AN EXPERIMENTAL STUDY OF NOx REDUCTION IN LAMINAR DIFFUSION FLAMES BY ADDITION OF HIGH LEVELS OF STEAM

Linda G. Blevins
Virginia Polytechnic Institute and State University
Department of Mechanical Engineering
Blacksburg, VA 24061-0328

Richard J. Roby
Hughes Associates, Inc.
Fire Science and Engineering
Columbia, MD 21045

ABSTRACT
An experimental study of the effects of steam injection on NOx formation in laminar, opposed flow diffusion flames was performed. This study was done to determine if the failure of high amounts of steam injection to totally suppress NOx in industrial gas turbine combustors is caused by the formation of Fenimore's "prompt NO" mechanism. Nitric oxide concentrations and temperatures were measured at various locations along the stagnation plane of the flame for varying amounts of steam injection. These tests were performed with either CH₄, C₂H₄, CO, CO/H₂ (1:1), or CO/H₂ (1:2) as the diffusion flame fuel. Results in the laboratory burner reproduced the observation from industrial combustors that at low levels of steam addition NO is suppressed, but that high levels of steam addition are unable to drive no concentrations to zero. However, the results also showed that high levels of steam injection were not effective at suppressing flame temperatures in the burner. In all cases, at least a sixty percent reduction in NO was observed as a result of the steam addition. Similar trends were observed for both the hydrocarbon and non-hydrocarbon fuels. Based on these results, it was concluded that the limit in NO reduction observed for these flames could be explained in terms of the limit in temperature reduction effected by the steam addition without the need to invoke Fenimore's "prompt NO" mechanism. Thus, the limit on NOx suppression at high levels of steam addition may be due to a limit on how much steam can diffuse into the flame front of diffusion flames, rather than on significant contributions from Fenimore's "prompt NO" mechanism.

BACKGROUND AND MOTIVATION
The most common way of reducing nitrogen oxides (NOx) production in industrial gas turbine diffusion flame combustors is to inject steam. Injected steam acts as a heat sink, which lowers flame temperatures, and thus decreases the amount of NOx formed. However, many gas turbine operators are now finding that steam injection alone does not suppress NOx concentrations to new lower levels required or proposed by regulatory agencies (Correa (1990)). In these cases, NOx concentrations initially decline with steam addition, but reach a minimum at high levels of steam injection. Profiles of NOx concentration as a function of steam flow rate "level off" at this minimum (Toof (1985)). The two NO formation mechanisms which may be important in explaining this phenomenon in diffusion flames, the Zeldovich mechanism (Zeldovich (1946)) and Fenimore's "prompt NO" mechanism (Fenimore (1971)), are discussed below.

Traditionally, the main source of NO formation in industrial gas turbine diffusion flame combustors was believed to be the Zeldovich mechanism. This mechanism is initiated when an oxygen atom (O) reacts with a nitrogen molecule (N₂) to create an N-atom and NO. The extended Zeldovich mechanism (including reaction with OH in fuel-rich regions) consists of the following steps:

\[
O + N_2 = N + NO
\]
\[
N + O_2 = O + NO
\]
\[
N + OH = H + NO
\]
NOx formed in diffusion flames is prompt NO, which Touchton, since Drake and Blint predict that most of the NOx formed in their diffusion flames was a result of Fenimore's prompt NO mechanism. They concluded that more than two-thirds of the NOx formed in their diffusion flames is prompt NO, which cannot be eliminated by temperature suppression.

The Zeldovich mechanism and the Fenimore mechanism are very different. Zeldovich NO is formed in the hot post-flame gases. Prompt NO, however, is formed very rapidly in the flame front of the hydrocarbon flames. Zeldovich NO requires only air at high temperatures, while Fenimore's prompt NO requires the presence of fuel and air. Zeldovich NO is a function of peak temperature; prompt NO is a dependent on the hydrocarbon content of the fuel.

In 1985, Touchton reported on a study of the effects of steam injection on NOx suppression in industrial gas turbine combustors (Touchton 1985). He compiled NOx data from several different combustors. In all cases, NOx decreased steadily with the amount of steam injected. Touchton never observed the "leveling off" trend of NOx emissions, although his study did not address the high amounts of steam injection being used to meet more recent emissions standards. Touchton concluded that almost all of the NOx could be eliminated using steam injection. He asserted that steam injection was entirely a thermodynamic effect which suppresses NOx formation by depressing peak flame temperatures and thus eliminating Zeldovich NO.

More recently, Drake and Blint (1991) used experiments and chemical kinetics modeling of a laminar, opposed flow diffusion flame burner to evaluate the relative importance of the Zeldovich and Fenimore NO formation pathways in diffusion flames. They concluded that more than two-thirds of the NOx formed in their diffusion flames was a result of Fenimore's prompt NO mechanism. These results seem to contradict the conclusions of Touchton, since Drake and Blint predict that most of the NOx formed in diffusion flames is prompt NO, which cannot be eliminated by temperature suppression.

However, Touchton's conclusions would not predict the "leveling off" of NOx emissions with increasing steam addition, while the conclusions of Drake and Blint would predict this trend.

The scope of this paper is to report on experiments which were performed to try to reproduce the "leveling off" of NOx concentrations in diffusion flames with high levels of steam injection in a laboratory burner. The experiments used both hydrocarbon and non-hydrocarbon fuels in order to determine if the minimum achievable NOx concentrations observed by Toof were a result of Fenimore's prompt NO mechanism.

**EXPERIMENTAL SETUP AND PROCEDURE**

The apparatus used for these experiments was a laminar, opposed flow diffusion flame burner. The burner included flow straighteners for both the fuel and air streams, and thus produced a "Type II" flame, according to the classification by Tsuji (1982). A schematic of the burner is shown in Figure 1. Fuel flowed in the downward direction, air flowed in the upward direction, and a flame was established on the air side of the stagnation plane.

A schematic of the fuel nozzle is shown in Figure 2. The fuel nozzle was a stainless steel cylinder that was 38 mm in diameter. The cylinder was filled with tiny stainless steel beads for flow straightening. The fuel exited the nozzle through 147 evenly spaced, 1.6 mm diameter holes in the flat end of the cylinder. This produced multiple tiny jets which combined to create a flat, uniform fuel supply. The nozzle was suspended in the air stream in a 76 mm Pyrex chimney.

The air side of the burner was a 32 cm diameter sheet metal housing containing flow straightening devices. The flow straighteners consisted of a perforated plate, coarse, medium and fine mesh stainless steel screens, and honeycomb. A converging nozzle was included to further condition the air flow before it entered the chimney. For all of the experiments performed, the air flowed in the chimney at a velocity of 0.5 m/s, which produced a characteristic radial strain rate of 13 s⁻¹. The strain rate, "a", was calculated assuming axisymmetric plug flow (Schlichting (1968)). The following relationship was used:

\[ a = \frac{U}{2R} \]

In this equation, U is the air stream velocity, and R is the radius of the fuel nozzle.

Figure 3 shows a schematic of the entire experimental setup, including the steam generator. Steam was generated with a small laboratory steam generator consisting of a heating coil inside a stainless steel chamber. A small
superheater was mounted at the exit of the steam generator. The steam flow rate was controlled by using a variac to change the amount of heat input to the boiler. The waster flow rate into the steam generator was measured using a calibrated fine needle valve with a vernier handle. Water was supplied at a rate so that the level in the steam generator sight glass remained constant during boiling. This assured that the water flow into the boiler matched the steam flow out of the boiler. Thus, since the waster flow rate was known, the steam flow rate was known.

Steam was delivered to the burner in a heated line. It was injected on the air side of the burner after the flow straightening matrix but before the converging nozzle, as shown in Figure 1. The steam and air were well mixed when they contacted the flame front. Because the flame front occupied thirty percent of the area of the chimney, the assumption was made that thirty percent of the overall steam flow rate contacted the flame. There was a trap at the lowest point in the steam line, so that the steam condensation rate could be measured and the steam flow rate was corrected for these losses.

The chimney was slotted so that a 3 mm uncooled quartz sample probe with a thermocouple attached could be inserted into the flame. A chemiluminescent analyzer was used to measure NO concentrations. A cold trap was included in the sample line to keep water from entering the NO analyzer. The chemiluminescent analyzer output was recorded with a strip chart recorder for later analysis. NO concentration measurements were accurate to within five percent.

Temperature was measured with an uncoated Pt/Pt10%Rh thermocouple corrected for radiation losses. The thermocouple wire was 0.13 mm in diameter with a measured bead size of .035 mm in diameter. An electronic compensator was used to simulate the ice bath junction. Thermocouple output voltage was amplified and recorded on a strip chart recorder. Temperature measurements were accurate to within five percent.

The air and fuel flow rates were measured using rotameters. For all tests, the air flow rate was maintained at 94 sl/min, so that the radial strain rate could remain constant. The fuels used for these experiments were methane (CH₄), ethylene (C₂H₄), carbon monoxide (CO),
FIGURE 3. SCHEMATIC OF LABORATORY SETUP.
50% carbon monoxide with 50% hydrogen (CO/H₂, 1:1), and 33% carbon monoxide with 67% hydrogen (CO/H₂, 1:2). Fuel flow rates varied, depending on the stability limits of the fuel in the opposed flow burner. The only exception to this was C₂H₄. The C₂H₄ flow rate was limited by excessive soot formation. The fuel flow rates were 0.77 sl/min of CH₄, 0.29 sl/min of C₂H₄, 1.1 sl/min of CO, 1.6 sl/min of CO/H₂ (1:1), and 1.2 sl/min of CO/H₂ (1:2). Overall steam flow rates ranged from 2 g/min to 12 g/min. Using the assumption that thirty percent of the steam contacted the flame front, the corrected steam flow rates were 0.6 g/min to 3.6 g/min.

The two hydrocarbon fuels and three non-hydrocarbon fuels chosen for these tests were used because Fenimore NO only forms in hydrocarbon flames. Thus, contrasting the NO trends of hydrocarbon flames with those of non-hydrocarbon flames would provide information about whether or not the achieved minimum NO concentrations were a result of the Fenimore mechanism.

Temperatures and NO concentrations were measured at various locations along the stagnation plane of the flame for varying amounts of steam addition. Beginning at the surface of the fuel nozzle, temperatures were measured at 0.5 mm increments, and NO concentrations were sampled approximately every 1 mm. The probe and thermocouple were mounted together, and were moved using a vertical translation stage.

Initially, total NOx measurements could not be determined during most experiments because sampling was done in the flame front. Certain species exist in the flame front which cause the catalyst in the NO₂ to NO converter to reduce both NO₂ and NO back to N₂ (Drake (1985)). However, Duterque et al. (1981) found that this problem could be avoided by lowering the catalytic converter temperature in the NOx analyzer from 600 C to 400 C. After this change was adopted, both NO and NOx were successfully measured.

Steam injection tests were performed twice for each fuel. After all of the first experiments were performed once, disassembly of the fuel nozzle revealed heavy coking on the stainless steel beads inside the nozzle. This coking was caused by pyrolysis of fuel in the hot stainless steel nozzle. Several CH₂ and C₂H₄ flames had been burned in the nozzle before testing began. As a result, partially pyrolyzed hydrocarbon fragments were deposited in the nozzle. Therefore, hydrocarbon fragments were available to form Fenimore NO during all of the first experiments, including the ones performed with non-hydrocarbon fuels. Once this coking was discovered, all the tests were run for a second time. The fuel nozzle and beads were thoroughly cleaned in an ultrasonic cleaner before each subsequent test. This cleaning affected the outcomes of the experiments. The differences in the results from the coked nozzle and the clean nozzle are discussed in the next section of this paper.

RESULTS

Traditionally, for steam injection studies, NOx concentrations are plotted as functions of the ratio of the mass flow rate of steam to the mass flow rate of fuel. A more meaningful quantity for comparing fuels with different heating values is the ratio of the mass flow rate of steam to the maximum heat release rate of the fuel. The maximum heat release rate is the product of the fuel flow rate and its lower heating value. The maximum heat release rate is proportional to the peak temperature that can exist in a flame. Since steam injection studies deal with suppressing this peak temperature by different amounts, the ratio of the mass flow rate of steam to the maximum heat release rate of the fuel is a meaningful quantity for comparison. This ratio will be referred to as the mass to heat release ratio.

Temperature as a function of distance from the fuel nozzle with no steam injection for all fuels is shown in Figure 4. If peak temperature is used to indicate the location of the flame front, this data shows that flames burning CH₄ stabilize about 2.5 mm away from the fuel nozzle. C₂H₄ and both mixtures of CO/H₂ produced flames that stabilize about 1.5 mm away from the fuel nozzle. The pure CO flame stabilizes closest to the nozzle, about 0.5 mm away from the fuel nozzle. The trend is that the CH₄ flames stabilized farther away from the fuel nozzle than the C₂H₄ flames or the non-hydrocarbons.

Temperature profiles for four amounts of steam injection into a CH₄ flame are shown in Figure 5. Graphs are shown for the mass to heat release ratios of 0.0 g/MJ, 28.3 g/MJ, 63.1 g/MJ, and 125 g/MJ. The profile for no steam injection peaks at 1720 K at a distance of 2.1 mm from the fuel nozzle. The profile of the mass to heat release ratio of 28.3 g/MJ peaks at 1660 K at a distance of 2.1 mm from the fuel nozzle. The profile for the mass to heat release ratio of 63.1 g/MJ peaks at 1610 K at a distance of 1.9 mm from the fuel nozzle. The temperature profile for the mass to heat release ratio of 125 g/MJ peaks at 1570 K at a distance of 1.7 mm from the fuel nozzle. This data shows that as the amount of steam injected increases, the peak temperature occurs physically closer to the fuel nozzle. In particular, this methane flame moves 0.5 closer to the fuel nozzle as a result of the maximum steam addition. This verifies the visual observation that the flame moved physically closer to the fuel nozzle as steam injection increased. Visual observations and
temperature profiles from other fuels show the same basic trends.

Because the flame moves physically closer to the fuel nozzle, NO measurement at Y = 1 mm with no steam injection may not compare with an NO measurement at Y = 1 mm with high steam injection. These may be physically two different points in the flame. To compensate for this ambiguity, to reach steam flow rate in a particular flame, the peak NO concentration, no matter how far it was located from the nozzle, was chosen for comparison with other peak NO concentrations. Likewise, for each steam flow rate, the peak temperatures were chosen for comparison.

Figure 6 shows peak concentrations of NOx as a function of the mass to heat release ratio. These results show that NOx profiles obtained from the laboratory burner reproduce the "leveling off" trend observed in gas turbine combustors. CH\textsubscript{4} levels off at an NOx concentration of 41 ppm. CO (H\textsubscript{2} (1:1) levels off at a concentration of 15 ppm. C\textsubscript{2}H\textsubscript{4} levels off at a concentration of 30 ppm. CO levels off at a concentration of 4.3 ppm. CO/H\textsubscript{2} (1:2) levels off at a concentration of 1.6 ppm. It should be noted that all of the fuels exhibit this "leveling off" in NOx concentration at values of the mass to heat release ratio around 125 g/MJ.

Peak temperatures as a function of the mass to heat release ratio are shown in Figure 7. In general, peak flame temperature decreases with increasing amounts of steam addition. However, a point is reached where temperature no longer decreases. The flame temperatures also "level off". For CO/H\textsubscript{2} (1:1), the temperature starts at 1877 K and levels off at 1841 K. For CH\textsubscript{4}, the temperature starts at 1722 K and levels off at 1589 K. For C\textsubscript{2}H\textsubscript{4}, the temperature starts at 1618 K and levels off at 1504 K. For CO/H\textsubscript{2} (1:2), the temperature starts at 1618 K and levels off at 1396 K. For CO the temperature starts at 1257 K and levels off at 1173 K. Also, as observed for the NO profiles, these temperature profiles level off at mass to heat release ratios of around 125 g/MJ.

An interesting way to look at NOx concentrations with steam injection is to divide them by the NOx concentration measured in the same flame with no steam injection. This gives a normalized quantity, RNOx, which ranges from zero to one. RNOx is plotted as a function of the mass to
heat release ratio for all fuels in Figure 8. Results are shown from three CH₄ flames, three CO/H₂ flames, a C₂H₄ flame and a CO flame. RNOx levels off with increasing amounts of steam injection. For CH₄, RNOx achieves a minimum of about 0.45. This means that 55% of the NOx in the CH₄ flame was eliminated with steam injection. Likewise, for CO/H₂ mixtures, the minimum RNOx is approximately 0.30, for CO the minimum RNOx is 0.40, and for C₂H₄, the minimum RNOx is 0.4. This data shows that with all fuels 55% or more of the NOx formed was eliminated using water injection.

Results shown above from flames burned with the clean nozzle are significantly different from those obtained with the coked nozzle. Table I shows peak NO, minimum RNOx, and peak and minimum temperatures obtained for various fuels from the coked nozzle. Table II shows the same quantities obtained for various fuels with the clean nozzle. For the hydrocarbon flames, absolute temperatures were higher with the clean nozzle than with the coked nozzle. For the non-hydrocarbon flames, absolute temperatures were lower with the clean nozzle than with the coked nozzle. For all fuels, absolute NO levels from the clean nozzle were lower than those for the same flame from the coked nozzle.

Behavior of the C₂H₄ flames changed dramatically between the coked nozzle and the clean nozzle. Figure 9 shows NO profiles as a function of distance from the fuel nozzle for C₂H₄ with no steam injection. With the clean nozzle, NO concentration was low on the fuel side of the burner, increased to a maximum of 86 ppm, and then decreased again on the air side of the burner. However, when the nozzle was coked, the NO concentration was at a maximum of 170 ppm very close to the fuel nozzle and steadily decreased through the fuel side of the flame. These two entirely different behavior patterns will be discussed below.

DISCUSSION

This study reproduced the observed "leveling off" of NOx concentrations in diffusion flames with increasing steam injection that has been reported for industrial gas turbine combustors (Toof (1985), Correa (1990)).
TABLE I. RESULTS FOR COKED NOZZLE.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak (NO) (ppm, dry)</th>
<th>Minimum RNO (ppm/100ppm)</th>
<th>Peak Temperature (K)</th>
<th>Minimum Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>96</td>
<td>0.42</td>
<td>1591</td>
<td>1462</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>72</td>
<td>0.40</td>
<td>1570</td>
<td>1378</td>
</tr>
<tr>
<td>COH₂ (1:1)</td>
<td>92</td>
<td>0.29</td>
<td>1892</td>
<td>1733</td>
</tr>
<tr>
<td>COH₂ (1:2)</td>
<td>45</td>
<td>0.28</td>
<td>1892</td>
<td>1750</td>
</tr>
<tr>
<td>CO</td>
<td>11</td>
<td>0.27</td>
<td>1257</td>
<td>1173</td>
</tr>
</tbody>
</table>

TABLE II. RESULTS FOR CLEAN NOZZLE.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Peak (NO) (ppm, dry)</th>
<th>Minimum RNO (ppm/100ppm)</th>
<th>Peak Temperature (K)</th>
<th>Minimum Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>75</td>
<td>0.40</td>
<td>1722</td>
<td>1599</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>86</td>
<td>0.10</td>
<td>1618</td>
<td>1504</td>
</tr>
<tr>
<td>COH₂ (1:1)</td>
<td>36</td>
<td>0.40</td>
<td>1877</td>
<td>1641</td>
</tr>
<tr>
<td>COH₂ (1:2)</td>
<td>4.1</td>
<td>0.10</td>
<td>1618</td>
<td>1396</td>
</tr>
</tbody>
</table>

Nonetheless, in all cases, at least fifty-five percent of the NOx formed in the laminar, opposed flow diffusion flames was eliminated using steam injection. This indicates that Zeldovich NOx comprised fifty-five percent or more of the NOx in these flames. This contradicts the assertion made by Drake and Blint (1991) that over sixty-six percent of NOx formed in laminar, opposed flow diffusion flames is formed by the Fenimore’s Prompt-NO mechanism.

Ideally, the increased heat capacity associated with increased steam flow rates should cause the temperature in the flame to drop uniformly with added steam. However, in these experiments, flame temperature dropped uniformly down to a minimum temperature level, but after this temperature was reached, further addition of steam had little effect on the flame temperature. Thus, the “leveling off” trend observed in the NOx concentrations can be explained by the effect that the temperature leveling off would have on the Zeldovich mechanism. Since this same trend was observed for both the hydrocarbon and non-hydrocarbon flames, it is not necessary to invoke the Fenimore NO mechanism to explain the minimum in NOx concentrations. In fact, the RNOx results for the non-hydrocarbon flames are nearly bracketed by the results of the two hydrocarbon flames. This suggests that the presence of hydrocarbons necessary for Fenimore NOx had little effect on the observed NOx trends.

Equilibrium calculations were used to show the thermal effect of steam injection. A temperature profile calculated by the equilibrium model is shown in Figure 7 for CH₄. The calculated temperatures were obtained by assuming an adiabatic, stoichiometric CH₄/air flame with various amounts of steam dilution. Although equilibrium predictions that temperature should decrease steadily, temperatures in the lab burner decreased only slightly from the maximum and then reached a minimum level. Figure 8 shows RNOx obtained from stoichiometric equilibrium modeling compared with RNOx obtained from these experiments. Equilibrium predicts that increased steam injection should drive RNOx essentially to zero. RNOx data from all fuels follows the same trend as equilibrium modeling predicts; however, RNOx is not driven to zero for any of the fuels. This appears to be because actual flame temperatures were not suppressed as much as the equilibrium model predicted.
There are at least two possible reasons that the temperatures leveled off in the burner. First, as steam injection amounts increased, the flames physically moved closer to the fuel nozzle. Since the nozzle was stainless steel, it conducted heat away from the flame. It is possible that as the flame moved closer to the nozzle, a point was reached where heat transfer to the nozzle dominated any thermal effect caused by the steam. This could have caused the flame to remain at a constant temperature. The second explanation for the "leveling off" of temperature is that there may be a limit to how much steam can diffuse into the flame front. Thus, steam injection may be a diffusion limited process.

Although these experiments did not show that Fenimore's prompt NO mechanism is important for explaining the minimum concentrations of NOx observed, there were some indications of the existence of prompt NO in these flames. Consistently, only about sixty percent of NO in the CH4 flames was eliminated before "Leveling off" occurred; however, in the non-hydrocarbon flames, the amount of NOx eliminated varied from sixty percent to eighty percent, depending on the fuel. It is possible that some of the forty percent of NOx remaining in CH4 flames was Fenimore NO.

Nitric oxide concentrations for all flames were higher when the nozzle was coked with hydrocarbons. These hydrocarbons may have contributed to Fenimore NO formation. This hypothesis is supported by the fact that in the ethylene flame, with the coked nozzle, the peak NO concentrations were at the surface of the nozzle. This was the location of these hydrocarbon coked beads, and it was possibly the location of excessive Fenimore NO formation.

Ultimately, the current results do not clearly agree with either Touchton (1985) or Drake and Blint (1991). Touchton stated that almost all of the NOx formed in diffusion flames is Zeldovich NO and thus can be eliminated using steam injection; only 55% of the NOx in the current study was eliminated by steam injection. Drake and Blint stated that less than 33% of the NOx formed in diffusion flames is formed by the Zeldovich mechanism; at least 55% of the NOx in the current study was formed by the Zeldovich mechanism.

The largest amount of steam used in Touchton's experiments corresponded to a mass of steam to mass of fuel ratio of 2.0. For the CH4 fuel used by Touchton, this amount of steam corresponded to a mass of steam per maximum heat release ratio of 40 g/MJ. With steam amounts up to 40 g/MJ, the NOx concentrations in the current study decreased uniformly, very much like the results compiled in Touchton's study. Thus, upon closer inspection, the results of the current study actually agree with the results of Touchton. However, Touchton assumed that the NOx emissions would continue to decrease uniformly with addition of more steam. If Touchton had studied larger quantities of steam injection, he most likely would have observed that the NOx emissions actually "level off," which was reported by Toof (1985), and which was shown in the current study. Because the "leveling off" of NOx concentrations coincided with the "leveling off" of temperatures in the current study, Touchton's conclusion that steam works by a thermodynamic effect may be correct. However, Touchton further concluded that almost all of the NOx is formed by the Zeldovich mechanism, and thus can be eliminated using steam injection. The "leveling off" results of this study show that only a portion of the NOx can be eliminated using steam addition. Thus, even though the results of this study at low steam amounts agree with Touchton's results, the conclusion of this study is quite different from Touchton's conclusion.

The results of the current study did not show that Fenimore's prompt NO mechanism is responsible for the "leveling off" of NOx emissions with high amounts of steam. However, the results did not eliminate the possibility that prompt NO is important. Because of this,
the conclusion of Drake and Blint that Fenimore NO is important in diffusion flames may be correct. However, the results of the current study show that there was a larger percentage of Zeldovich NO in opposed flow diffusion flames than was predicted by Drake and Blint. This discrepancy is at least partially due to differences between the flames studied by Drake and Blint and the flames of this study. First, the flames of Drake and Blint had strain rates of 42 s\(^{-1}\), 70 s\(^{-1}\), and 140 s\(^{-1}\), which were much higher than the strain rate of 13 s\(^{-1}\) used in this study. Higher strain rates result in lower temperatures and shorter residence times. Since Zeldovich NO is proportional to both the peak temperature and the residence time, higher strain rates would make the contribution of the Zeldovich mechanism less important. Also, the experiments used in the study by Drake and Blint were performed with the fuels of CO/H\(_2\)/N\(_2\) and CH\(_4\)/N\(_2\). Addition of N\(_2\) on the fuel side of the burner probably gave an exaggerated importance to Fenimore's prompt NO mechanism. This is because the N\(_2\) was available in the hot nozzle where the fuel pyrolyzed, which encouraged initiation of the Fenimore mechanism. Because Drake and Blint studied a specific type of diffusion flame, their conclusion that Fenimore's prompt NO mechanism is important in all diffusion flames is not valid. In fact, the results of the current study prove that the conclusion of Drake and Blint does not even apply to the specific case of the current laminar, opposed flow diffusion flame. Thus, the conclusion of the current study that at least 55% of the NOx formed in laminar, opposed flow diffusion flames is Zeldovich NO contradicts the conclusion of Drake and Blint.

**SUMMARY AND CONCLUSION**

The effects of high amounts of steam injection on NOx reduction in laminar, opposed flow diffusion flames were studied. Equilibrium modeling predicted that both NOx concentration and temperature should decrease steadily with increasing steam. Results showed good agreement with this modeling up to a certain "leveling off" point where NOx concentrations reached a minimum level and then could not be further reduced with steam. This minimum level was different for different fuels; however, in all cases, at least sixty percent of the original NOx was eliminated with steam injection. Flame temperatures also reached a minimum level and could not be further reduced by additional steam injection.

Based on these results several conclusions can be drawn. First, the observation from industrial gas turbine combustors of a "leveling off" of NOx concentrations with increasing steam injection can be reproduced in a laminar, opposed flow diffusion flame. Second, in this study, the leveling off of NOx can largely be explained by a leveling off in flame temperatures at high steam addition levels. These temperatures may be the result of a limit to how much steam can diffuse into the flame front of a laminar, opposed flow diffusion flame. Finally, most of the NOx formed in laminar opposed flow diffusion flames is from Zeldovich NO. Results indicate that sixty percent or more of the NOx formed is Zeldovich NO. This finding contradicts the conclusion by Drake and Blint (1991) that more than two-thirds of NOx formed in these types of diffusion flames is due to Fenimore's prompt NO mechanism.

**REFERENCES**


Touchton, G. L., 1985, "Influence of Gas Turbine Combustor Design and Operating Parameters on Effectiveness of NOx Suppression by Injected Steam or Water," *Transactions of the ASME*, 107, 706-713.
