Fuel Interchangeability Effects on a Scaled Industrial Boiler

Anthony Jordan, Vince McDonell, and Scott Samuelsen

UCI Combustion Laboratory
University of California, Irvine CA 92697-3550

In this study a 400 MBTU/hr industrial boiler operates on various mixtures of natural gas and propane using optimization and control techniques to complete three objectives: minimize NOx emissions, maintain flame stability, and maximize overall system efficiency. Sensors have been selected based on their ability to characterize one of the four required observation categories: fuel properties, flame stability, emissions, and efficiency. Preliminary data has been conducted that maps the various performance indices for this burner over its set operation range. This paper outlines the research done thus far to achieve the preliminary burner performance data and no details into specific optimization techniques will be discussed.

1) Introduction

In this study an industrial boiler operates on various mixtures of natural gas using optimization and control techniques to complete three objectives: minimize NOx emissions, maintain flame stability, and maximize overall system efficiency. Fuel mixtures being considered are natural gas with blends of propane, ethane and potentially carbon monoxide that will represent various natural gas compositions derived from different extraction techniques (shale gas, biogas, etc). Increase production and consumption of these interchangeable fuels are just one part of the motivation behind conducting this research. Both the Bay Area AQMD and SoCal AQMD have regulations going into effect that lower the previous NOx and CO allowable limits [1]. For this particular burner the allowable NOx limits are moving from 30ppmv to 20ppmv corrected to 3%O2. As will be shown later, this new requirement is very difficult to achieve with the selected boiler unit operating just on natural gas. The emissions as well as flame stability will change when new fuels are incorporated. Therefore, there needs to be a burner system that will be able to adapt to these more stringent regulations while simultaneously being able to optimize performance for dynamic fuel variability.

Several researchers have investigated various aspects of this topic, but none that have been all inclusive. First there are the projects that have applied various control and optimization techniques for combustion systems. While this paper will not focus on this topic in particular, the information and methods will later be used in completing the project goals. St. John et al. demonstrated that optimization techniques such as Powell’s direction-set method and genetic algorithms are capable of locating and then maintaining optimal performance for a natural gas fired burner. Demayo et al. later verified and then further expanded on the direction-set method over a wider operational range used by [2]. References [3], [4] both used downhill simplex algorithms to control heat release and emission levels for single fuel flames. Artificial neural networks, which can learn and adapt to changing environments, have also been demonstrated to be viable optimization algorithms; however, these techniques require prior knowledge of the burner characteristics and are slightly more difficult to implement [5], [6]. An important variable to be able to sense in many of these papers is the heat release of the flame, which can most commonly be measured by imagining or chemiluminescence techniques as demonstrated in [7], [8].

Besides control and optimization concerns, the other important aspect of this project is to study fuel interchangeability effects. Fuel interchangeability has been defined as the ability to substitute one fuel for another in a combustion application without significantly altering operation or performance [9], [10]. For this project the three primary fuels to be investigated are methane, ethane, and propane due to their significant presence in various natural gas supplies. Minimum and maximum values of methane 75-98%, ethane 0.5-13%, and propane 0-20% (with peak shaving) have been found to be present in some lines in the U.S [11]. A considerable amount of research has been conducted in the area of fuel interchangeability in regards to lean-premixed flames used specifically in gas turbines [9], [10], [11],
[12], [13], [14]; however, this project is using a lean non-premixed boiler system. Therefore, it will be important to establish whether previous trends and results can still be applied to this particular case study.

2) Methods

Burner Geometry

A commercially available Coen Quantum Low NOx (QLN) burner scaled to 400 kBTu/hr is used in this study. A top down and side view of the burner geometry can be found in Figure 1. The burner is 6.5 inches in diameter and 14.5 inches in total length. The combustor is comprised of three main fuel injection circuits (Core, Radial, Outer) and one central location for air mixing. The Core and Outer fuel circuits are non-premixed systems, while the Radial injector has the ability to change premixedness with air depending on the location of the Radial tube. Based on the work done by [15] the optimal geometry for natural gas was determined and is the basis for this work. This configuration defines the height and angle of the Outer injector ports as well as the Radial injector depth.

The Core injector consists of a 0.25 inch diameter tube capped at the top and has four 0.05 inch diameter holes equally spaced around the circumference. The injection holes are placed 0.125 inches above the distribution plate and aligned with the four slots seen in the top view of Figure 1. The flow is constrained to 25% of the total fuel flow and primarily acts as a pilot flame to the Radial injectors. This circuit is a non-premixed system.

The Radial injector is located beneath the distribution plate and has the capability to move along the length of the burner. The injector tube has four spokes that branch from the center of the burner and are aligned with the four slots of the distribution plate. Each spoke consists of four equally spaced 0.12 inch diameter holes placed facing upward in the normal direction of the distribution plate. Air enters through the bottom of the windbox and exits flowing over the Radial spokes and through the distribution slots. For this study the Radial tube has been placed flush with the distribution plate, which offers very minimal mixing with the incoming air. The remaining 75% of the total fuel flow of the system is split between the Radial and Outer injectors, which is a parameter being investigated known as fuel split (FS) and will be discussed in a later section.

The Outer injector is comprised of four 0.5 inch diameter tubes placed on the upper ring of the burner. Each tube has two holes slightly angled toward the center of the burner and are angled tangentially to the inner circle. The tubes sit 0.25 inches from the top plate while the distance between the top plate and the distribution plate is 1.125 inches. Like the Core injector, the Outer injector is a non-premixed system and serves primarily as a flame stabilizer to the overall flame.

Figure 1: Burner Geometry

Experimental Setup

The furnace enclosure, as seen in the left image of Figure 2, is octagonal in cross section that is 2.0 feet across and 3.0 feet in height. The lower half of the enclosure is surrounded by 9.0” x 10.75” quartz windows that allow for optical access for various sensors and measurement systems. Above the quartz windows sit cooling panels where the cooling water is cycled through a closed loop system. The water heated by the burner is cooled by the laboratory’s internal water cooling system before reentering the boiler unit. The temperatures of the supply and return water of the boiler is monitored in order to define the boiler’s efficiency.
Above the furnace enclosure is the exhaust stack. The stack is designed in a conical to cylindrical configuration in order to increase exhaust gas mixing/uniformity and propel the pollutants into the laboratory’s ducting system. The exit of the stack has a manual damper valve that can cause a slight positive pressure inside the combustion chamber to purge any leaks that may exist in the system.

Flow control is achieved currently by a system of sonic orifices for the fuel and a combination of a sonic orifice and Brooks mass flow controller (MFC) for the air. The system diagram can be found in the right image of Figure 2. Currently the experiment is setup in such a way to investigate various mixtures of natural gas (assumed to be pure methane) and propane. The full load scenario (400 kBtu/hr) equates to 6.58 scfm of natural gas flow based on the higher heating value of natural gas. For subsequent mixtures of natural gas and propane, the total fuel flow is adjusted to keep a constant 400 kBtu/hr heating load.

Originally, the natural gas flow circuit was established using MFCs; however, after several hardware and circuit modifications the MFCs experienced significant variations in flow and lack of response sensitivity. Thus sonic orifices were then selected in order to achieve steady and repeatable flow conditions. This configuration does pose a problem when considering the overall goal of achieving closed loop system control due to the manual human manipulation required to adjust flow rates for a sonic orifice. However, these issues can be minimized by the incorporation of pressure transducers and/or remotely controlled pressure regulators.

For each fuel type the flow is directed into the three main fuel injector lines. A fuel property sensor labeled (SOS) is attached to the Core line to measure the corresponding mixture’s Wobbe number and C/H ratio, which can be used to correlate emissions to fuel properties. The primary source of air is sent through the sonic orifice circuit, which allows the combustor to reach stoichiometric conditions. Any further air required to reach the desired equivalence ratio is regulated by the MFC air circuit to allow for easy flow manipulation. The information gathered by the various sensors is logged using National Instruments Field Point modules. This data will later be used when establishing feedback control of the system.

**Sensors**

The main sensor information required to complete this project can be divided into four categories: fuel identification and properties, flame stability, emissions, and efficiency. Sensors were chosen based on accuracy, cost, and ease of implementation. Brief descriptions of the sensors chosen for each category can be found below:

1) **Fuel Identification and Properties**

The RPS-409A-IS ultrasonic sensor from Migatron was chosen to act as a speed of sound measuring device that can then be used to correlate to fuel properties. This intrinsically safe sensor is 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 terms from the previous equation, 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. Complications arise when the medium is composed of several substances since multiple solutions can be achieved. For this project the
The main gases being investigated are methane, ethane, and propane. A blend of 85-15 methane-propane by volume percent can have the same speed of sound as an 80-10-10 methane-ethane-propane blend. It must be noted here that knowing the exact fuel blend might be irrelevant in finding correlations between fuel interchangeability and burner performance. Alternative parameters such as the carbon to hydrogen (C/H) ratio or the Wobbe number could potentially be used as explained in [10]. Once the speed of sound $C$ of the gas can be estimated it can be correlated to the Wobbe number and C/H ratio by plotting against $C^2/T$, where $T$ is the absolute temperature in the chamber.

![Figure 3: Speed of Sound (SOS) model and physical hardware](image)

While the measured time varies for a fixed object with a fluctuating medium the output of the Migatron sensor is only the “appeared” 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 “appeared” distances to the speed of sound of an unknown gas:

$$C_{gas} = \frac{D}{D_{gas}} \cdot C_{air}$$

where $C_{gas}$ and $C_{air}$ are the speed of sounds in the gas and air, respectively. $D_{gas}$ is the appeared distance of the wall and $D$ is the actual distance of the wall. For example, if methane was the medium the appeared distance $D_{CH4}$ would be less than the actual distance $D$ due to methane’s lower density (higher speed of sound), as seen in Figure 3. In order 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 3.

2) Flame Stability

Monitoring flame stability is an important parameter when operating in very lean conditions in order to prevent lean blow-off. For this reason a fiber optic probe coupled to a photomultiplier tube was chosen to measure the luminosity of the emitted light from the flame. Currently no physical filter is attached to the fiber optic probe, which results in measuring all emitted light frequencies. In order to negate the potential effects from ambient light, the experiments are conducted in complete darkness. Obtaining filters that would isolate the OH* or CH* frequency bands, as used in [7], is currently being investigated.

There are three main categories the data gathered from the fiber optic probe can be used: flame detection, emission estimator, and flame oscillations. The simplest method using the luminosity data would be to detect whether a flame is present or not. This is very important when operating in large enclosed vessels with lean flame conditions. If a flame is extinguished, but the fuel is not immediately shut off the combustion chamber will be filling with hot and easily combustible material. If there was a spark or if the fuel was able to autoignite then there could be a devastating explosion or puff in boiler industry terms. Thus having the ability to detect when a flame is present becomes an important safety mechanism. This method will later be determined by a parameter labeled as Light AVG.

An interesting aspect of luminosity data is its ability to correlate with NOx emissions [16]. The fiber optic measures the light intensity of the flame, which for natural gas blends is correlated to the heat output of the flame. It is common knowledge that NOx emissions increase with increase flame temperature. Therefore, by measuring flame luminosity one can measure indirectly the NOx emissions in the exhaust. Figure 4 represents the measured luminosity data verses NOx emissions for this particular boiler. This result means a sensor that can measure luminosity can also estimate emissions, which can make an expensive emission analyzer not necessary.
The last important measurement the luminosity data can provide is information of the oscillation characteristics of the flame. The minimum and maximum peaks in the luminosity signal can vary significantly at very unstable conditions. By measuring the distance between two peaks one can measure how much the flame is oscillating, which can then be used to quantify stability regions. This parameter will later be referenced to as Light PkPk.

3) Emissions

The emissions measurement device that is being used for this study is a Horiba PG250 emission analyzer. The analyzer measures NOx, CO, CO2, and O2 using EPA approved methods. The gas sample comes from the burner exhaust stream via a stainless steel probe that is inserted inside the exhaust stack and is water cooled. The probe is designed to take an average spatial measurement across the exhaust stack diameter. The analyzer is recalibrated before every experiment.

4) Efficiency

There are two efficiency measurements that are utilized in this work. The first uses the standard definition of boiler efficiency: heat in cooling water divided by the heat input from the fuel. The heat generation in the cooling water is calculated based on the temperature of the supply and return values of the water circuit. Recall the furnace enclosure is designed to have the cooling panels located above where the flame is burning. Therefore the amount of heat transfer from the flame to the walls is not optimal. This results in very poor boiler efficiencies as well as minimal change in values for various flow conditions. For this reason an alternative efficiency measurement based on the amount of excess air being used is proposed. The laboratory is equipped with a high pressure air line; however, in normal commercial applications there will be a compressor unit that does the same function. The compressor consumes more energy when more air is required. Thus, by basing the efficiency on the amount of compressed air required a more accurate efficiency model is produced.

3) Results and Discussion

Preliminary data has been gathered for natural gas at various operating conditions. The two parameters that are of primary concern for this study are fuel split (FS) and excess air (EA). Recall the Core fuel flow is held constant at 25% of the total fuel flow. The remaining 75% of fuel flow is split between the Radial (R) and Outer (O) injectors. The fuel split is defined as the percent Outer minus the percent Radial (FS = %O - %R). For example, a FS of +5 would correspond to more fuel in the Outer injector (40%O – 35%R); whereas a FS of -5 corresponds to more fuel in the Radial injector (35%O – 40%R). The FS is varied between -5 to +5 in increments of 2.5 for subsequent tests. The EA is varied between 10 to 35 in increments of 5. Remember that EA is another version of the equivalence ratio where we have chosen to use the prior definition due its popularity in the boiler industry. The ranges used for these tests were established by [15] and recommended by the manufacture specifications. The third parameter that investigates fuel type (i.e. addition of propane) is currently being conducted and is not presented in this paper at this time.
The two primary output variables presented here are NOx corr. 3%O2 and Light PkPk (i.e. stability). Figure 5 contains two contour plots where the x-axis is EA and the y-axis is FS. The color variation corresponds to the output variable where red has been categorized as “Bad” and dark blue has been categorized as “Good.” Recall the NOx level that is trying to be achieved is below 20ppm. Using the left graph in Figure 5, the results would suggest the burner needs to operate in a region where it has high EA (approx. > 27) and with higher Outer fuel flow (FS > 0). The high EA level is not surprising; however let’s focus in on the FS result before continuing. Consult for a moment the burner geometry in Figure 1. If the FS favored more Radial (FS = -5) it would mean that locally around the air mixing region the flammable mixture would be slightly more rich in equivalence ratio (i.e. lower EA). This richer mixture will produce higher flame temperatures and thus greater levels of NOx. When the FS favors more Outer (FS = +5) the local air mixing region around the Radial tubes is more lean, which results in lower NOx production.

The stability of the reaction is shown in Figure 5 (right), which is quantified by the oscillations in flame luminosity (Light PkPk). A large value of Light PkPk corresponds to large oscillations in the flame, which is a sign of instability. At very lean conditions (high EA) the flame becomes very unstable as indicated by the red zones in the upper right of the graph. This result is somewhat predictable since lean flames are notoriously known to have issues with stability. An interesting interaction occurs when analyzing NOx and stability concurrently. Lower NOx levels correspond to a decrease in flame stability. This poses a difficult problem when trying to optimize the system since the goal is to lower NOX, but it comes at the cost of decrease flame stability.

![Figure 5: Excess Air (EA) vs Fuel Split with NOx (left) and Light PkPk (right)](image)

4) Summary

This paper outlines the goals and hardware selection for this investigation. Studying fuel interchangeability effects on commercially available burners is an important area of research due to the increase necessity of future burners being able to cope with dynamic mixtures of fuels. By using various sensor technologies, such as the ones described in this paper, burner design engineers can increase the information available to them in order to make intelligent decisions on performance. Moving forward this research will begin implementing various optimization and control techniques, as briefly mentioned in the introduction, in order to find the optimal operating conditions. Such optimization algorithms will need to be able to use prior knowledge of burner characteristics as well as learn and adapt to current scenarios.

Acknowledgements

This research was funded by the California Energy Commission through an interagency agreement with CIEE (Contract 500-10-048). The author would also like to acknowledge all the staff and students at the UCI Combustion Laboratory that have helped make this work possible.

References


