The Effect of Primary Air Distribution on Emissions from a Natural Gas Water Heater

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THE EFFECT OF PRIMARY AIR DISTRIBUTION ON EMISSIONS FROM A NATURAL GAS WATER HEATER

by

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The NOx emissions of a 40,000 BTU/hr (11.7kW) natural gas water heater are studied at different primary equivalence ratios (Φ). CO emission, O2 content in the flue gas and other related parameters are measured to assess the potential for NOx emission reductions with relatively modest changes in current burner and combustion chamber designs. In addition, N2 is introduced into the primary fuel and air flow to simulate flue gas recirculation (FGR) in order to estimate what benefit such a strategy might provide. NOx concentration in the exhaust decreases from 84 ppm to 34 ppm (at 3% dry O2) when the primary equivalence ratio is decreased from 4.8 to 1.3. The flame structure also varies with primary equivalence ratio. When Φ is lower than 2.1, the flame starts to show a highly unsteady structure, and NOx emissions fluctuate at this range of Φ. However, the observed NOx emissions decrease with a decreasing Φ indicates a potential method of significant NOx reduction in natural gas water heaters if the flame could be stabilized. Introducing 10 standard liters per minute (SLPM) N2 (15% of the primary air at Φ=3) into the primary fuel and air flow further decreases NOx emission levels by 20% to 29%, which indicates that flue gas recirculation (FGR) may be a viable method of reducing NOx of natural gas water heaters using on pancake burners.
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# TABLE OF CONTENTS

ACKNOWLEDGMENTS.......................................................................................i

LIST OF SYMBOLS........................................................................................iv

LIST OF TABLES..............................................................................................v

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

CHAPTER

1 INTRODUCTION.............................................................................................1

   MOTIVATION.................................................................................................1

   PANCAKE BURNER BACKGROUND............................................................2

   PRIMARY EQUIVALENCE RATIO.................................................................4

   NO\textsubscript{x} EMISSION INDEX (EINO\textsubscript{x}) BACKGROUND...............5

   NO\textsubscript{x} EMISSION TERM (PPM @ % DRY O\textsubscript{2}) .......................6

   NO\textsubscript{x} EMISSIONS FORMATION AND REDUCTION.......................6

      BACKGROUND

   OBJECTIVE.................................................................................................15

2 EXPERIMENTAL SETUP AND PROCEDURES...........................................17

3 RESULTS AND DISCUSSION.....................................................................22
LIST OF SYMBOLS

1. PPM — Parts Per Million
2. EINOx — Emission Index of NOx
3. $\Phi$ — Primary Equivalence Ratio
4. SCAQMD — South Coast Air Quality Management District
5. $M$ — Molecular weight
6. $\omega_{\text{NO}}$ — Molar rate of production of NO per unit volume
7. $\omega_{\text{CH}_4}$ — Molar rate of consumption of CH$_4$ per unit volume
8. $\int dz$ — The integral over z goes from the upper to lower duct exit in Fig. 4
9. FGR — Flue gas recirculation
10. $\sigma_{\varepsilon}$ — Uncertainty
11. $\sigma_{f_i}$ — Uncertainty for a given measurement
LIST OF TABLES

1. NOx, EINOx and CO emissions versus primary equivalence ratio..........................33
2. Major measurements with introducing 5 SLPM nitrogen ...................................34
3. Major measurements with introducing 10 SLPM nitrogen .................................34
LIST OF FIGURES

1. Pancake burner .................................................................2
2. Pancake burner in operation..................................................3
3. Effect on NO$_2$ emission due to changes in peak turbulent flame temperature........8
4. Schematic diagram of a two-stage methane-air flame in a counter flow air steam.....9
5. Comparison of NO concentration and temperature at different primary..............10
   equivalence ratio
6. EINOx versus primary equivalence ratio comparison of different experiments......12
7. A simplified diagram of the bray burner, showing the burner port region.........14
8. Flue-gas NO$_x$ emission (ppm) for 5 heat inputs and increasing flue-gas...........15
   recirculation
9. Experiment setup...............................................................17
10. Premixing chamber and pancake burner assembly.......................................18
11. Combustion chamber (A) a and rectangular flame arrester (B) ......................19
12. Calculated flame temperature at different amount of N$_2$ or flue gas recirculation...21
13. Flame structure at different primary equivalence ratio..................................23
14. NO$_x$ and CO emission trend by varying primary equivalence ratio..................24
15. EINOx plotted as a function of primary equivalence ratio.............................26
16. NO$_x$ emission plotted with & without N$_2$..........................................28
Chapter 1

Introduction

1. Motivation

Residential gas water heaters are widely used in the United States. In 2005, the estimated number of gas water heaters was 58.7 million (EIA 2005). They are highly cost-effective (ACEEE 2011), and as a result, gas water heaters tend to dominate the market wherever natural gas is available in residential areas. With the increasing supply of domestic natural gas from new extraction technologies, the domestic gas network will likely continue to increase and along with it, the use of natural gas appliances.

While an average residential gas water heater consumes a comparatively small amount of fuel annually, the combined effect of their emissions is significant. In 2005, the Energy Information Administration (EIA) estimated that in the United States the natural gas consumption by residential water heaters was 1,368 billion cubic feet (38.75 Teraliters) (EIA 2005). A 40,000 BTU/hour (11.7kW) natural gas water heater’s NO\textsubscript{x} emissions range between 10 and 80 ppm (after dilution) (Battelle 1998). According to measurements made in our lab, typical NO\textsubscript{x} emissions from the burner studied in this work are 60 ppm (dry 3% Oxygen). Using this value as an average, the total NO\textsubscript{x} emissions from residential gas water heaters was about 23 billion standard liters in the United States in 2005, this is 14% of Motorcycles’ NOx emission in United States in 2003 (EPA 2003).
NOx emissions from water heaters are being increasingly targeted for reduction through legislative action. Sections of California already mandate emissions as low as 10 ng of NOx produced per Joule of energy put into the water (about 14 ppm at 3% dry O2). The South Coast Air Quality Management District (SCAQMD) updated the rules in 2006, for water heater (less than or equal to 400,000BTU/hour) that are sold after January 1, 2012. This change now requires that NOx emission must be less than 14 ng of NOx per joule of heat output or 20 ppm (3% dry O2). Other regions are beginning to increase standards as well. Although ultra-low NOx burners in water heaters are already available with emissions lower than 10 ng/J, their cost is significantly higher than the pancake burner that is found in most water heaters and their addition adds significant cost to the manufacturing process and subsequent retail price. Hence, finding a means of reducing NOx levels using burners that are more similar to the current low cost models could reduce emissions without sacrificing consumer power.

2. Pancake burner background

![Figure 1. Pancake burner](image-url)
A pancake burner, found in the combustion chamber below the water tank, is widely used on gas storage water heaters. The burner is named for its flat and round shape as shown in Figure 1, which depicts a 40,000 BTU/hour burner.

![Pancake Burner Image](image)

**Figure 2. Pancake burner in operation**

Figure 2 shows an operating burner with sketches of the key gas flows. Primary air is entrained by the fuel jet from the nozzle exit as it flows into the enclosed portion of the pancake burner through a hole in the bottom plate. Secondary air entrainment occurs at or after the flame.

The burner was designed several decades ago when cost and safety (mainly in the form of flame stability) was the primary design criteria, and its design has undergone relatively minor changes as emission standards have been implemented. As emission limits continue to be lowered, however, there remains a question as to whether the
pancake burner, in some optimized form can achieve lower emission levels. Therefore, an objective of this study is to explore what gains in emissions characteristics could be achieved by the pancake burner with slightly different operating conditions. Specifically, we aim to address two questions. First, what is the effect of varying the distribution between primary and secondary air? Second, what is the effect of exhaust gas recirculation, if it could be implemented with the current burner?

3. Primary Equivalence Ratio ($\phi$)

When the flow of air into a combustor occurs at two distinct times, as depicted in Fig. 2, some care must be taken in defining the amounts of air. The primary equivalence ratio is defined as the ratio of the fuel-to-primary air ratio to the stoichiometric fuel-to-air ratio. In contrast, the overall equivalence ratio is defined by total air (the sum of primary and secondary) rather than primary air in Equation 1. When $\phi > 1$, the combustion is under fuel-rich condition. At $\phi < 1$, it is at fuel-lean condition (Hasegawa 2003). The fuel and primary air is typically fuel-rich ($\phi > 1$) in a pancake burner, while the overall flow is fuel lean. Previous researchers studied the pollutant emission of partially premixed flames for a fixed overall equivalence ratio, but the amount of air in the primary flow was varied, thus varying the primary equivalence ratio. This study also partially premixes air and fuel by controlling the amount of the primary air while holding the overall air flow rate fixed. Hence, the main variable of interest is the primary equivalence ratio, and it is used for comparison with previous studies.

$$\phi = \frac{\text{Fuel}}{\text{Primary Air}} \frac{\text{Primary Air}}{\text{Fuel}}_{\text{stoichiometric}}$$
Primary air plus secondary air is equal to the total air flow during the combustion process. If combustion is complete and fuel lean overall, the oxygen content in the flue gas is a direct indicator of the total amount of the air in the combustion chamber, and if it and the fuel flow rate remain constant, the overall equivalence ratio is fixed as well. Hence, by increasing the amount of the primary air (i.e., decreasing the primary equivalence ratio) while holding the oxygen content in the flue gas fixed, the secondary air decreases by the same amount as long as combustion is complete. In this way, only the distribution between primary and secondary air is varied while the overall flow is held fixed. This air distribution effect on NOx emissions can thus be measured without varying the overall frictional losses through a naturally aspirated combustor and heat exchanger like the low cost gas storage water heater studied in this work.

4. NOx emission index (EINOx)

NOx emission levels are the primary figure of merit in this study; however, the levels may be reported in several forms. This report will utilize the NOx emission index (EINOx). Following the formulation of Li (Li 1998), the emission index can be expressed as

\[
EINOx = \frac{1000 \int M_{NO} \omega_{NO} \, dz}{\int M_{CH_4} \omega_{CH_4} \, dz} \left( \frac{g}{kg_{CH_4}} \right)
\]  

(2)

where \( M \) denotes molecular weight, \( \omega_{NO} \) the molar rate of production of NO per unit volume and \( \omega_{CH_4} \) the molar rate of consumption of CH₄ per unit volume (Li 1998). The measurements were recorded by the unit of parts per million (ppm), however, most of the
previous studies on NOx emission use EINOx. Therefore, we use EINOx in this report in order to compare with other studies.

5. NOx Emission term (PPM @ % Dry O2)

Another commonly used term to measure NOx Concentration is ppm @ % Dry Oxygen. % Dry O2 stands for the oxygen content in the flue gas on a moisture-free basis, which helps to standardize the condition of the NOx emission measurement.

6. NOx emission formation and reduction background

A. NOx formation

There are three major types of NOx formation mechanisms, classified according to the types of reactions that lead to NOx formation and the conditions under which they tend to dominate: thermal NOx, fuel NOx and prompt NOx (EPA 1999). The thermal or Zeldovich mechanism dominates at high temperatures. Thermal NO formation occurs primarily via three principal reactions (Equation 3 to 5) that are fast at high temperatures (Ya.B.Zeldovich 1985; Miller 1989).

\[
\begin{align*}
N_2 + O & \leftrightarrow NO + N \\
N + O_2 & \leftrightarrow NO + O \\
N + OH & \leftrightarrow NO + H
\end{align*}
\]

Ozturk notes that thermal NOx is formed rapidly and dominates at temperatures over 1573K (Ozturk 2010). The adiabatic flame temperature for a natural gas water heater operating with an overall equivalence ratio of 0.7 is approximately 1900K (including equilibrium minor product species). Therefore a significant fraction of the
NOx emissions from a typical natural gas water heater is likely to be from the thermal NOx mechanism.

Fuel NOx refers to NOx formation from fuel that contains nitrogen (EPA 1999). The Fuel-bound N2 that contribute to the fuel NOx is a particularly important source of NOx emissions for residual fuel oil and coal (ANSYS 2006).

Prompt NO involves a series of reactions (Equation 6 to 9 show some of the reactions) that dominate the formation of NO at lower temperatures than those of the thermal NOx mechanism. CH is an important radical that must be present for this pathway, and the mechanism is thus faster under fuel-rich conditions. These conditions maybe encountered near the high temperature flame zone of premixed flames or in staged air flames where the fuel-rich combustion constitutes the initial reaction zone. Slower than thermal NO, its contribution to total NOx formation is often small, but may become significant when the proper conditions exist and thermal NOx is kept to a minimal level (Miller 1989).

\[
\begin{align*}
CH + N_2 & \leftrightarrow NCH + N \quad (6) \\
N + O_2 & \leftrightarrow NO + O \quad (7) \\
HCN + OH & \leftrightarrow CN + H_2O \quad (8) \\
CN + O_2 & \leftrightarrow NO + CO \quad (9)
\end{align*}
\]
One can find several experimental observations to support the strong link between thermal NOx production and temperature. As shown in Figure 3, NO₂ shows an increasing trend as peak temperature increases in turbulent jet flame in a furnace, where the flame temperatures were measured using a monochromatic optical pyrometer. At higher peak flame temperatures, there is more NO₂ than at lower temperature. Falcitelli concludes that overall NOx levels are predicted by the unchanged model of NO₂.

Li measured the NO emission and temperature while varying the primary equivalence ratio in a two-stage methane/air laminar flame in a counter flow air stream as depicted in Figure 4. As shown in Figure 5, the decreasing trend of NO emission as temperature decreases at different primary equivalence ratios is observed. NO₂ was measured to make no more than 10% contribution of total NOx emission in Li’s

Figure 3. Effect on NO₂ emission due to changes in peak turbulent flame temperature (Falcitelli. M 2002)
experiment, therefore, total NOx was employed as indicative of NO (Li 1998). Further experiments to introduce water spray into the counter flow air stream were performed. The measurements indicated NOx emission decreases as the flame temperature is reduced by adding the water spray. Hence, Li’s experiment further proves the relationship of NOx emission and temperature.

Figure 4. Schematic diagram of a two-stage methane-air flame in a counter flow air steam (Li 1998)
B. NOx reduction

Because most NOx production occurs via the thermal mechanism, and production from this mechanism accelerates as temperature increases, many NOx reduction strategies revolve around attempting to reduce the peak temperature in the combustion zone. Examples are given below.

1) Water and steam injection

Water or steam injection is very effective in reducing NOx emissions (by reducing the flame temperature) for gas turbines. The injection of water at a rate of 2% (percentage of primary air and fuel) can reduce NOx emissions by 80% in gas turbine (IFC 1998). This carries an energy penalty of approximately 1% (of energy given to turbine).
However, the energy penalty can reach 10% (of energy transferred to water) in boiler applications (IFC 1998). Due to the wide range in energy penalty, this method has not been tested in this work.

2) Staged-air combustion (varying primary equivalence ratio)

Staged combustion is one of the NO\textsubscript{x} emission reduction methods. It separately controls the process of combustion within two or more stages. This method utilizes the concept of controlling the reactions at each stage of combustion in order to reduce peak temperature.

Previous studies indicate a potential method of NO\textsubscript{x} emission reduction for the natural gas water heater. Lyle researched the NO\textsubscript{x} emission characteristics of partially premixed turbulent jet flames with fixed overall equivalence ratio of 0.5. His study shows the phenomenon that an optimum amount of partial premixing could reduce pollutant emissions (Lyle 1999). As shown in Figure 6, Lyle’s experiment found the NO\textsubscript{x} emission index (EINO\textsubscript{x}) decreases as primary equivalence ratio (\( \Phi \)) decreases from 5 to 1.5. His experiment was carried out under a heat release rate of 20 kW. EINO\textsubscript{x} reached a minimum value as equivalence ratio decreases from 5 to 1.5±0.2, and increased significantly while the ratio gradually decreases from 1.5 to 1.
Gore and Zhan performed their experiments with laminar partially premixed methane/air jet flames (fixed overall equivalence ratio of 0.5) and measured the minimum EINO$_x$ reached at $\Phi \approx 2.0$ in Figure 6 (Gore and Zhan 1996). This research further confirms the existence of a minimum EINOx on a different flame when compared to Lyle’s experiment.

Kim confirmed that laminar partially premixed ethane/air jet flames (fixed overall equivalence ratio of 0.5) have an optimum primary equivalence ratio of 2.2 (Kim T.K 1995), which is a similar conclusion to that of Lyle and Gore’s study in Figure 6.

Figure 6. EINOx versus primary equivalence ratio comparison of different experiments (Lyle 1999) (Gore and Zhan 1996) (Kim T.K 1995)
The aforementioned studies indicated the existence of an optimum primary equivalence ratio for minimizing NOx emissions under different conditions. However, the optimum primary ratio varies under different conditions as can be seen by comparing the studies of different flames and gases. Therefore, in this study, we will seek an optimum $\Phi$ with respect to NOx emissions on a natural gas water heater running on a pancake burner.

3) Flue Gas Recirculation (FGR)

FGR is a method of recirculating a portion of the flue gas back into combustion chamber. Foster studied the impact of various FGR rates on NO$_x$ emission of burner (Figure 7) in a combustion chamber with a water-cooled heat exchanger and a fan in the flue (Foster 1994). The plots in Figure 8 show a decreasing trend of NOx emission as the FGR increases. The maximum NO$_x$ emission reduction reached over 50% at high heat input, although methane emissions were detected to be significant at high levels of FGR, probably indicating significant amounts of incomplete combustion.
Figure 7. A simplified diagram of the bray burner, showing the burner port region (Foster 1994)

Foster also explains the principle of how FGR could help to reduce the NO$_x$ emissions. The first reason is that FGR reduces the combustion-zone temperature as well as flame temperature, which helps to reduce the NO$_x$ emission. Secondly, the reactions between hydrocarbon radicals and NO in the flue gas compete against the reaction of NO formation (Foster 1994). The effect on NOx emission of FGR applied to natural gas water heater would be sought in this study.
Figure 8. Flue-gas NO\textsubscript{x} emission (ppm) for 5 heat inputs and increasing flue-gas recirculation (Foster 1994)

7. Objective

The above mentioned NO\textsubscript{x} emission characteristics of turbulent or laminar partially premixed flames (Figure 6) show a trend that NO\textsubscript{x} emission decreases as primary equivalence ratio decreases below 4.8. The NO\textsubscript{x} emission reached a minimum value when primary equivalence ratio was between 1.5 and 2.2 in Lyle and Gore’s experiments, and increased as primary equivalence ratio deceased further from 1 to 1.5. Since these conclusions show a minimum NO\textsubscript{x} emission maybe located at primary equivalence ratio between 1.5 and 2.2, it is reasonable to expect a similar trend could occur on a natural gas
water heater with partially premixed fuel/air. According to the experiments in our lab, a
typical natural gas water heater (40,000 BUT/hour) has primary equivalence ratio of 3.5.
Therefore, this study will focus on seeking an optimum primary equivalence ratio at
lowest NO\textsubscript{x} emission by varying the fuel/air premixing condition.

Previous experiments showed EGR’s and FGR’s positive effect on NO\textsubscript{x} emission
reduction of diesel engine and other water-heating appliances. Foster’s experiment
showed around 50% NO\textsubscript{x} emission reduction on water-heating appliances(Foster 1994).
Therefore, we expect to see a similar effect of FGR on NO\textsubscript{x} emission of natural gas water
heater. This study will quantify this effect on the natural gas water heater.
Chapter 2

Experimental setup and procedures

A 40,000 Btu/hour natural gas water heater was used in this experiment. As shown in Figure 9, compressed fuel gas (methane), nitrogen and air can be introduced as primary mixture in a controlled manner. Gas flow rates are controlled by three flow meters (OMEGA: FMA-2608A, FMA-2610A, FMA 5426). The premixing chamber connected to the gases supply pipe is made and assembled at the bottom of the pancake burner in figure 10. As shown in Figure 11, a rectangular flame arrester (photo B) is assembled on the bottom of the combustion chamber (photo A) in order to prevent flame
coming out of the combustion chamber. Combustion products (NOx, CO, O₂) and flue gas temperature were sampled by a Testo 350-S located approximately 4 inches inside the exit of the flue gas chamber.

Figure 10. Premixing Chamber and Pancake Burner Assembly
The study was divided into two experiments: The first experiment runs the water heater by varying the primary equivalence ratio without adding nitrogen. The second experiment simulates flue gas recirculation by adding nitrogen in the methane/air mixture.

In order to perform the experiments at the standard firing rate of the water heater (at the full capacity of 40,000Btu/hour), methane was delivered at 21.4 standard liters per minute (SLPM). The water tank was heated to 145°F before the experiments. To ensure the experiments are performed under steady state, an energy balance is calculated on the natural gas water heater running at 11.7 kW. According to the calculation, the water inlet
and outlet temperature was controlled at 50°F and 145°F, respectively, so that the steady state could be reached at water flow rate of 0.7 GPM under the standard firing rate.

By increasing the premixed air flow rate from 34 to 156 SLPM, the primary equivalence ratio decreases from 4.8 to 1.3. A number of variables were monitored and recorded at each primary equivalence ratio, including the NO₂, CO and O₂ emissions; flue gas and water temperatures; environmental parameters including pressure, temperature and humidity; and flame structure. The second experiment was performed while nitrogen was added into the combustion. The same data were collected at two different nitrogen flow rates (5 and 10 SLPM). The overall gas/air flow was controlled by the fixed oxygen content in the flue gas (4%).

Since we use cold N₂ to simulate the flue gas in this study, a temperature difference of 203K between cold N₂ (297 K) and flue gas (500 K) is considered. The adiabatic flame temperature is calculated under the condition of Nitrogen’s introduction or flue gas recirculation into the combustion chamber. Data in Figure 12 show the flame temperatures comparison of the specific amount of N₂ introduction or flue gas recirculation (from 5 SLPM to 30 SLPM). The flame temperature at 5 SLPM Nitrogen’s introduction is 1941 K, and the flame temperature is 1945 K at 5 SLPM FGR. The temperature difference between two conditions (N₂ introduction or FGR at 5 SLPM) is 4K, and the temperature difference increases to 24 K as N₂ or FGR increases to 30 SLPM. Since the flame temperature difference between the two conditions (N₂ or flue gas) is fairly small at lower level of N₂ introduction, the effect on NOx emission of this temperature difference is expected to be very small while using Nitrogen to simulate flue gas, especially at lower level of nitrogen’s introduction. Furthermore, since we mentioned
that the main reason FGR could help reduce NOx emissions is FGR cools down the flame temperature, if we could reduce the flue gas temperature as much as possible before recirculation, it would be helpful to cool down the flame temperature. One possible method is to recirculate the flue gas through the relative cold water in the water heater. Therefore, the flue gas temperature could be reduced to a temperature lower than 500 K (the temperature measured at the exit of the water heater) after goes through cold water, which means the temperature difference between the Nitrogen and Flue gas could be less. Hence, the effect on NOx emissions of the temperature difference between N₂ and flue gas is expected to be very small at low level of nitrogen’s introduction.

Figure 12. Calculated flame temperature at different amount of N₂ or flue gas recirculation
Chapter 3

Result and Discussion

1. Effect of Primary air and Secondary air distribution on NOx emission

Photographs of the flame structure at different $\Phi$ are shown in Figure 13. The flame structure changes significantly across the measured range of primary equivalence ratio. During the most fuel-rich experiment (e.g. $\Phi > 3.8$ in Fig. 13) the flame clearly exhibits sooting behavior with the presence of yellow tips. As more air was added to the primary mixture, the velocity issuing from the pancake burner increased, and the flame shortened and became more horizontal. At $\Phi = 1.5$, the flame structure becomes almost completely horizontal due to the large air flow and associated velocity out of the burner and the near-stoichiometric primary flow. Primary air is 136 SLPM at $\Phi = 1.5$. This doubles the primary air flow rate 68 SLPM ($\Phi = 3$) when a stable flame structure is observed in picture three of Figure 13. A typical primary equivalence ratio of an operating water heater is 3.5.
Figure 13. Flame structure at different primary equivalence ratio
Figure 14. NOx and CO emission trend by varying primary equivalence ratio

A decreasing trend of NOx emission as a function of $\Phi$ is observed in Figure 14. As $\Phi$ varies from 4.8 to 2.1, NOx emission illustrates stable decreasing trend. The unsteady flame structure observed at $\Phi < 2.1$ was consistent with a large fluctuation of NOx emission data shown in Figure 13. However, a decreasing trend of NOx emissions could still be predicted at $\Phi < 2.1$.

As shown in Figure 14, CO emissions are significant at $\Phi > 3.8$. At the same time, the yellow flame in Figure 12 at $\Phi = 3.8$ visually illustrates the incomplete combustion that cause the significant rise in CO measurement. CO emission drops to around 2 ppm at $\Phi < 3.6$. Then, it increases from 0 ppm to 16.5ppm at $\Phi$ from 1.7 to 1.3, where the yellow flame is again observed. The yellow flame shown in the photo at low primary equivalence ratio is a sign of incomplete combustion which also matches the increasing CO measurement.
EINOx is calculated based on a method provided by Driscoll (Driscoll 1992). As in Figure 15, the decreasing trend of NOx emissions agreed with a portion in the conclusions of previous studies made by Lyle and Gore. Lyle found the NOx emissions have a decreasing trend as $\Phi$ decreases from 3.5 to 1.5 (Lyle 1999). Gore and Zhan found the decreasing trend started around $\Phi=3.5$ and 2.7, ended when $\Phi \approx 2$ (Gore and Zhan 1996). Both studies show that a minimum in NOx emissions exist for flames with fuel rich primary mixtures. In Figure 14, the data shows a decreasing trend as $\Phi$ decreases from 4.8 to 2.1, which is a similar trend with Lyle and Gore’s studies. However, because the unsteady flame structure is observed at $\Phi$ less than 2.1, the measurement was stopped at $\Phi=1.3$ due to extreme instability of the flame. Therefore, the existence of an optimum primary equivalence ratio at lowest NOx emissions on current pancake burner was unable to be tested due to insufficient and/or inadequate data. A further increasing trend is unpredictable as well.

As shown in Figure 15 (Lyle’s data), Lyle concludes that the decreasing trend of NOx emissions from $\Phi = 3.5$ to 2 could be explained by the simultaneous flame temperature decrease. The NOx emissions continue in the decreasing trend from $\Phi = 2$ to 1.5 and reaches a minimum value at $\Phi \approx 1.5$, then changes to an increasing trend. However, the measured flame temperature increases from $\Phi=2$ to 1.2, the decreasing trend of NOx emissions between $\Phi=2$ to 1.5 (Figure 14) is contradictory to the expectation that the NOx emissions are supposed to increase as temperature increases. In Gore’s experiment, a similar phenomenon was found between $1.3 < \Phi < 4$, which could not be explained by the temperature trend as well. Both Lyle and Gore state that the
decreasing NOx production rate as primary equivalence ratio decreases could be related to changes in the contributions of the prompt NOx mechanisms (Gore and Zhan 1996; Lyle 1999). This study is not able to test the existence of the lowest NOx emissions at an optimum primary equivalence ratio due to the unsteady flame structure at $\Phi < 2.1$. However, 21% to 38% EINOx reduction at $\Phi = 2.1$ compares with $\Phi = 3$ to 4.8 is observed during this study.

![Figure 15. EINOx Plotted as a function of Primary Equivalence Ratio](image)

2. Effect of N2 on NOx emissions

In order to simulate flue gas recirculation, an experiment was performed by introducing N2 into the combustion. Two different N2 flow rates (5 and 10 SLPM) were
used in the experiment for comparison. Due to the unsteady flame structure at lower primary equivalence ratio discussed in the previous section, the measurement stop at $\Phi = 2$. Figure 16 shows the NOx emissions at different N$_2$ flow rates. A significant drop of NOx (7% to 16% NOx reduction) is observed when 5 SLPM N$_2$ (7% of primary air at $\Phi = 3$) is introduced in the combustion. More NOx reduction (20% to 29% NOx reduction) is achieved when N$_2$ flow rate increases to 10 SLPM (15% of primary air at $\Phi = 3$).

Due to the limited capacity of the flow meters in this experiment, a higher N$_2$ flow rate could only be tested when using a lower firing rate. 30 SLPM of nitrogen was tested at a lower firing rate of 9.86 kW in Figure 16, where a 33% to 40% NOx reduction was observed. A further NOx reduction by introducing more N$_2$ could have been predicted based on the observed trend, but was not tested. Foster found there was approximately 50% NOx emissions reduction by FGR at a high firing rate (27.8 kW), however, methane is detected in the emission at this level of FGR (14%) (Foster 1994). This indicates high level of FGR running at high firing rates has a potential to cause incomplete combustion, which would result in the reduction of combustion and energy efficiency. Although an incomplete combustion was not found in this study with a high level of N$_2$ introduction (36% N$_2$ at $\Phi = 2.5$), an unsteady flame structure is observed at $\Phi = 2.5$ with 30 SLPM N$_2$ (40% NOx reduction). A maximum of 29% NOx reduction was achieved at standard firing rate with 10 SLPM N$_2$ (15% N$_2$ at $\Phi = 3$) in this study. Therefore, by considering a natural gas water heater running at standard firing rate with a stable flame structure and complete combustion, at minimum a 29% (drops from 79ppm to 56ppm) NOx emissions reduction by N$_2$ can be attained (15% N$_2$ at $\Phi = 3$).
According to this experiment, if the natural gas water heater could run in a stable state (flame structure) at $\phi \approx 1.5$, where NOx emissions were tested to be 34ppm (59% NOx reduction compared to $\phi = 3.6$). By introducing FGR into the combustion, an additional 20% to 29% NOx reduction could be achieved. Therefore, the NOx emission would have the potential to achieve 24±7ppm. This is very close to the natural gas water heaters’ NOx emission rules (equal or less than 20ppm) issued by SCAQMD.
Chapter 4

Conclusions

Summary of Work

The NOx emissions and related data are measured and analyzed by varying the primary equivalence ratio from 1.3 to 4.8. The effect of primary air on NOx emission has been sought. By simulating flue gas recirculation with N\textsubscript{2}, an effect of N\textsubscript{2} on NOx emissions is found. Therefore, the FGR’s effect on natural gas water heater could be predicted. Analysis of this study is compared to studies done by previous researchers.

Key Results

- NOx emissions of natural gas water heater running on pancake burner are found to have a decreasing trend as primary equivalence ratio decrease from 4.8 to 2.1. A NOx emission decreasing trend at \( \phi < 2.1 \) could be predicted from the plot in Figure 10, page 14.

- The existence of an optimum primary equivalence ratio at lowest NOx emissions could not be tested on the pancake burner due to the unsteady flame structure at \( \phi < 2.1 \).

- N\textsubscript{2} introduced in the combustion of natural gas water heater has a positive effect on NOx emission reduction. A range of 7\%~29\% NOx reduction is achieved by introducing N\textsubscript{2} from 7\% to 15\% of primary air at \( \phi = 3 \).

Future Work
Since a decreasing trend of NOx emissions when reducing the primary equivalence ratio has been sought, a method of reducing NOx emission is suggested by introducing more primary air to the current pancake burner.

In previous discussion, the unsteady flame structure at $\Phi=2.1$ to 1.3 with decreasing NOx emissions trend raises another possibility of NOx emission reduction by redesigning the current pancake burner. If the redesigned burner is capable of providing stable flame structure at $\Phi \leq 2.1$, further experiment could be performed in order to test the NOx emission at lower primary equivalence ratio. An optimum primary equivalence ratio at lowest NOx emissions might be sought / determined.

FGR is predicted to be effective in NOx emissions reduction in natural gas water heaters with installed pancake burners. The result shows that NOx emission reduction of 7% to 29% is achieved. A newly designed water heater with FGR could be considered for NOx emissions reduction. Since flame temperature is found to be one of the main reasons of NOx emissions reduction (Falcitelli. M 2002), effectively reducing the flue gas temperature before recirculating it back into combustion could be considered for NOx emissions reduction.

According to the previous discussion, by reducing the primary equivalence ratio and introducing the FGR into the combustion of natural gas water heater, the NOx emissions could reach close to the requirement of SCAQMD. Therefore, investigating the cost and possibilities of applying both low primary equivalence ratio and FGR to the natural gas water heater is suggested.
Reference


Ozturk, S. (2010). "NOx Formation in combustion of Natural Gases used in Turkey under different conditions." Thermal Science and Technology.


Appendix A

NOx emission and related data

This table shows some major measurements in the experiment without introducing nitrogen.

<table>
<thead>
<tr>
<th>Primary Equivalence Ratio</th>
<th>Natural Gas Flow (SLPM)</th>
<th>NOx Emission at 3% O2 (PPM)</th>
<th>EINOx</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>21.4</td>
<td>84.1</td>
<td>1.8</td>
<td>115</td>
</tr>
<tr>
<td>3.8</td>
<td>21.4</td>
<td>79.9</td>
<td>1.7</td>
<td>56</td>
</tr>
<tr>
<td>3.0</td>
<td>21.4</td>
<td>66.7</td>
<td>1.4</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>21.4</td>
<td>45.6</td>
<td>1</td>
<td>6.4</td>
</tr>
<tr>
<td>1.3</td>
<td>21.4</td>
<td>39.3</td>
<td>0.8</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 1. NOx, EINOx and CO emissions versus primary equivalence ratio
Appendix B

NOx emission and related data with introduction of nitrogen

<table>
<thead>
<tr>
<th>Primary Equivalence Ratio</th>
<th>Primary Air Flow (SLPM)</th>
<th>EINOx</th>
<th>CO (PPM)</th>
<th>O2 Content (% of Flue Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>69</td>
<td>1.2</td>
<td>0</td>
<td>3.5</td>
</tr>
<tr>
<td>2.4</td>
<td>84</td>
<td>1.0</td>
<td>0</td>
<td>3.6</td>
</tr>
<tr>
<td>2.0</td>
<td>100</td>
<td>1.0</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 2. Major measurements with introducing 5 SLPM nitrogen

<table>
<thead>
<tr>
<th>Primary Equivalence Ratio</th>
<th>Primary Air Flow (SLPM)</th>
<th>EINOx</th>
<th>CO (PPM)</th>
<th>O2 Content (% of Flue Gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>69</td>
<td>1.1</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>2.5</td>
<td>84</td>
<td>0.9</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>2.0</td>
<td>101</td>
<td>0.8</td>
<td>0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 3. Major measurements with introducing 10 SLPM nitrogen
Appendix C

Error bar (Uncertainty calculation)

The combustion products analyzer (Testo 350-S) has uncertainties of ±5ppm NO and ±5ppm NO₂. According to the equation provided by Putko (Putko 2001):

\[ \sigma_{\varepsilon}^2 = \sum_{i=1}^{N} \left( \frac{\partial \varepsilon}{\partial f_i} \cdot \sigma_{f_i} \right)^2 \]  

(10)

The uncertainty of NOx emission measurement is calculated to be ±7ppm.