Well-Mixed Idealized Configuration.

The NO_x emissions from the 1/5-scale LSB with the three swirlers (all with the 40 percent open perforated plate) are compared in Figure 31. The data were obtained using the same fuel as the experiments of Figure 30. As can be seen, the discrepancies in the NO_x emissions are within experimental uncertainties. Therefore, we concluded that under near ideal flow and premixed conditions, the number of vanes in the LSB swirler has no significant effect on its fuel-flexible capabilities nor its pollutant formation characteristics.

Premixer

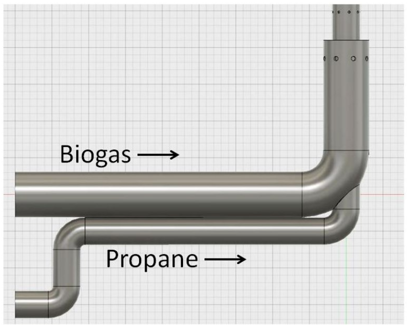
For a lean premixed burner system, the fuel delivery, fuel injection, and premixing components are critical to NOx control because non-uniform fuel/air mixing leads to local hot-spots that elevate NOx formation. For burner systems, an effective way to promote uniform fuel/air mixing is by a multi-port fuel injector that distributes the fuel evenly within the air flow passage. Because the fuel injector and its supply tube protrude into the air passage, the flow disturbances they generate in their wake, if not managed properly, can affect the LSB flame stabilization mechanism.

To develop the fuel injector for the prototype, the research team sought guidance from our development partners in the industrial heating sector. What was learned led to the creation of the basic LSB layout as seen in Figure 25 that is well-suited for operating at a lower supplied air pressure. This straight-through configuration requires more space to install as it protrudes outside of the boiler. However, the estimated dimension of the full size LSB showed that its total length would only be slightly longer than the existing Alzeta burner at CWRP demonstration site.

As discussed previously, to achieve the same thermal output as natural gas the flow volumes of biogases may need to be up to 50 percent higher than that of natural gas due to the low heating values of biogases. In a simple single stage fuel injector system, the jet velocity of the biogas leaving the fuel orifices would be higher than that of natural gas. The differences in the fuel jet velocities can affect the mixing process which then affects the NO_x emissions and possibility flame stability. Additionally, the fuel pressures of biogas and propane at CWRP are different. Because the fuel jet velocity exiting a fuel orifice is also dependent on fuel pressure, the difference created another layer of complexity to the design of a simple stage fuel injection system to deliver both propane and biogas to the CWRP boiler. Consequently, a composite fuel injector having separate tubes and orifices for the two fuels was deemed the appropriate solution.

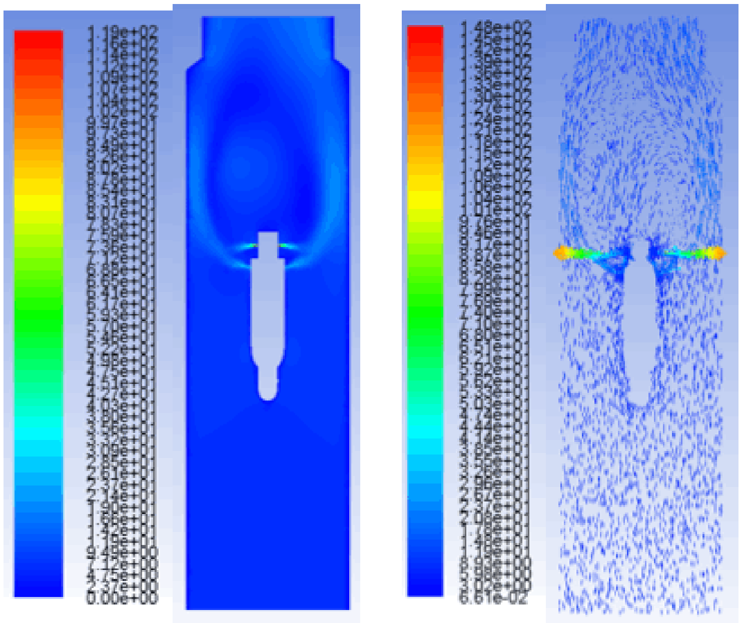
The design of the composite fuel injector was guided by computational fluid dynamic (CFD) calculation. CFD is a commercially available computational tool for designing flow systems. The software used to the design the composite fuel injector was ANSYS Fluent V17.0 CFD. Figure 32 shows the basis layout of the composite fuel injector. It has two fuel inputs with propane and biogas injected through separate sets of injection holes. The role of the CFD was to determine the appropriate injection hole sizes and the optimum placement of the injector for delivering a well-mixed fuel/air mixture with a near uniform velocity distribution to the LSB nozzle.

Figure 32: Schematic of a Composite Fuel Injector for the 1/5-Scale Burner Showing Separate Tube for Propane and Biogas



After 11 design iterations, the final design was a fuel injector with 16 holes of 1/40″ diameter for propane and 16 holes of larger 5/64″ diameter for biogas. The holes are optimized to allow an outlet velocity that penetrates into the bulk flow thus producing better mixing. Figure 33 shows the CFD results of the fuel injector. As can be seen the velocity exiting the computational domain is near uniform. Additionally, the results computed for fuel distribution were also satisfactory.

Figure 33: CFD of the Composite Fuel Injectors Showing Contours of Velocity (Left) and Velocity Vectors (Right)

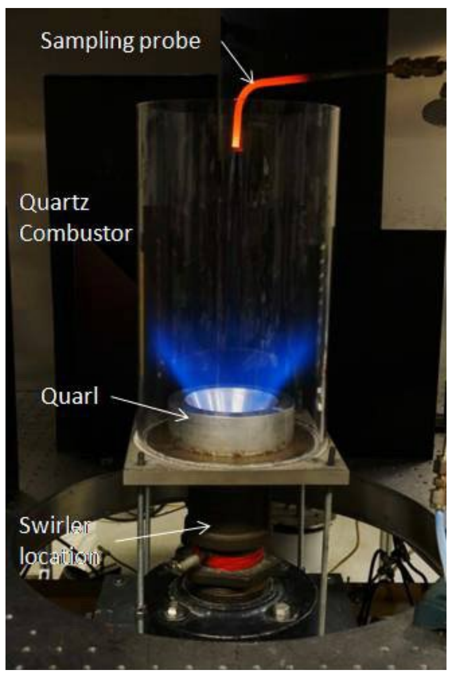


Flame Quarl Selection

As described in Section 2, the LSB divergent flow naturally expands into the combustion chamber when leaving the nozzle. In a typical boiler configuration, the burner connects to the combustion chamber on a so-called spill plate that is flat with a center opening for the burner nozzle. Because the flow of reactants through the burner nozzle is relatively fast, sudden expansion of this flow into the larger combustion chamber creates a strong shear layer that forms at the nozzle rim. Laboratory study (Therkelsen et al, 2013) has shown this shear layer, which consists of a large doughnut shaped ring vortex that grows (smoke ring-like) as it moves downstream with the flow. The ring vortex eventually reaches the combustion chamber wall and interacts with the trailing edge of the LSB flame. The interaction causes the flame position to oscillate near the wall. Local flame oscillation is a symptom of temporal heat release fluctuations which when coupled with the natural acoustic mode of the combustion chamber can incite large scale flame oscillation at a regular frequency. The consequence of thermal-acoustical coupling is very loud noises and high pressure fluctuations that could damage the combustion system. Mitigating combustion oscillations in a lean premixed system such as the LSB continues to be an active combustion research topic.

For the LSB, a simple and effective means to mitigate flame oscillations is to attach a divergent quarl at the entrance of the combustion chamber (Figure 25). The main function of the quarl is to prevent the formation of a strong shear layer at the nozzle exit by providing a smoother transition from the LSB to the combustion chamber. A secondary function is to guide the formation of the divergent flow. As depicted in Figure 34, the flame is established inside the quarl. Due to the fact that the flame anchors and burns from the center, it does not touch the quarl and overheating is not an issue.

Figure 34: 1/5-Scale Laboratory Setup Showing the Burner Quarl and the Quartz Tube



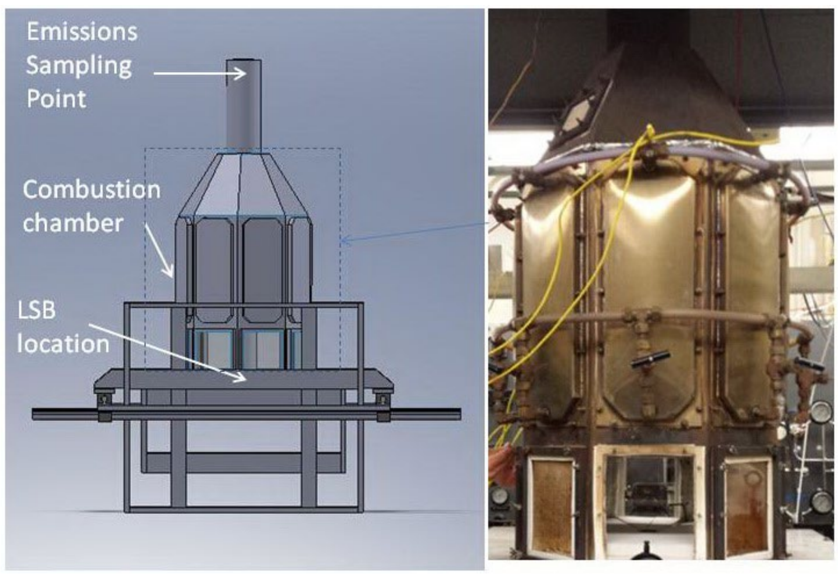
The Quartz tube that simulates the combustion chamber. The emissions sampling probe is near the exit.

The conical shape quarl we adapted for the 1/5-scale LSB evolved from the ones developed for the Maxon LSBs whose commercial names are M-PAKT burners and Optima burners. It has a 30° half angle with an exit diameter of 4.5" which is twice that of the LSB nozzle. As seen in Figure 34, the trailing edge of the flame extends beyond to quarl exit. This is intentional so as to accommodate the changes in the flame size (volume) when switching between natural gas and biogas. This so-called half-quarl has been shown to be effective in mitigating combustion oscillations. Though there are some interactions between the trailing edge of the flame with the combustor wall, these interactions do not generate a significant amount of noise.

Verification of the 1/5-scale LSB Prototype at UCI

The verification of the 1/5-scale LSB prototype was conducted at the boiler simulator facility at UCI (Figure 35). The facility was developed as a standard platform to evaluate burner performances under conditions that simulated those of a typical boiler. It has an octagonal shaped combustion chamber with four windows for optical interrogation of the flame generated by the burner. The upper walls of the combustion chamber are fitted with controllable water cooled panels to measure heat transfer. Emissions sampling probes are installed at the exhaust line. The air and fuel supply has the capability to simulate the full-load conditions of the CWRP boiler. The "fully-functional" LSB consisting of the fuel composite injector, the LSB nozzle, and the flame quarl was installed at the entrance of the combustion chamber as indicated in Figure 35.

Figure 35: Schematic and Photograph of the UCI Boiler Simulator Facility



The goal of the test was to determine the capability of the 1/5-scale LSB to maintain flame stability during fuel switching when following the surface of a given T_{AD} as prescribed by the fuel loading map of Figure 16. This strategy allows for emissions control during fuel-switching. The burner control was programmed to use the fuel loading map as the look-up-table to set the state points based on the fuel compositions during fuel transition and to maintain a constant temperature in the boiler. The test matrix was based on technical information obtained at CWRP: from the fuel sensor data obtained at CWRP, the biogas composition of 60 percent CH_4 and 40 percent CO_2 is typical. This composition was chosen as the representative biogas fuel. All tests were performed with the 60 percent CH_4 and 40 percent CO_2 fuel (blended from gas cylinders) and propane. Two electronic flow controllers were used to control the fuel supply during fuel-switching and single fuel operation.

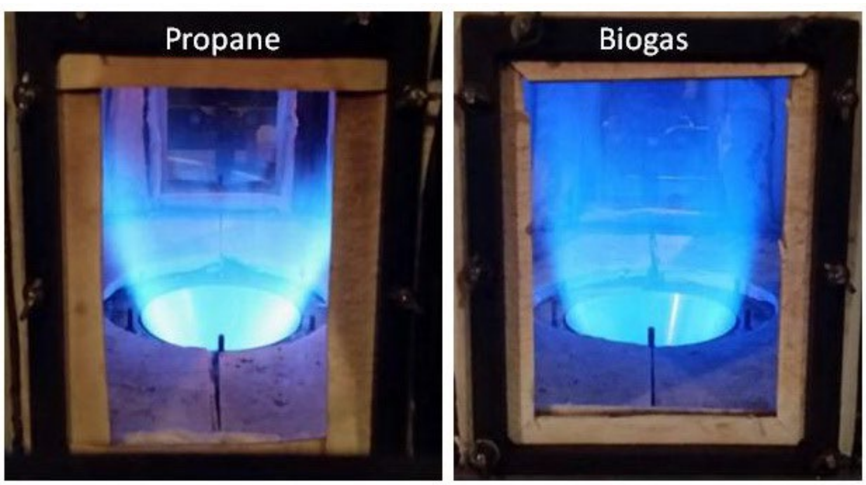
The control concept for the CWRP demonstration involves a closed loop feedback system with an O_2 sensor in the exhaust serving as an indicator for the fuel-air ratio. Measurement of CO_2

concentration in the exhaust is another indicator of the fuel-air ratio thus providing additional information to confirm the operating condition. From the O_2 and CO_2 concentrations in the exhaust, the system can respond by adjusting the volumetric flow rates of fuel and air according to the fuel loading map and a set performance target (i.e., load, T_{AD}). This control concept was implemented at UCI by enabling adjustments of air and fuel based on desired load and the relative percentage of propane compared to the 60 percent CH_4 and 40 percent CO_2 biogas.

The LSB were evaluated at rates of 200, 300 and 400 kBtu/hr which correspond respectively to one-half, three-quarter, and full load conditions of a full scale LSB at CWRP. Reference conditions for the tests were set to generate flames at T_{AD} = 1800K. Real-time fuel-switching tests between biogas to propane and vice versa were performed at these conditions. Additional tests were conducted at lower T_{AD} to evaluate the burner's capability to attain ultra-low emissions for biogas and propane. These tests started with the flame at a stable operation point; air is then added to lower the fuel-air ratio. As flame blow off was eminent, emissions at points close to the presumed blow off were recorded.

Figure 36 shows the biogas and propane flames generated by the 1/5-scale LSB prototype. The leading edges of the flames are nested inside quarl and only the tailing parts of the flame are seen. The thermal outputs for both flames are 382 kBtu/hr simulating the full load conditions (1.99 MMBtu/hr) of the CWRP boiler.

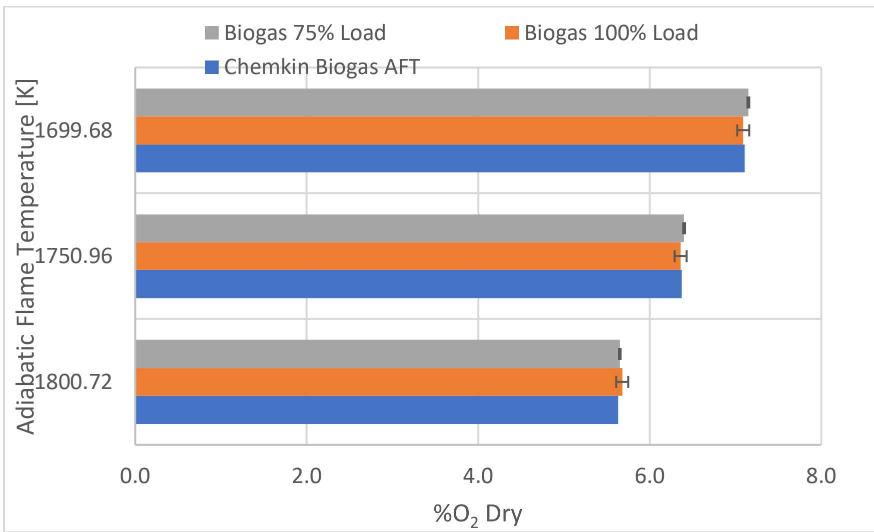
Figure 36: Flames Generated by the 1/5-Scale LSB in UCI Boiler Simulator



Real-time fuel-switching was successfully demonstrated by the 1/5-scale LSB at simulated full and three-quarter loads. The flame remained stable when the flow rate of one fuel was lowered and simultaneously the flow rate of the other fuel increased at a proportion according to the information given by the fuel loading map. The transition times at full and three-quarter loads were approximately 2 minutes. The duration of the transition was limited by the flow controllers' response times. Transition tests at half loads were also attempted but could not be completed due to the large uncertainties in the flow controllers when operating them at the bottom of their ranges. We expect the use of correctly sized flow controllers will show that the transition time at three-quarter and half load to be the same as at full load.

To demonstrate the feasibility of the close-loop control strategy, the concentrations of O_2 and CO_2 in the exhaust gas stream measured by their respective sensors were compared with the concentrations obtained from theoretical chemical kinetics calculations. Figure 37 compares the LSB O_2 emissions from biogas flames with O_2 concentrations calculated by CHEMKIN. As can be seen, the measured O_2 emissions at full and three-quarter loads, are very close to those calculated by CHEMKIN. The comparison between the measured and calculated O_2 exhaust concentrations for the propane flames also shows a high degree of consistency. These results confirm that the O_2 exhaust can be used as the control parameter for setting the fuel-air ratio at CWRP. In contrast, the measured and calculated CO_2 concentrations are not highly consistent. They show that CO_2 is not a reliable control parameter for our scheme.

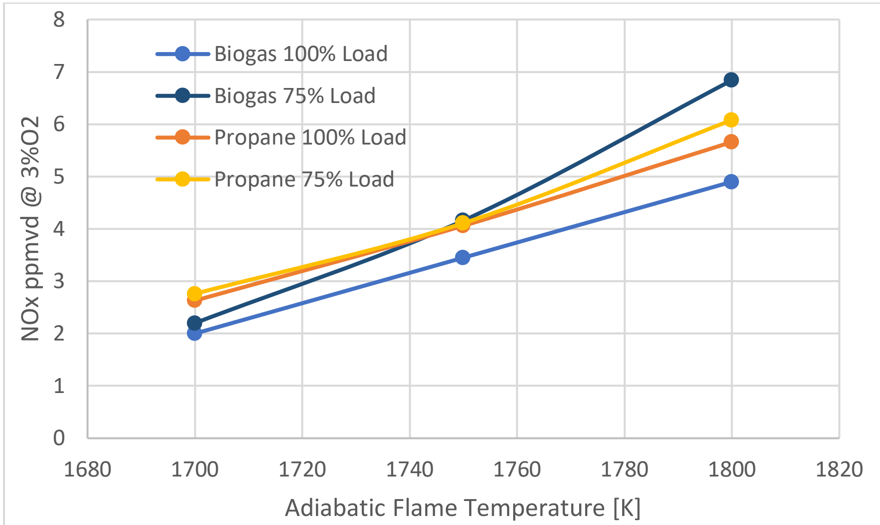
Figure 37: Comparison of Exhaust O_2 Concentrations from Biogas Flames



Two Loads Measured at UCI Boiler with Theoretical CHEMKIN Calculated at Three Adiabatic Flame Temperatures

The NO_x emissions from biogas and propane are shown in Figure 38. The emissions concentrations are corrected to 3 percent O_2 as required by air quality rules in California for stationary heating systems. These NO_x emissions data show a decreasing trend with adiabatic flame temperatures. Most significantly, these data are below the ultra-low 10 parts per million (ppm) (at 3 percent O_2) target, confirming that the design of the LSB with a composite fuel injector can meet our goals at full and three-quarter loads. However, the NO_x emissions at one-half loads are inconclusive. The inconsistencies are possibly due to the large uncertainties associated with operating the flow controllers at their bottom ranges.

Figure 38: NOx Emissions from the UCI Boiler with a 1/5-scale LSB



The tests performed at UCI show that the design of the 1/5-scale LSB prototype, fitted with composite fuel injector (with two separate fuel lines) and a flame quarl, meets all our operational targets for real-time fuel-switching and ultra-low NOx. This design would be the basis for scaling up to the full size burner to be installed at CWRP. The test results also confirm the functionality of the fuel load map for the propane/biogas system and the use of the O_2 concentration at the boiler exhaust as a control parameter for the feedback control scheme to be developed for the CWRP full scale burner.

Control System

As discussed in Chapter 3, the large difference in the fuel delivery pressures at CWRP is not amenable to our original idea which was to blend the two fuels before supplying to the low-swirl burner. Moreover, the fuel and air controller for the boilers do not have adequate precisions needed for controlling the transitional set points during fuel-switching. To minimize the high cost involved in designing, procuring, and installing a new dual-fuel system, the approach to controls real-time fuel-switching was to utilize much of the existing boiler control hardware and software supplemented by an auxiliary control system with hardware and software for fuel-switching. The auxiliary control system, fabricated and installed by a boiler controls subcontractor, operates synchronously and in parallel with the boiler control. The basic strategy is to use the boiler control to start the boiler with biogas or propane. After reaching a steady state, fuel-switching can be accomplished by activating the auxiliary control system connected to the new components.

Figure 39 shows schematics of the modifications made to the fuel lines for the boiler. For clarity's sake, the two fuel lines are shown separately. As seen, new components added or replaced included the LSB with a variable frequency drive (VFD) controlled air blower, a lambda sensor in the exhaust to monitor equivalence ratio changes and referee fuel composition, a fuel sensor upstream of biogas fuel valve to monitor fuel variability, pressure regulator for biogas to increase pressure from 15" water column to 10 psi to 15 psi, mass flow controller to replace an existing fuel/air valve for biogas, a flame arrestor in the biogas fuel line that operates at a higher pressure of 10 psi to 15 psi, and a mass flow controller replacing propane actuator valve. These new components are shown in blue (indicating new installations) and purple (indicating changes). The auxiliary system connects to these new hardware components as well as to some of the existing boiler components. It has a control panel that is separate from the boiler control panel. The control strategy and hardware modifications were presented to the engineering team at CWRP for review and endorsement prior to sourcing mechanical and electronic hardware from commercial vendors for boiler equipment installations.

Figure 39: Schematics of the Modified Fuel Trains for Biogas (Top) and Propane (Bottom)

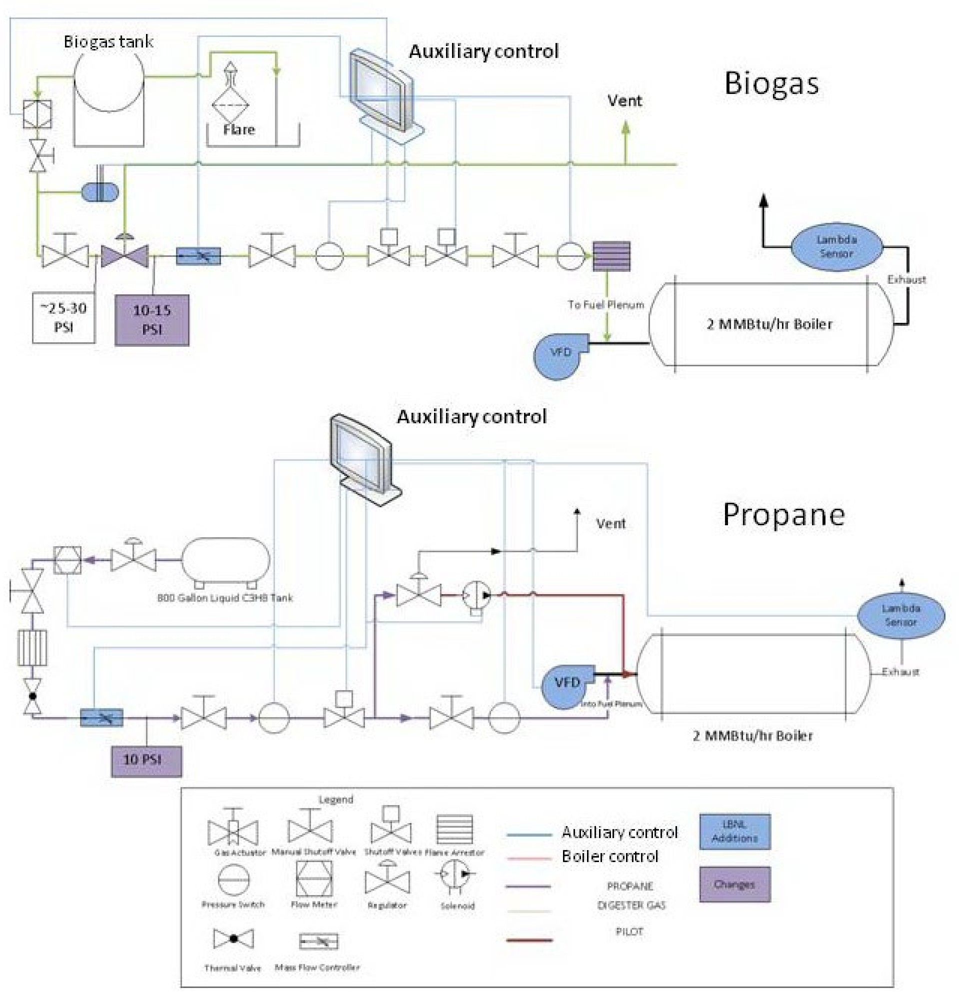
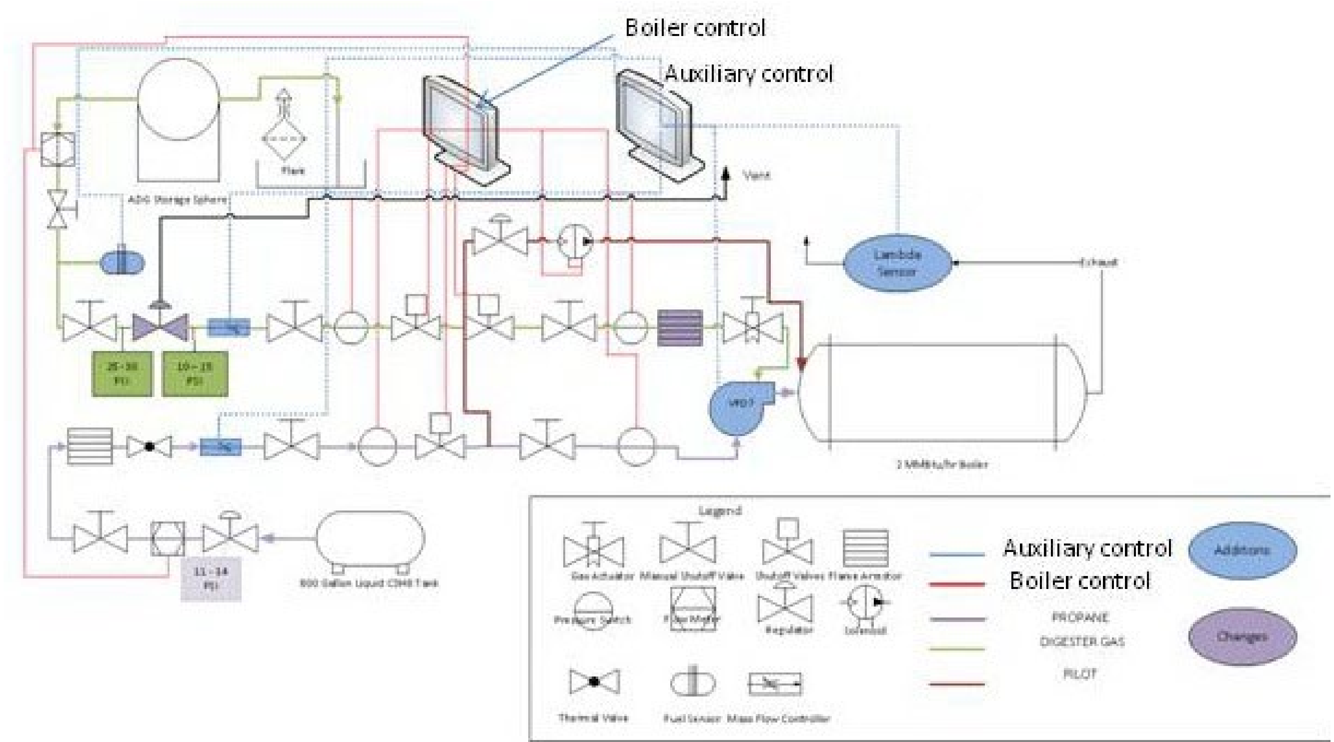


Figure 40 shows the schematics of the integrated control system for real-time fuel switching at CWRP. The existing components are seen in black, the new components in blue, and replacement components in purple. The role of the boiler control was to start the boiler at a given load and shut it down. The boiler control system remained fully functional for operations as monitoring the water temperature, and load. Fuel-switching was demonstrated only when the boiler reached a steady state at a given load by the auxiliary control system.

Figure 40: Schematics of the Boiler Control System to Demonstrate Real-time Fuel Switching



During fuel-switching, the role of the auxiliary control was to:

1. Use the mass-flow controllers to set fuel flow rates to maintain a steady load based on the feedback from the fuel sensor and setting from the fuel loading map.
2. Set air flow rates via VFD-controlled air blower based on feedback from fuel sensor and settings from the fuel loading map to maintain a predetermined fuel air ratio for NO_X and CO control.
3. Monitor air-fuel ratio with lambda sensor as a referee for gas compositions measurements.
4. Monitor all input parameters.
5. Monitor water temperature according to the same procedure and frequency as the boiler control.
6. Turn burner on when water temperature is below the set-temperature range.
7. Turn burner off when water temperature is within the set water temperature range.
8. Follow safety protocols by controlling single pole, single throw shut-off valve block on ADG line and shut-off valve on propane line.

The hardware and software for the auxiliary control system were provided by commercial vendors such that the demonstration burner system is essentially a pre-commercial prototype.

Engineering Guidelines for Fuel-switching LSB

As one of the main goals of this project is to apply the knowledge from demonstrating a LSB in a 1.99 MMBtu/hr boiler to other industrial heating systems, a set of engineering guidelines for a LSB that enables real-time fuel-switching was developed. These guidelines are intended for the design engineers to scale and size the LSB to systems smaller or larger than the CWRP boiler. As much of the research and development on the LSB involved natural gas, a set of engineering guidelines for scaling the LSB from 50 kBtu/hr to 100 MMBtu/hr was developed. These guidelines, listed below for the three LSB components, served as the starting points for developing the engineering guidelines for the fuel flexible propane/methane/biogas systems.

The Fuel-switching LSB Nozzle

In almost all respects, the engineering guidelines for the fuel-switching LSB nozzle are the same as those for natural gas except for a modification of the guideline for sizing the nozzle diameter when fitted to a combustion chamber. The main difference is in the fuel-injector/ premixer design. The modified guidelines can be applied to scale the fuel-flexible LSB from 200 kBtu/hr to 10 MMBtu/hr heat output.

The basic scaling parameter of the LSB nozzle is its radius Rb. The optimum Rb can be determined by the following:

1. Apply constant velocity scaling, i.e., at a constant bulk flow velocity of the reactants, the heat output is directly proportion to R_b^2.
2. The swirler is to be installed at a distance L of $2R_b$ to $3R_b$ from the exit.
3. Minimum bulk flow velocity of the reactants is to be set above 9 m/s to prevent flame flashback. In general, LSB can operate above 100 m/s.
4. For LSB firing into a combustion chamber, the burner radius, R_b, could be 1/4 of the chamber radius to account for the larger biogas flame (than the natural gas and propane flames) that has a lower heat release density due to its lower heating value. The recommendation ratio for natural gas and propane LSB is 1/3.

The design parameters for the swirler are the ratio of the center channel radius (R_c) to the burner radius (R_c) R_c/R_b, the vane angle α, the number of vanes installed in the annulus, the aerodynamic shape of the vane, and the blockage ratio of the center channel screen. Guidelines for these parameters are:

1. $0.5 < R_c/R_b < 0.8$, larger R_c/R_b increases drag (i.e., requires air pressure to drive LSB).
2. Vane angle $37^0 < \alpha < 45^0$, larger α increases drag and create high shear turbulence that may lead to flame instability.
3. Number of vanes can be between 8 to 16.
4. Vane profile can be curved, tear-drop shape or straight. Aerodynamic shaped vane profile (i.e., curved, tear-drop shaped) reduces drag; straight vanes increase drag but lowers manufacturing costs.

The blockage ratio of the center screen is specified explicitly because it varies with specific swirler configuration (i.e., values for R_c/R_b, α and the number of vanes as well as the vane profile). For a specific swirler configuration, the purpose of the center screen is to set the swirl number of the swirler, S, to between 0.4 and 0.55. There are two approaches to set the swirl number:

1. This step can be accomplished after a prototype of the swirler is fabricated. First, the drag coefficient of the swirl annulus needs to be determined. Then, select a perforated plate with blockage ratio that has a drag coefficient which when combined with the drag coefficient of the swirl annulus according to the LSB's swirl number definition, gives a swirl number within the design target range of 0.4 to 0.55.
2. The alternative is to use computational fluid dynamics to estimate the drag coefficients of the swirler annulus and center-plate designs.

The geometry of the perforated plate is not important. Larger opening may be preferred to avoid clogging.

The LSB swirler designed for CWRP has 16 constant radius curved vanes with an exit angle of 37^o. The vanes are attached to a center channel of R_c/R_b of 0.6. A perforated plate with 40 percent opening is fitted to the center channel. The swirl number of this swirler is S = 0.5. The design can be scaled linearly using the LSB nozzle diameter as the independent variable.

Fuel-injector/Premixer for Fuel-switching

To enable fuel-flexible operation, the design of the fuel-injector/premixer must be optimized for the differences in the heat contents and molecular weights of the different fuels. For a natural gas/propane/biogas LSB, the fuel injector developed for the CWRP LSB has two separate fuel circuits each with its dedicated set of fuel injection orifices. One fuel circuit is for natural gas and/or propane, and the other is for biogas. The unit is an integration of two fuel injectors into a streamlined unit in which propane/natural gas is injected through one set of orifices and biogas through another set. For larger diameter burners where space restriction may not be a major concern, two separate fuel injectors can be used. This will lower the cost of manufacturing. Regardless of which fuel injector configuration is considered (integrated or separated), computation fluid dynamics can be used for sizing of the fuel orifices and optimizing the injector geometry and their placement positions. The criteria for evaluating the effectiveness of the design are: (1) a homogeneous premixture is produced when one of the fuel injection orifices is used, and (2) the premixture being supplied to the LSB swirler has a uniform velocity distribution with minimal flow imprint associated with the flow around the physical body of the injector.

Flame Quarl

The flame quarl prevents the LSB flame from interacting with the corners at the entrance of the combustion chamber. The quarl is conical shaped and has a half angle less than the vane angle α. Generally, a flame quarl that expands from the LSB nozzle to twice the nozzle radius (2Rb) is sufficient. Long quarls with exit openings up to $3R_b$ are also used (as seen in Maxon's

LSB commercial products). Since the LSB does not touch the inner wall of the quarl, it can be made from conventional materials.

Blower and Plenum Considerations

The function of the air blower and flow plenum is to generate a uniform flow of air with minimum flow non-uniformity. An effective and simple approach is to attach the air blower directly to the LSB. This is the configuration selected for the CWRP LSB. However, this straight-in flow configuration is not practical for many installations because it requires a large space outside of the boiler unit. Space saving configurations, such as that adopted by Maxon for their LSB commercial products, have the air blower mounted above the burner nozzle. Air is delivered perpendicular to the burner axis into a windbox which redirects the air into the LSB. As the air passage inside the wind box/plenum has many turns, shear flows (due to flow separation) and even large-scale spiraling motions may be present when the air enters the LSB. These flow non-uniformities, if not mitigated, can affect the LSB performances and may even render it inoperable. Consequently, means to mitigate flow separation and rotational fluid motions are necessary when designing the wind box/plenum for the LSB. Usually, such means can simply be flat guide vanes or flow straighteners placed strategically inside the wind box. Computation fluid dynamics has shown to be an effective tool for guiding the windbox design.

CHAPTER 5:
Fuel-switching LSB for the Demonstration

1.99 MMBtu/hr LSB for CWRP Boiler

The burner for the 1.99 MMBtu/hr Johnston Boiler at CWRP is a direct scale up from the design of the 1/5-scale burner that tested at UCI. Shown in Figure 41 is the engineering drawing of the LSB nozzle and quarl whose configurations are in accord with the engineering guidelines presented in the previous chapter. The LSB nozzle has an inner radius of R_b = 5”. The dual fuel injector (described in the previous chapter) with separate inlets for each fuel is positioned 14” downstream from the air blower inlet and 13” upstream of the swirler inlet. The swirler design is a direct scale up of the model CV37-16 described in Chapter 4. It has a center of $0.6R_6$ with the swirl annulus having 16 constant radius vanes with 37-degree discharge angle (Figure 42). The full-scale swirler was fabricated from 3D printing by Direct Laser Metal Sintering. Its centerplate containing 37 strategically placed holes of 0.03” diameter is welded to the center channel of the swirler. The swirler is mounted on a bolted flange and has a distance of 5” from the top of the swirler to the entrance to the quarl section.

Figure 41: Engineering Drawing and Renderings of the LSB Nozzle and Quarl for the Johnston Boiler at CWRP

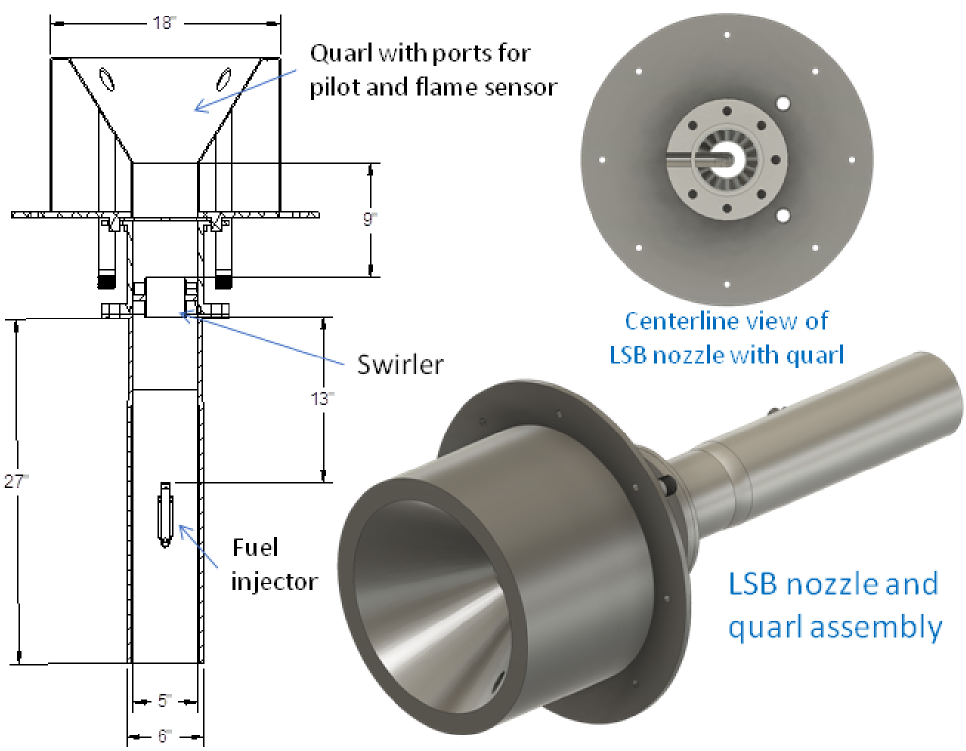
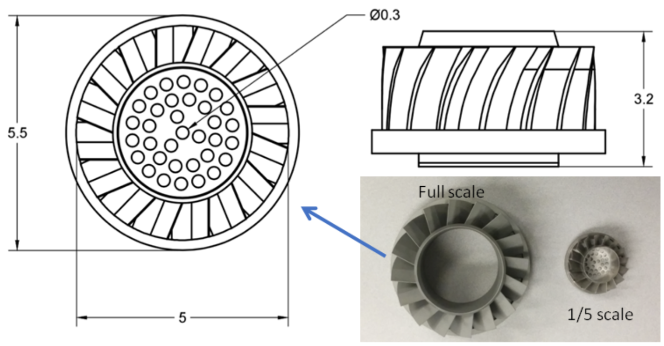
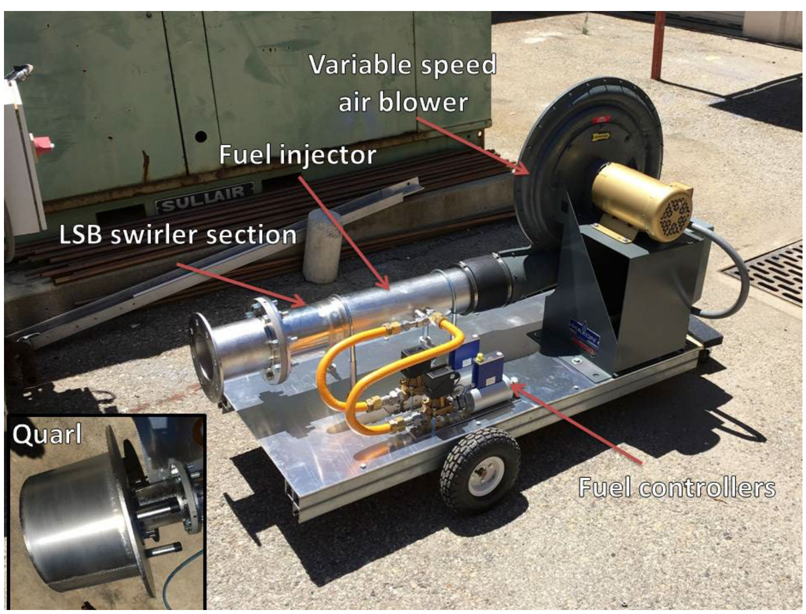


Figure 42: Engineering Drawing of the Swirler for the LSB Installed in the Johnston Boiler and a Comparison of its Size to the 1/5-scale Prototype



The quarl assembly has a straight section connected to a 30-degree divergent section that extends to 15” in diameter with the exit flush with the entrance wall of the boiler. As seen in Figure 41, the net distance from the swirler to the divergent quarl is 9”. The quarl section is nested inside a cylindrical housing that provides strength supports. The flange of the quarl section serves as the mounting plate to the Johnston boiler. On the conical face of the quarl are two ports, one to house a pilot flame to light the LSB and the other to mount a flame sensor as a safeguard monitor. These are the necessary components for boilers. The two ports were designed to accommodate the pilot and flame sensors used for the existing Alzeta burner to allow the existing boiler control system to start the boiler and monitor the flame. Almost all LSB components were made from steel for low cost, ease of manufacturing, and durability.

Figure 43: LSB for the Demonstration is Mounted on a Skid for Ease of Installation at CWRP

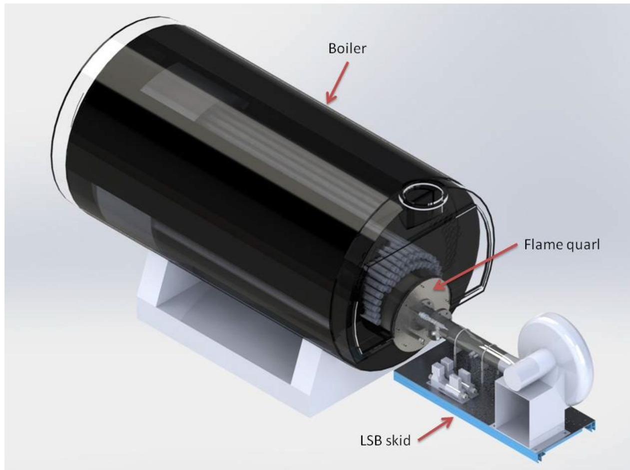


Flame quarl shown in insert has not been attached

The burner assembly is seen in Figure 43 with the components mounted on a skid for easy transportation and installation at the CWRP site as well as for direct integration into the plumbing and control system of the boiler. The assembly consists of a variable frequency drive

(VFD, Franklin GS-Series) for the air blower (Maxon) that connects the LSB nozzle. Two fuel mass-flow controllers (Bronkhorst), one for propane and the other for biogas supply fuel to the two separate lines of the fuel injector. A rendering of the LSB mounted to the boiler is shown in Figure 44.

Figure 44: Rendering of the LSB Skid Mounted to the CWRP Boiler with the Flame Quarl as the Connecting Piece



Laboratory Commissioning of Fuel-switching LSB

Test Procedure

Prior to the first firing of the full-scale LSB, the fuel mass-flow controllers were calibrated to account for possible effects caused by the pressure drop through the fuel circuit. The calibration instrument was a NIST traceable Laminar Flow Element (Merriam model 50MW20-2 rated at a max flow of 41.467 CFM at 8" H_2O). By setting a fixed input current to the propane and biogas flow-controllers, the NIST instrument reported flow volumes that were consistent with the manufacturer's calibrations. Next the pressure drops across the fuel injectors were measured at different load points and the results show linear trends that confirm the functionality of the fuel delivery and control circuit.

Initial testing of the LSB was performed at UCI using natural gas as fuel. Even though natural gas is not available at CWRP for the demonstration, it was used for the initial tests because of its availability at UCI. Previous experiences in commissioning LSB had shown that once the LSB is optimized for natural gas, it can operate with most other hydrocarbon fuels except for those with over 50 percent hydrogen. First tests of the LSB were conducted with the flame burning in open air without the flame quarl. Firing in the open is a necessary step to verify that the LSB nozzle is capable of generating the divergent flow critical for stabilizing lean flames. Additionally, visual inspection of the flame position is important to infer if adjustment to the swirler (via changing the blockage ratio of the center plate) is needed to optimum flame position.

The first firing of the full-scale LSB with natural gas was successful and the performance of the burner was consistent with previous developments e.g., ease of lighting-off. A photograph of a natural-gas/air flame generated by the full-scale LSB is shown in Figure 45. Because the test was conducted in bright daylight, the flame was barely visible and was rendered as a faint blue object above the burner nozzle. The conical flame silhouette was the same as those generated by the 1/5-scale prototype. The full-scale LSB was also tested at various load points and equivalence ratios. The pollutant emissions at the flames were consistent with those from the 1/5-scale prototype confirming that the scaled-up fuel injector and premixer produce the expected results. A second set of tests with natural gas was conducted using the flame quarl and verified the functionality of flame quarl in terms of assisting the formation of the divergent flow without affecting LSB performance.

Figure 45: Lean Methane/Air Flame Generated by the Full-Scale LSB Prototype

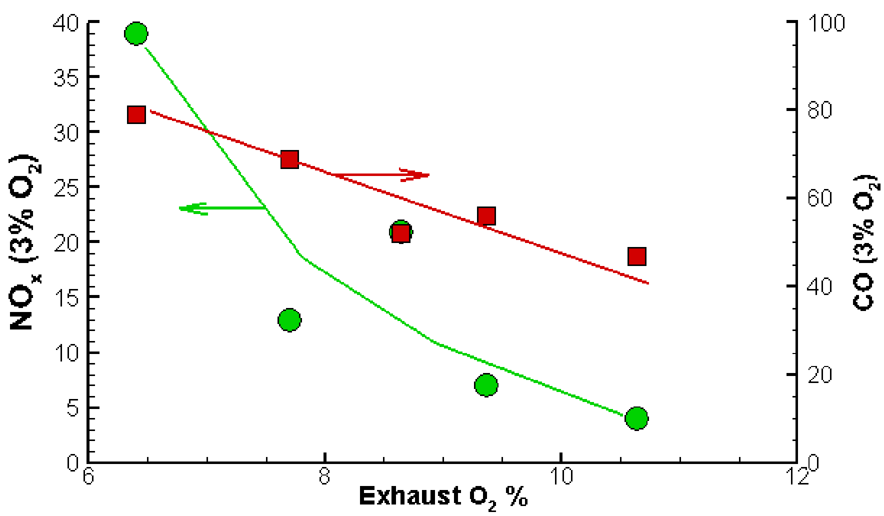
The second set of tests was conducted using propane as fuel. Additionally, an 18" stainless steel duct was used to simulate the combustion chamber of the boiler (Figure 46). The duct slipped over the quarl and a loose fit was intentional to leave the quarl in an as-is condition for mounting in the boiler. As such, the test configuration did not replicate the sealed enclosure of the boiler combustion chamber but was acceptable to examine the behavior and some characteristics of the enclosed flames.

Figure 46: Setup to Commission Full-Scale LSB Using an 18" Steel Duct to Simulate Combustor Enclosure

Tests of the enclosed LSB with propane were performed at full load of 2.0 MMBtu/hr at near stoichiometric to lean conditions by increasing air flow while maintaining a constant fuel flow rate. Lean blow-off tests were conducted at partial loads from 1.0 to 1.4 MMBtu/hr by reducing the fuel flow rate while running the air flow at a constant rate. The general behavior of the flames was as expected with the stable flame generated at all conduction except at near blow-off. Emissions were sampled at the exit of the ducts. However, O_2 concentration at the exhaust was higher than expected indicating that the flow acceleration inside the duct generated by combustion heat release entrained a significant amount of outside air. The fact that the two ports on the quarl were unsealed provided air entrainment passages in addition to the unsealed fitting between the quarl and the duct. Nevertheless, the NO_x and CO emissions from these tests has shown that the system is capable of burning at ultra-lean conditions.

Shown in Figure 47 are the NO_x and CO emissions at full load of 1.99 MMBtu/hr. Note that the exhaust O_2 percentages of 6 percent to 11 percent are significantly higher than the typical values of less than 6 percent in a sealed combustion system. Despite these measured high O_2 concentrations, when corrected to 3 percent O_2 according to emissions reporting regulation, NO_x emissions show a trend consisted with those observed in other lean premixed combustion systems and attain below 9 ppm at 3 percent O_2. The CO emissions on the other hand, are higher than expected most likely due to a combination effect of air dilution and incomplete combustion.

Figure 47: NO_x and CO Emissions from the Full-Scale LSB Operating with Propane at 1.99 MMBtu/hr



The unsealed port on the quarl during the propane test created a problem because air entering through these ports caused skewness in the flame that generated a hot-spot on the quarl surface. Due to uneven heating, the quarl surface became uneven and needed to be repaired. Uneven burning is not expected to occur when the LSB is installed in the demonstration site boiler because the two ports will be sealed by the flame sensor and pilot.

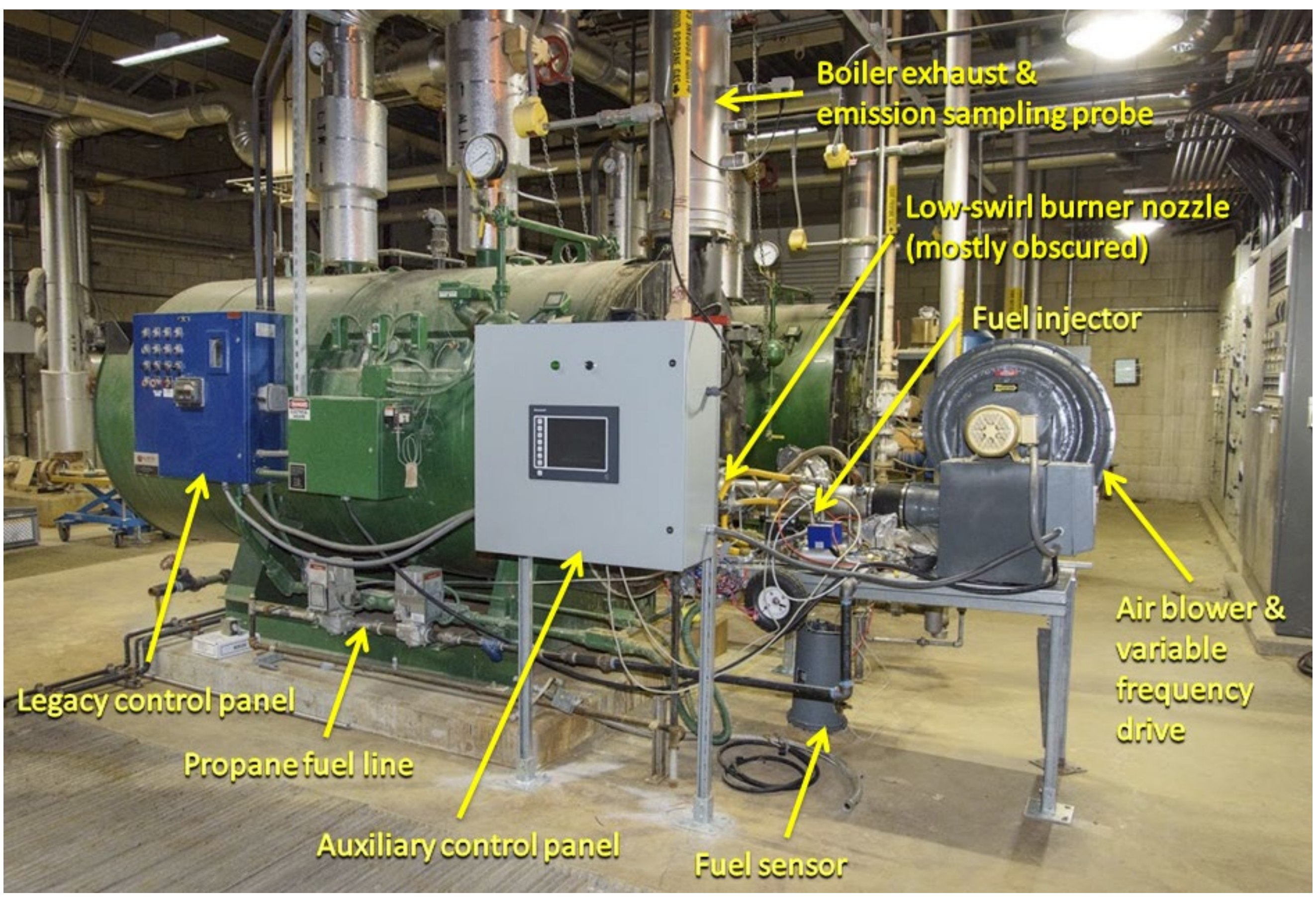
CHAPTER 6: Fuel-switching Demonstration

Boiler Layout

The installation of the LSB and the control hardware for the auxiliary system was performed by Porter Boiler Service of Signal Hills in Southern California. The company has a contract with CWRP to service and maintain the two boilers and the technicians have the expertise and vast experience necessary to adapt the LSB to the Johnston boiler. The integration of the electronics for the auxiliary control system and programming of the control software were performed by George T. Hall Company of Anaheim in Southern California. The company specializes in control system integration for large combustion devices. The two companies have a long-standing working relationship.

To prepare for the installation of the LSB, the Alzeta burner was removed from one of the two boilers and the interior of the combustion chamber was cleaned. These are typical normal servicing procedures for the Johnston Boilers. This was followed by adding additional control valves and fuel sensor to the fuel lines, mounting, and pluming the LSB to the boiler and installing the auxiliary control panel.

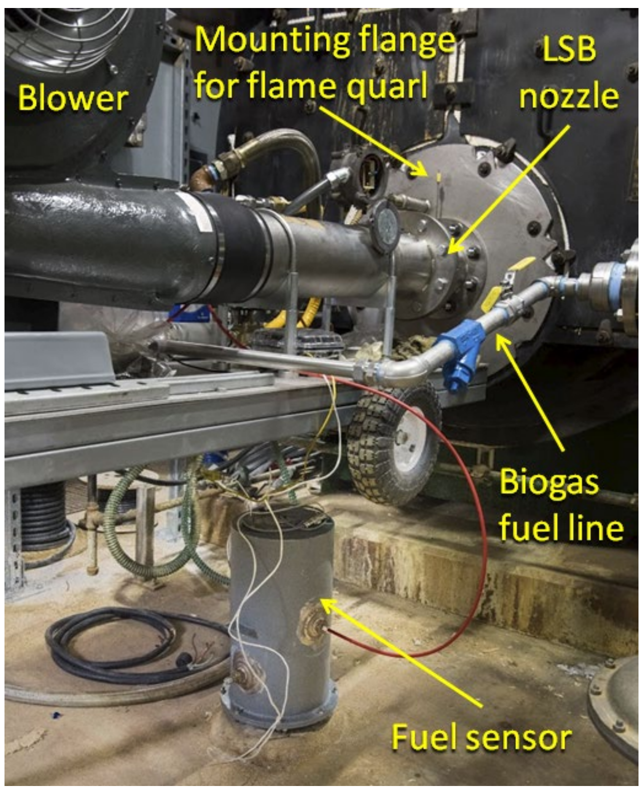
Figure 48: Photograph of the Boiler to Demonstrate Real-time Fuel-switching



The photograph of the modified boiler (Figure 48) shows the LSB skid elevated to a level in line with the boiler's combustion chamber and the fuel sensor is seen below. The auxiliary control panel which controls the boiler for real-time fuel-switching was housed in a separate standard metal case. It should be noted that the hardware inside occupied only a small volume. The electronics were connected to the legacy control panel to its left and to the electronic fuel controllers and the variable frequency air blower drive on the LSB skid. As discussed in Chapter 4, the legacy control system was used to start the boiler on either biogas or propane. Upon reaching a steady state, the auxiliary control system was used to switch the fuel from one to the other according to a set of conditions that maintain the flame burning at a fixed adiabatic flame temperature.

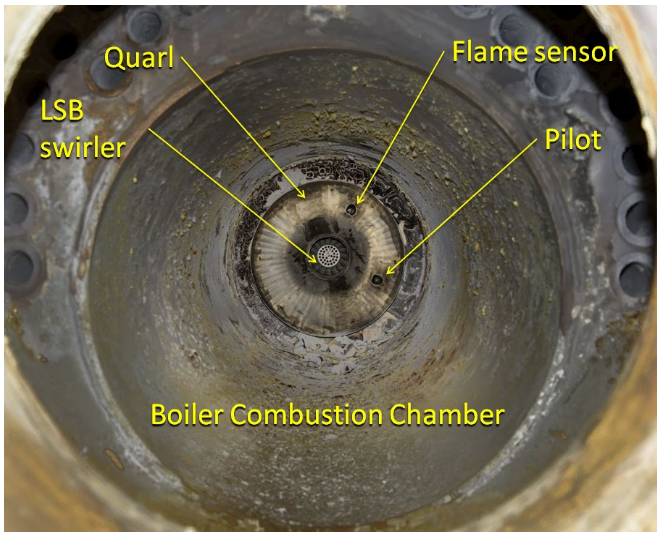
Figure 49 shows the LSB was mounted to the boiler by a flange built into the flame quarl. The length of the flame quarl was designed so that its exit was flushed with the entrance of the combustion chamber. Also seen is the fuel sensor placed on the floor. This fuel sensor was fabricated based on the geometry illustrated in Figure 24. It is larger than the second prototype shown in the photography of Figure 22.

Figure 49: LSB Mounted to the Boiler



The interior view of the combustion chamber with the LSB is seen in Figure 50. This photograph was captured when the end-wall of the boiler was removed. The LSB was mounted centrally in the cylindrical combustion chamber of 21″ diameter and 8′ long. The chamber diameter is slightly larger than the quarl exit diameter of 18″. The Porter Boiler Service technician used refractory foam insulation material to seal the gap between the quarl and the combustion chamber. The openings for the pilot and the flame sensor were built into the wall of the quarl. At start-up, the pilot used propane to generate a jet flame to ignite the fuel/air mixture delivered through the LSB nozzle. Once the flame sensor detects a LSB flame, the pilot was shut down. The flame sensor continued to monitor the LSB flame during normal operation and fuel-switching. If a flame was not sensed by the flame sensor, the boiler would shut down.

Figure 50: Interior View of the Combustion Chamber with the LSB



Demonstration Steps and Goals

The demonstration at CWRP was conducted by following the steps below. Each step has a specific goal toward achieving the objective of demonstrating real-time fuel-switching in an industrial scale heating system.

Commission Control System

Goal: Operate non-reacting flows to verify the hardware and software of the auxiliary control system and its compatibility with the legacy control system

1. Operate blower
2. Operate biogas control valves
3. Operate propane control valves
4. Operate pilot
5. Purge system and shutdown

Commission Johnston Boiler Fitted with LSB

Goal: Verify operating LSB with the legacy control system for propane and biogas

Operate with 100 percent biogas (0.58 CH_4 - 0.42 CO_2) at 0.95 percent O_2 dry (ϕ = 0.95, T_{ad}≈2000K)

1. Purge and light off with biogas at partial load of 75 percent
2. Check flame stability, flow rates, flow conditions

3. Ramp to 90 percent load, check flame stability, attain steady state, then record biogas composition, flow rates, emissions, flow conditions
4. Increase air to 2.17 percent O_2 dry (ϕ = 0.88, $T_{ad}\approx$1900K), check flame stability, attain steady state, then record biogas composition, flow rates, emissions, flow conditions
5. Shutdown boiler
6. Make adjustments if necessary

Operate with 100 percent propane at 3.93 percent O_2 dry (ϕ = 0.8, $T_{ad}\approx$2000K)

1. Purge and light off with propane at partial load of 75 percent
2. Check flame stability, flow rates, flow conditions
3. Ramp to 90 percent load, check flame stability, attain steady state, then record flow rates, emissions, flow conditions
4. Increase air to 5.95 percent O_2 dry (ϕ = 0.7, $T_{ad}\approx$1880K) check flame stability, attain steady state, then record flow rates, emissions, flow conditions
5. Shutdown boiler
6. Make adjustments if necessary

Demonstrate Real-time Fuel Switching

Goal: Verify operating LSB with the auxiliary control system for real-time fuel switching

Operate at 90 percent load with 100 percent biogas at 0.95 percent O_2 dry (ϕ = 0.95) and transition to 90 percent load with 100 percent propane at 3.93 percent O_2 dry (ϕ = 0.8)

1. Purge and light off with biogas at 90 percent load using legacy control system and attain steady state and record biogas composition
2. Use auxiliary control for transition to 100 percent propane at 20 percent increments (intermediate conditions entered from touch screen according to a lookup table), check flame stability during transition (rate of transition will be determined by flame responses to changes)
3. Attain steady state with propane, then record flow rates, emissions, flow conditions
4. Shutdown boiler

Operate at 90 percent load with 100 percent propane at 3.93 percent O_2 dry (ϕ = 0.8) and transition to 100 percent biogas at 0.95 percent O_2 dry (ϕ = 0.95)

1. Purge and light off with propane at 90 percent load using legacy control system and attain steady state
2. Use auxiliary control system for transition to 100 percent biogas at 20 percent increments (intermediate conditions entered from touch screen according to a lookup table), check flame stability during transition (rate of transition will be determined by flame responses to changes)
3. Attain steady state with biogas then record biogas composition, flow rates, emissions, flow conditions
4. Shutdown boiler

Independent Verification of Emissions by FerCo

Goal: FerCo connect emissions sampling equipment to boiler exhaust and operate boiler to make independent measurements of exhaust emissions

Verify emissions from 100 percent biogas

1. Purge and light off with biogas at 90 percent load at 0.95 percent O_2 dry (ϕ = 0.95)
2. Check flame stability, attain steady state, then record flow rates, emissions, flow conditions
3. Increase air to 2.17 percent O_2 dry (ϕ = 0.88) and 3.3 percent O_2 dry (ϕ = 0.82) check flame stability and attain steady state after each air change, then record biogas composition, flow rates, emissions, and flow conditions
4. Shutdown boiler

Verify emissions from 100 percent propane

1. Purge and light off with propane 90 percent load at 3.93 percent O_2 dry (ϕ = 0.8)
2. Check flame stability, attain steady state, then record flow rates, flow conditions
3. Increase air to 5.95 percent O_2 dry (ϕ = 0.7) and 7 percent O_2 dry (ϕ = 0.65) check flame stability and attain steady state after each air change then record flow rates, emissions, flow conditions
4. Shutdown boiler

Real-time Fuel Switching at 50 Percent Load (Optional)

Goal: Determine the robustness of the LSB for partial load for each individual fuel, fuel-switching at half load is optional

Transition from 100 percent biogas and to 100 percent propane

1. Purge and light off with biogas at 50 percent load
2. Transition to 100 percent propane at 20 percent increments
3. Check flame stability, flow rates, emissions, flow conditions

Transition from 100 percent biogas to 100 percent propane

1. Purge and light off with biogas at 50 percent load
2. Transition to 100 percent biogas at 20 percent increments
3. Check flame stability, flow rates, emissions, flow conditions

Demonstration Results

Commissioning Control System

The commissioning of the control system involved five steps as listed in the section above. The purpose was to verify that the communications between the legacy control system with the auxiliary control system were synchronous to control all functions of the burner and the boiler during normal operations and fuel-switching. Additionally, the commissioning process also served the purpose of refining the user interface of the auxiliary control panel to allow flexibilities in setting the conditions during fuel-switching.

Participants of the commissioning process included LBNL and UCI researchers and commercial boiler technicians Porter Boiler and George T Hall. All five steps (1) operate blower, (2) operate biogas control valves (3) operate propane control valves (4) operate pilot and (5) purge system and shutdown were accomplished after some minor adjustments.

Commissioning Johnston Boiler Fitted with LSB

The goal of this step was to verify the operation of the LSB using the legacy control system to perform normal functions such as light-off, shut down, load following as well as purging the boiler system. To start the boiler, the standard procedure was to purge the combustion chamber with air for a period of time to rid of any residual fuel. The next step was to ignite the pilot flame whose role was to ensure that the fuel being introduced to the LSB would be lit. This is an important part of safe operation of a boiler to prevent the combustion chamber from being filled with a large volume of a potentially explosive mixture of fuel and air. Once the flame sensor confirms that the pilot is lit and is stable, the control system sends a signal to open the fuel valve to allow fuel through the burner to initiate the main flame.

A problem was discovered while performing the light-off sequence in that the flame sensor could not detect the presence of the pilot flame even though the pilot flame was clearly visible to the human eye. Because the flame sensor could not confirm the presence of the pilot flame, the control system did not proceed to opening the fuel control valve. Instead, the control automatically truncated the start-up sequence after a time-out period and shut down the system. As a result, the boiler could not be started. Because the boiler was in an industrial installation, control sequence could not be overridden to allow for that fact that the pilot flame could be verified by human eyes. It would be a violation of standard boiler safety operation procedure.

In examining this problem, it was concluded that it was caused by two issues. First, the distance between the pilot and the flame sensor ports were too far apart for the sensor to detect flame luminosity (see Figure 50). Second, the pilot flame generated inside the LSB quarl was faint compared to the one generated in the original setting with the Alzeta burner. This first issue could only be addressed by positioning the two ports closer together. The second issue was due to the interaction of the pilot flame, which is basically a jet diffusion flame, with the different flowfields of the LSB and the Alzeta burner. The Alzeta burner utilized surface-stabilized combustion technology that distributed the fuel/air. The low velocities in the combustion chamber fitted with an Alzeta burner allowed for a bright yellow and long diffusion pilot flame. In contrast, the pilot flame of the LSB enters through the side the quarl where the flow velocity was high. During the start-up sequence, the cross-flow was pure air and thus the pilot flame received a significant amount of air entrainment and burned in a pale-blue lean premixed mode making it less readily detectable to the flame sensor.

Even though the issues with the pilot and flame sensors were problems typical of those encountered during the commissioning of a new burner system, a decision was made to terminate the work due to two main reasons: (1) The boiler at CWRP needed to be put back into regular service and the equipment schedule could not accommodate the extra time needed to modify the quarl for relocating the pilot and flame sensor ports, and(2) The end date for the project was near and the project performance period could not be extended to allow the completion of the demonstration at a later date.

CHAPTER 7: Findings and Recommendations

It is an understatement that all involved in the project were reluctant to terminate the project without reaching the ultimate goal of demonstration in a commercial boiler. However, the tasks performed leading to the demonstration had yielded a wealth of knowledge and significant insights to form the technological foundation and a basic engineering framework for the deployment of a real-time fuel-switching concept to commercial waste-to-energy systems.

The technological achievement of this project for the heating equipment industry was the development and validation of a real-time fuel-switching concept based on using the adiabatic flame temperature, T_{AD}, as a parameter to control the burner operating conditions during the transition from one fuel to the other. The foundation for this concept was the development of fuel-loading maps which consisted of T_{AD} data computed from fundamental combustion chemical kinetics of various fuel blends and fuel-air ratios. Advanced technologies and boiler control protocol for commercial implementation of this concept was developed and verified in laboratory settings. The first technology was a fuel sensor to provide feedback on fuel constituency to control burning at a fixed T_{AD} during fuel transition. The second technology is a fuel-flexible burner that maintained stable flames with ultra-low emissions during steady state and transient fuel-switching conditions. A boiler control system and protocol were also developed from commercial boiler hardware and software showing the readiness of the fuel-switching concept for industrial and commercial applications.

Development of the speed-of-sound fuel sensor for fuel-switching was to expand the identification range of a previous development for identifying slight variations in natural gas constituency. The goal was to capture the natural gas/biogas fuel system consisting of fuels with 0 percent to 60 percent CO_2 in CH_4. The first prototype fuel sensor was built from commercially available electronic distance sensors and was mounted in the biogas supply line at CWRP and tested successfully. Knowledge gained from the test led to a redesign of the dimension of the fuel sensor chamber and the selection of an ultrasonic distance detector to enable high precision throughout the fuel range for a natural-gas/biogas system. A second prototype with an updated design for installation at the CWRP boiler was constructed and its operation verified in the laboratory. It was mounted in the fuel supply-delivery circuit of the CWRP boiler. Even though the fuel-delivery system of the boiler at CWRP precluded the need for a propane/biogas fuel sensor, the basic layout and engineering framework was also developed for future development. These results showed the readiness of the speed-of-sound sensor technology for commercial applications.

Burner development involved designing a low-swirl burner that functioned as a retrofit for the boiler at CWRP. The first step was scaling the LSB to fit the size and geometry of the boiler's combustion chamber and optimize the various burner components for fuel-switching. The swirler, which was the heart of the LSB, was based on a design developed previously for ultra-low emissions gas turbines. This swirler tested at 1/5 scale had shown to support stable natural-gas, propane, and biogas flames that emitted NOx levels of less than 10 ppm. Another critical component of the LSB for the boiler was the fuel injector. To accommodate the different fuel propane and biogas pressures at CWRP, the fuel injector developed for the LSB had two separate fuel circuits for propane and biogas. This fuel injector was an elaboration of a simple "shower head" fuel nozzle. It integrated two such nozzles into a streamlined unit with separate fuel injection orifices for the two fuels. This composite fuel injector was tested at 1/5 scale and showed its capability to distribute the two fuels uniformly in the air stream to produce a homogeneous fuel/air mixture for the LSB to achieve its ultra-low emissions targets. A 1/5-scale prototype of a fully functioning LSB, i.e., one that consists of the main components of the swirler, the fuel injector, and a flame quarl, was tested in a boiler simulation facility at UCI. These tests produced the first experimental verification of real-time fuel-switching capability of the LSB and verified the control of T via air-fuel ratio allowed for switching from one fuel to the other without interruption.

Based on the findings from the 1/5-scale LSB tests, a full scale LSB for demonstration in the CWRP boiler was fabricated. To control the fuel and air supplies to this LSB, a suite of electronic hardware was selected and procured. Since the demonstration was developmental, the procured air blower and electronic fuel control hardware were more sophisticated than those for typical commercial boilers. This was necessary to attain precision control of the fuel air-ratio under ultra-low emissions operation and during fuel-switching. A "packaged" LSB unit was designed as a plug-in for ease of retrofitting to the boiler. The burner head (which included swirler, fuel injector, and flame quarl), the air blower, the fuel-controllers, and other plumbing hardware were mounted on a rolling skid. Operation of the LSB package was verified at UCI by firing into a cylindrical enclosure that simulated the geometry of the boiler combustion chamber. The results showed that the full-scale LSB package supported stable flames at full-load and partial loads that achieved an ultra-low emissions target of less than 10 ppm NO_x, corrected to 3 percent O_2. This showed the capability of the LSB to achieve ultra-low NO_x emission targets sought by California's air quality management districts. Intended as a general purpose retrofit the LSB package used the flame quarl as the connector to the combustion chamber. It had the flexibility to be converted for other boilers or heating systems by simply configuring the connector to fit the geometry of the combustion chamber.

The brain of the fuel-switching LSB was the control system. The original plan to redesign the fuel-delivery circuits and control the burner by a computer was deemed too complicated and disruptive to the boiler, which had to be brought back into service in its "as found" condition after the demonstration. Information gained from consulting with professional boiler engineering companies indicted that contemporary control hardware and software had attained advance capabilities to enable the control of the intermediate steps, albeit manually, to implement the fuel-switching protocol. With this knowledge, a decision was made to use commercial equipment for fuel switching control because the demonstration would be more compelling to show the readiness of the LSB system for commercialization.

The control hardware architecture and system protocol for the boiler were engineered by the LBNL and UCI researchers. Hardware installation and software programming to integrate the fuel loading maps were performed by professional boiler companies. The control system consisted of two main parts: (1) the "legacy" control system for the boiler was kept mostly intact and (2) an auxiliary control system was installed to operate synchronously with the legacy controls. Except for changing out few components, this control system made minimum alterations to the fuel delivery circuits of the boiler. The legacy control system was left mostly intact. It communicated with the electronic hardware of the LSB for boiler start-up and shutdown with either propane or biogas as fuel. The function of the auxiliary control was to set the intermediate step during fuel switching from propane to biogas or the reverse. These were the same steps taken in the laboratory to demonstrate real-time fuel-switching. The only difference is the laboratory experiments used a multi-function computer and the auxiliary control used dedicated commercial electronic controls interfaced with a touch pad panel. To switch from one fuel to the other required the operator to use the touch pad to manually key in the changes in the relative percentages of propane and biogas feeding the burner. The auxiliary system automatically computed and set the flow rates of fuel and air and the fuel-air ratio to maintain stable operation. By manually changing the set points, the intent was to gain insight on how many intermediate steps would be necessary and how rapidly the switch-over would be accomplished. With such knowledge, the auxiliary system could be re-programmed to include the transition step conditions and the transition time so that fuel-switching could be accomplished autonomously by pushing a button on the touch pad. With commercial equipment being used, the final control system could be operated by a trained and licensed boiler professional making it a pre-commercial prototype. Even though the LSB and its controls had yet to be commissioned and put into service in the boiler, the system showed that combustion heaters with real-time fuel-switching could be realized cost effectively without invoking specialized equipment.

The obvious recommendation henceforth is to seek support to complete the demonstration and show the real value of this project. It was regrettable that the project had to end when all the hardware and software were installed but the equipment and project schedules could not allow for the necessary trouble-shooting and refinement steps leading to the demonstration.

CHAPTER 8: Lessons Learned and Wisdom Gained

In technological development projects, it is expected that the proposed processes and pathway would need to be adjusted or changed to accommodate new discoveries and to address unforeseen issues. It is rare that a project could be completed without changes. During the course of this project a major change from the original proposed plan was made due to the discovery of some engineering constraints at the demonstration sites. Seeking resolution to these constraints led to an opportunity to pursue a demonstration plan that produced a product that would be closer to commercialization than originally proposed. In technology-transfer terminology, the demonstration unit described has a higher technology-readiness level that what was proposed to the California Energy Commission. Understandably, pursuing a higher technology-readiness level took on higher risks and caused much of the delays.

Conducting the technology demonstration at an operating plant was a rare opportunity that the researchers at LBNL and UCI greatly appreciated. However, installing the hardware and scheduling the demonstration, which were disruptive to the 24-hour year-round operation of the plant, meant very tight coordination and scheduling of plant and installer personnel that left little margin for unplanned events. Recognizing these time constraints earlier in the process could have prevented some of the delays. An extended performance period could also have been helpful to enable this project to reach its modified objectives.

The original plan was to demonstrate fuel-switching between natural gas and biogas with an option to demonstrate fuel-switching between propane and biogas. The intent was to blend natural gas into the biogas supply line and sample the changes in CH_4 concentrations as feedback to a controller built from a personal computer. Since natural gas was not as readily available at CWRP as propane and renting a natural gas tank was deemed both costly and disruptive to the plant's operation, fuel-switching between propane and biogas remained the sole option. Propane/biogas fuel switching involved a fuel system with three major components (i.e., C_3H_8, CH_4, and CO_2) making it a more challenging process than the two components (i.e., CH_4, and CO_2) natural gas/biogas fuel system. The propane and biogas were delivered to the CWRP boiler at different pressures, which added more complexity. The team contemplated re-engineering of the fuel-supply system to equalize the fuel pressures, but the estimated cost and effort for such a significant overhaul could not be afforded by the project budget. At one point, it was considered that the only option remaining was to limit the demonstration to a laboratory setting. The approach to integrate the legacy boiler control with an auxiliary control owed much to the ingenuity of Mr. Rich Hack, one of the UCI investigators of this project, whose clear insight into the boiler fuel circuit led to the solution that was pursued. Mr. Hack's unexpected passing deprived this project of a key technical contributor.

Implementing the propane biogas fuel-switching scheme required changes to the engineering design of the LSB system. A composite fuel injector to accommodate the different fuel pressures as described in Chapter 4 was essential. Having separate fuel inputs to the LSB allowed for retaining most of the existing fuel control hardware for the boiler. More significantly, the auxiliary control system, which had to operate synchronously with the legacy control system, could be built using commercial hardware and electronics control components. Trained boiler professional technicians could install the auxiliary control hardware and program the auxiliary control processor to include the fuel-loading map. As such, the LSB system built and installed, albeit not operated, at the CWRP boiler was essentially a pre-commercial prototype of a retrofit to operate a boiler with real-time fuel-switching capability. Even though the demonstration of this system was not complete, to strive for and build a system with a higher technology-readiness level than originally planned were well worth the extra effort and risk. As gaining the support from the equipment installers and operators is essential to the development and commercialization of new technologies for heating, the pre-commercial LSB prototype with a control system that could be adapted to many boiler and heating systems remained a valuable asset to promote waste-to-energy in California.

The important lesson of the project is that the problem with the flame sensor and pilot could have been discovered and corrected earlier had the two pieces of equipment been available for the commissioning tests at UCI. Unfortunately, the flame sensor and pilot were working parts of the boiler at CWRP and were not available for testing with the LSB until the boiler was modified and fitted with the new burner system.

The participation of boiler professionals to prepare and install the demonstration unit was not in the original plan. Though the two companies performing the tasks were familiar with advanced clean energy systems, many aspects of the works contracted were unlike their typical services. The LBNL and UCI researchers could have facilitated progress by providing clearer and more frequent communications with the boiler professionals on the technologies and the overall approach.

Much of the engineering challenges to the development of the demonstration system were associated with retrofitting an advanced system to an existing boiler. However, burner retrofitting is a common practice because replacing the burner is a routine maintenance practice for heating systems. To retrofit a boiler or industrial oven for fuel-switching, a lesson learned from this project is that the on-site fuel delivery systems would need to be modified to allow simultaneous delivery of the two fuels to the burner. The fuel-system changes and thus the control hardware would be different for each individual case. Retrofitting a fuel-switching system would be a customized endeavor. For new systems, the insight from this project could be applied to design a basic fuel delivery and control system optimized for fuel-switching. Standardizing the approach for fuel delivery and controls would help to promote the fuel-switching technology for new installations.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ADG	anaerobic digester gas is produced by anaerobic digestion of biodegradable materials (e.g., organic waste), which is a biological process in which microorganisms break down biodegradable material such as animal wastes in the absence of oxygen
Anaerobic digestion	A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen
biogas	biogas is a gaseous fuel derived from biodegradable materials principally composed of methane (CH_4) and carbon dioxide (CO_2). ADG is a type of biogas produced by anaerobic digester process
biomethane	A gaseous fuel produced by purifying biogas to remove most other substances for injection into natural gas line for distribution and consumption
blowoff	A phenomenon in which the flame extinguishes during normal burner operation
Btu, kBtu, MMBtu	British thermal unit, kBtu = 1,000 Btu, MMBtu = 1,000,000 Btu
c	speed of sound - propagating speed of sound wave in a fluid (e.g., air, gas, or water). It is a property of the molecular weight of the fluid, temperature, and pressure
CEC	California Energy Commission
CH_4	methane
CO	carbon monoxide, a poisonous gas that is a byproduct of combustion
CO_2	carbon dioxide
CWRP	Chiquita Water Reclamation Plant
digestate	Solid materials remaining after the anaerobic digestion of a biodegradable feedstock
ϕ equivalence ratio	In the context of this report, the equivalence ratio is an indicator of the whether the fuel-air mixture is fuel-rich or fuel-lean
flashback	A phenomenon in which the flame burns back into supply line. Flashback has the potential of causing serious damages to the combustion equipment
Fuel-flexible	In the context of this report, fuel-flexible means a combustion system that can be adjusted to operate on different fuels
Fuel-switching	In the context of this report, fuel-switching means a combustion system than has the capability of operation on different fuels and switch from

Term	Definition
	one fuel to another during normal operation without requiring system shutdown and purge
K	degrees kelvin
kHz	kilohertz
LBNL	Lawrence Berkeley National Laboratory
leachate	A highly corrosive toxic liquid generated by decomposing wastes in landfills
LCD	liquid-crystal display
LSB	low-swirl burner, an ultra-low emissions lean-premixed combustion technology
Metric ton	Unit of weight equivalent to 1,000 kilograms
NDIR	nondispersive infrared
NOx	oxides of nitrogen, a harmful byproduct of combustion that is an aid pollutant
NREL	National Renewable Energy Laboratory
HHV	higher heating value – a parameter quantifying the heat potential of a gaseous fuel
PIV	particle image velocimetry – a laser-based diagnostic method that measures the velocities (in two dimensions) in fluid flows (e.g., a flame or flow around aerodynamic objects)
ppm	parts per million - concentration of a given gas molecule in a gas mixture
ppm at 3 percent O_2	ppm concentration of a given gas molecules in a gas mixture corrected for oxygen to compare emissions concentration, e.g., NO_x and CO on an equivalent basis. Exhaust concentrations of the pollutants are corrected to reference 3 percent oxygen using a standard equation
premixed combustion	Burning of a mixture of fuel (e.g., biogas or propane) and oxidizer (e.g., air)
psi	pounds per square inch
PVC	polyvinyl chloride
recirculation	In fluid mechanics, this term represents fluid flows with forward and backward flow regions
S	swirl number
S_L	laminar flame speed
scf	standard cubic foot
stoichiometry	Calculation of reactants and products in chemical reactions such as the reaction of methane and propane with air

Term	Definition
swirler	A mechanical device engineered to impart rotational motions (swirl) in a stream of moving fluids (e.g., combustible fuel/air mixture).
T	Absolute temperature °K
T_{AD}	adiabatic flame temperature – idealized temperature attained by combustion of a given fuel and air mixture assuming that no heat lost to the environment
UCI	University of California at Irvine
VFD	variable frequency drive
$w = C_3H_8/(C_3H_8+CH_4)$	Parameter used in the fuel loading map that represents the ratio of C_3H_8 and CH_4 concentrations in the fuel
Wobbe Index	Engineering parameter to estimate the similarity or differences of various gaseous fuels
$z = CO_2/CH_4$	Parameter used in the fuel loading map that represents the ratio of CO_2 and CH_4 concentrations in the fuel

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Appendix A: Hardware and Engineering Services for Fuel-Switching Demonstration at CWRP

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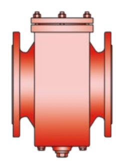
APPENDIX A:
Hardware and Engineering Services for Fuel-Switching Demonstration at CWRP

Table A-1 lists the pieces of hardware equipment installed in the boiler at CWRP to control real-time fuel-switching demonstration.

Table A-1: Hardware Used for Fuel-Switching Demonstration

Hardware & Services	Description	Supplier
Bosch Lambda 4.9 Sensor	Exhaust Oxygen Sensor 	Bosch (Distributor Huntingdon Beach)
Protego FA-CN-IIA1 In-line Arrestor	In-line Deflagration Flame Arrestor (max press. 36.3 psia; stainless steel housing) 	Protego
Itron B35R; Orange Spring	Itron gas pressure regulator (200psig max) 	Itron
Propane and Biogas Mass Flow Controllers	400 LPM and 2X 1000 LPM 	Brooks
Baldor variable frequency drive	AC INVERTER 460V,15H,5/7.5/10HP 	Practtecllc
Maxon Air Blower	Series FG Blower 	Maxon
LSB installation	Plumbing, electrical wiring Electronics and installations	Porter Boiler Services
Control system	Control software logic and user interface for auxiliary control system	George T Hall