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**NO_x EMISSIONS OF A JET DIFFUSION FLAME
WHICH IS SURROUNDED BY A SHROUD OF
COMBUSTION AIR**

By
P.X. Tran
F.P. White
M.P. Mathur
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**NO_x Emissions of a Jet Diffusion Flame which is
Surrounded by a Shroud of Combustion Air**

P.X. Tran, F.P. White, M.P. Mathur, and J.M. Ekmann

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ABSTRACT

The present work reports an experimental study on the behavior of a jet flame surrounded by a shroud of combustion air. Measurements focussed on the flame length and the emissions of NO_x , total unburned hydrocarbons, CO_2 , and O_2 . Four different fuel flow rates (40.0, 78.33, 138.33, and 166.6 cm^3/s), air flow rates up to 2500 cm^3/s and four different air injector diameters (0.079 cm, 0.158 cm, 0.237 cm, and 0.316 cm) were used. The shroud of combustion air causes the flame length to decrease by a factor proportional to $1/[(\rho_a/\rho_f) + C_2(\mu_a \text{Re}_a/\mu_f \text{Re}_f)^2]^{1/2}$. A substantial shortening of the flame length occurred by increasing the air injection velocity keeping fuel rate fixed or conversely by lowering the fuel flow rate keeping air flow rate constant. NO_x emissions ranging from 5 ppm to 64 ppm were observed and the emission of NO_x decreased strongly with the increased air velocity. The decrease of NO_x emissions was found to follow a similar scaling law as does the flame length. However, the emission of the total hydrocarbons increased with the increased air velocity or the decreased fuel flow rate. A crossover condition where both NO_x and unburned-hydrocarbon emissions are low, was identified. At an air-to-fuel velocity ratio of about 1, the emissions of NO_x and the total hydrocarbons were found to be under 20 ppm.

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1. INTRODUCTION

Fuel-air mixing plays an important role in combustion. It has a strong effect on combustion efficiency and flame length, as well as the composition of the combustion products. Poor mixing produces fuel-rich and fuel-lean zones within a combustor, leading to a long, unstable and incomplete burning flames and unwanted exhaust gases. Mixing becomes even more important in high-speed combustion applications and for the development of super-lean burners where ultra fast mixing of fuel and oxidant is required.

The present work reports an experimental study on the behavior of a jet flame surrounded by a shroud of combustion air. The air causes gas recirculation. The present study has two major objectives. The first is to study the role of the combustion air shroud in improving the fuel-to-air mixing rate. It is known that the fuel-air mixing rate can be improved significantly by introducing internal recirculation flow [1-3] or acoustically modulating the exit velocity of a coflowing jet [4]. Chen and Driscoll [1], in a study of the role of the recirculation vortex in improving fuel-air mixing within swirling flames, concluded that the vortex recirculation governs the mixing process of a swirling flame and that the flame length of a swirling flame follows a different scaling trend than that of a simple jet flame as fuel flow is increased. They found that, as fuel flow is increased, the length of a simple turbulent jet

flame remains unchanged, yet the length of a swirling flame increases linearly with the increased fuel flow rate. Although acoustic excitation of isothermal jets has produced significant increase in the near-field spreading and entrainment rates, the far field has remained essentially unchanged for small perturbation amplitudes. Large amplitudes and high frequencies, therefore, are required to affect the far field significantly [5].

Attempts have been also made to improve the fuel-air mixing rate by burning fuel puffs. It has been shown that individual fuel puffs have a considerably higher mixing rate compared to steady jets in both quiescent media [5] and transverse flow [6,7]. Johari and Motevalli [5] reported that burning of small, well-separated fuel puffs in quiescent air created intense and compact blue flames and for larger, closely-coupled puffs the flames were mainly yellow in color. They measured the flame length of burning fuel puffs and found that the flame length of individual puffs increases with the initial volume of the puff when the ratio of the injection time to the puffing period is small. As the ratio of the injection time to the puffing period increases for a specific flow condition, the flame length reduction stops as a result of the interaction among neighboring puffs. Eroglu and Breidenthal [6] and Vakili et al. [7] showed that introduction of fuel puffs into a quiescent media or a cross flow results in totally different flow patterns and features which

could be considerably valuable in increasing diffusion and entrainment. For example, a train of puffs into a cross flow has a deeper penetration depth in comparison to steady jets, and sweeps through the surrounding gases, thereby increasing the mixing rate.

The second objective of the study is to investigate how an improved mixing rate affects the emission of NO_x from a steady-jet flame. The Zel'dovich chain mechanism of the thermal NO_x has been assumed to be the dominant NO_x formation process in the combustion of natural gas. However, compared to the combustion process, it occurs at a rather high temperature and at a slow rate, spread over a few milliseconds. Thus, to control the NO_x exhaust, both the combustion temperature and the combustion time need to be reduced. Present-day burners usually utilize low levels of excess air combustion, such as partially aerated and slotted burners, with flame cooling by water injection, ceramic or metal rods placed in the flame, or radiating surfaces such as ceramic or metallic fiber burners. Although these burners can reduce the NO_x exhaust to some degree, many disadvantages still remain. For example, reducing the excess oxidant prolongs the flame length, which might result in the formation of carcinogenic products of incomplete combustion of benzopyrene type; flame cooling by metallic rods or radiating surfaces reduces the overall thermal output.

The most effective way to reduce NO_x emissions from natural gas burners is to create a reverse flow of the combustion products into the flame before it reaches its maximum temperature. Recirculation can be introduced either externally by swirl or a central bluff body, or internally by the dynamic action of the fuel and air flowing out of the burner into the furnace.

Peters and Donnerhack [8] studied the NO_x production in a turbulent diffusion flame and observed a dependence of NO_x emissions on Reynolds and Froude numbers. A theoretical formula was developed to predict the influence of the kinetics, the residence time, and the flame length on the NO_x emission index (defined as the NO_x production rate normalized by the fuel mass flow rate). A $\text{Re}^{-0.66}\text{Fr}^{0.33}$ dependence was proposed for scaling the NO_x -emission index to account for the influence of the nozzle diameter.

Chen and Driscoll [9] studied the effects of coaxial air velocity, Reynolds number, and Damkohler number on the total nitric oxide emissions of a hydrogen diffusion flame. They reported a significant reduction of NO_x by forcing coaxial air into the flame. By using the ratio of air velocity to fuel velocity (V_a/V_f), together with the fuel gas Reynolds number, they were able to predict successfully the reduction of the NO_x with the increased V_a/V_f . For methane flames with coaxial air flow, however, the NO_x emission levels did not decrease for V_a/V_f up to 0.15

and the decrease of NO_x emission was expected to occur for larger values of V_a/V_f .

Tomeczek et al., [10,11] studied NO_x emissions from large-scale natural gas flames. They concluded that good mixing of the flue gases with the combustion air is necessary to attain successful NO_x abatement. A reduction of NO_x up to 70% with only 15-20% flue gas recirculation was reported. The influences of air and fuel velocity, air-swirl angle, air-preheat temperature, furnace wall temperature, etc., on NO_x emissions were also investigated. The effect of the ratio of the coaxial air-to-fuel velocity on the NO_x emissions was found to have a similar trend to that reported by Chen and Driscoll [9]. The influence of gasdynamics on NO_x emissions was described very well using the ratio of the coaxial air-to-fuel velocity together with the air-preheat temperature and the wall temperature.

The influence of mixing on the flame characteristics and the formation of NO_x in semi-industrial scale oxy-natural gas flames was investigated by Hedley et al., [12]. They reported that the mixing angle and increased oxygen injection velocity resulted in increasing strength of the recirculation and hence, reduced NO_x .

Because the properties of a diffusion flame depend strongly on both the fuel and air flow conditions, the present work will study the NO_x emissions of a natural gas flame for a variety of fuel and air flow

conditions. The aim is to develop a NO_x scaling useful for burner design. It will be shown later that an increase of the air velocity shortens the flame length and forces the jet flame to exist closer to the nozzle tip where the velocities are larger. This reduces the local residence time and the combustion zone volume. The reduction of NO_x by increasing the air velocity may possibly affect the emissions of other unwanted species, such as the unburned hydrocarbons. Thus, it is also of equal importance to investigate the emissions of the unburned hydrocarbons for a variety flow conditions to identify a crossover condition that can lower both NO_x and THC emissions.

2. EXPERIMENTS

2.1. Apparatus

The experimental apparatus used in the study is shown in Fig. 1. It consisted of a combustion chamber, a nozzle for fuel injection, an air injection unit, and a gas-handling system coupled with a gas mixer and an electrical heater.

The combustion chamber was a pyrex glass tube of 20 cm diameter and 70 cm long. At one end, the chamber was attached to an aluminum base designed to house a gas/air injection unit at its center and to have ports for temperature monitoring and mounting an ignition source. The other end was attached to an aluminum flange fitted with gas lines for on-line monitoring NO_x , unburned hydrocarbons, CO_2 , and O_2 . The combustion chamber is schematically shown in Fig. 2.

The air injection unit, which was made out of brass, had a cylindrical shape with an inside diameter of 2.5 cm, an outside diameter of 5 cm, and a length of 2 cm. The end facing the chamber was attached to a removable brass orifice plate while two air-supply lines were fitted into the other end. The orifice plate, shown in Fig. 3, had 19 holes of equal size. The holes were drilled at 20 degrees intervals and 3 cm from a centerline. To provide a variety of air injection conditions, twelve orifice plates were made. These plates were grouped into three sets for three different injection angles (zero, 30 and 60 degrees). Each set had

four orifices that have the same injection angle but different hole diameters (0.079, 0.158, 0.237 and 0.316 cm).

The gas-nozzle unit had a contoured nozzle and a solenoid valve with the associated electronic control circuit. The nozzle, which is shown in Fig. 4, was made from stainless steel with the inlet diameter of 2.5 cm and exit diameter of 0.158 cm. It was situated inside the air injection unit. The solenoid valve had an opening diameter of 0.65 cm and maximum operating frequency of about 15 Hz. Opening and closing the solenoid valve was accomplished with a solid-state relay that was controlled by a digital output board (DAS-08). The frequency and duration of the injection was controlled by software to produce square non-symmetrical waveforms.

2.2. Procedures

Methane (density $\rho = 0.652 \text{ kg/m}^3$, and viscosity $\mu = 1.1 \times 10^{-5} \text{ kg/m-s}$) and air (density $\rho = 1.177 \text{ kg/m}^3$, and viscosity $\mu = 1.846 \times 10^{-5} \text{ kg/m-s}$), from high-pressure cylinders were used in the present study. Methane and air were delivered to the test unit using the gas handling system. The gas handling system was controlled by a Program Logic Controller (PLC) via an air-actuated gas control box, and was interlocked with appropriate sensors for the vent exhaust and gas leaks. The gas pressure was regulated and set at 160 kPa throughout the tests. Steady flow rates were maintained constant between 38 to 170

cm³/s for methane and 300 to 2800 cm³/s for air. For the pulsed-jet flame, the frequency was varied between 0 to 5 Hz and fuel injection times were varied between 60 to 200 ms. Combustion experiments were instrumented by on-line total hydrocarbons, oxygen, NO_x, CO₂, and O₂ analyzers. A high-speed digital imaging system was used to visualize the flow patterns and mixing processes.

Figure 1. Experimental apparatus

Figure 2. Sketch of the combustion chamber

Figure 3. Sketch of the air injection orifice

Figure 4. Sketch of the fuel injection nozzle

3. RESULTS AND DISCUSSIONS

It is shown in Fig. 5 that without air injection, the flame was lazy, yellow, and long (Fig. 5a). When air was injected through the orifice, a stagnation point region was formed on top of the flame. The stagnation point region was clearly shown by the contour sitting on top of the flame that marked the farthest penetration of the fuel jet. The stagnation region then acted like an obstacle to reverse the flow of both fuel and air back to the nozzle creating a strong recirculation zone at the flame base (Fig. 5b). This flow pattern dramatically increased the fuel-to-air mixing process. For a given fuel-flow rate, as air-flow rate was increased, the stagnation point region moved toward the nozzle, and the recirculation became stronger. As a result, the flame was seen to burn closer to the nozzle tip. The flame was noisy, compact, and so intensely blue that the flame was visible only when the laboratory was darkened. It appears that pre-mixed combustion processes were created within the combustion chamber. For a fixed-air flow rate, as fuel-flow rate was increased, the stagnation contour was deformed and moved upward, weakening the recirculation zone. The flame became longer with an open-yellow top. Further increasing the fuel-flow rate, the fuel jet penetrated through the stagnation contour and air entrained into the flame along its axis. The flame completely reverted from short, intensely blue, and noisy to a longer, jet-like premixed flame (Fig. 5d).

A

B

C

D

Figure 5. Effect of the combustion shroud on the flame length; ($d_f = 0.158$ cm; $d_a = 0.158$ cm; A: $Q_f = 40$ cm^3/s ; and $Q_a = 0.0$ cm^3/s ; B: $Q_f = 40.0$ cm^3/s and $Q_a = 1000.0$ cm^3/s C: $Q_f = 40.0$ cm^3/s and $Q_a = 1233.0$ cm^3/s ; D: $Q_f = 166.66$ cm^3/s and $Q_a = 1233$ cm^3/s)

3.1. Flame Length

Flame lengths were measured for a wide range of fuel-flow rates (Q_f), air-flow rates (Q_a), and air-injection velocity. For a given test, the desired fuel-flow rate and flame length for a steady-jet diffusion flame were determined first. After the solenoid valve was activated to fully open for about 5 min, the flow rate was determined by adjusting the control valve of the flowmeter on the gas control panel. When the fuel-flow rate was set, the combustion air was introduced via the combustion air ring. The air-flow rates were increased and the flame length was recorded using two high-speed digital video cameras. The video tapes were then analyzed frame-by-frame to obtain an averaged measurement. Data from more than 1800 frames per test were used to form the ensemble average.

Typical data showing the effects of fuel-flow rate, air-flow rate, and air-injection velocity on the flame length are given in Figs. 6 and 7. In Fig. 6, data on $L_f/L_{f, \text{no air}}$ were plotted against the air flow rate for three values of air injection diameters, (d_a). $L_f/L_{f, \text{no air}}$ is the flame length with air injection (L_f) normalized by the flame length of the simple jet flame for the same fuel-flow rate in a quiescent air ($L_{f, \text{no air}}$). In Fig. 7, data on the flame length, normalized by nozzle diameter (d_f) as a function of the fuel-flow rate for three different values of the air-flow rate, are given.

Figure 6. Flame length with air injection normalized by the flame length without air injection as a function of air flow rates (Fuel flow rate: $43.33 \text{ cm}^3/\text{s}$; d_f : 0.158 cm ; d_f : 0.079 cm ; +: 0.158 cm ; $\square$: 0.316 cm)

Figure 7. Flame length normalized by nozzle diameter as a function of fuel flow rates (d_n : 0.237 cm; d_t : 0.158 cm; air flow rates: ■: 1317 cm^3/s ; +: 1678 cm^3/s ; □: 2450 cm^3/s)

In general, the flame length with air injection was five-to-six times shorter than that of a simple flame in a quiescent air. A substantial reduction of the flame length occurred by increasing the air-flow rate while keeping fuel flow rate fixed or conversely, by lowering the fuel-flow keeping air-flow rate fixed. A substantial shortening of the flame length also occurred by increasing the air-injection velocity while both fuel and air-flow rates were kept constant.

3.2. *Scaling*

The flame length has been defined as the distance required to entrain sufficient air to mix with the fuel to stoichiometric proportions, r_s . Hawthorne et al. [13] used a mixing length concept to scale the air entrainment where the flame length was given as:

$$\frac{L_f}{d_f} = \frac{C_1 \rho_f V_f d_f}{\rho_a V_c \delta r_s} \quad (1)$$

where C_1 is a constant, r_s is the stoichiometric ratio of the fuel mass flow rate to the air entrainment mass-flow rate, ρ_a and ρ_f are the air and fuel densities, δ is the characteristic radial-mixing distance, and V_c is the characteristic mixing velocity. They argued that V_c is the r. m. s. velocity fluctuation and scales with V_f so that the flame length of a turbulent jet is independent of fuel velocity. A similar result was also obtained by Broadwell and Breidenthal [14], who used an eddy

engulfment concept to scale the characteristic mixing velocity with $\Delta V/V$. Chen and Driscoll [1] argued that for a swirl-stabilized flame, air entrainment is also controlled by a vortex engulfment so the scaling used by Broadwell and Breidenthal [14] can be used. However, for the toroidal vortex in the swirl-stabilized flame, the characteristic mixing velocity is the tangential velocity of the vortex, V_{RZ} , and the characteristic mixing length corresponds to the circumference of the toroid center, $W=2\pi\delta$. Thus, the air-flow rate entrained by the recirculation vortex is proportional to the net vortex recirculation and $V_c\delta$ was scaled with $V_{RZ}\delta+\Delta V d_f/V$.

It is clear from the present observation that both air and fuel velocities have a strong effect on the flame length of a jet flame surrounded by a shroud of combustion air. Dahm and Mayman [15] argued that for an arbitrary jet source, details of the jet source, such as its geometry or exit profiles, cannot remain dynamically relevant at downstream distances that are large in comparison with the scale of the source. Rather, only integral quantities derived from these details can be relevant far down stream. Among such integrals, the source mass flux cannot remain relevant since the total mass flux of the jet increases with down stream distance and eventually must dominate any influence of the source mass flux. The total momentum flux of the jet, however, must remain invariant and equal to the source momentum flux. The

"far field" of a turbulent jet is defined as distances sufficiently far from the source so that the only dynamically relevant characteristic of the jet source is its momentum flux. Thus, the local characteristic mixing velocity V_c and mixing length δ , which set the local molecular mixing rate V/δ were scaled by the authors as

$$\delta \sim L_f \quad (2)$$

$$V_c \sim \left(\frac{\rho_a V_a^2 d_a^2 + \rho_f V_f^2 d_f^2}{\rho_a} \right)^{1/2} L_f^{-1} \quad (3)$$

Thus, the flame length given by Eq. 1 becomes

$$\frac{L_f}{d_f} = \frac{C_1 / r_s}{\left(\frac{\rho_a}{\rho_f} + C_2 \frac{R_{e,a}^2 \mu_a^2}{R_{e,f}^2 \mu_f^2} \right)^{1/2}} \quad (4)$$

where C_2 is a constant, $R_{e,a} = \rho_a V_a d_a / \mu_a$ and $R_{e,f} = \rho_f V_f d_f / \mu_f$ are the air and fuel Reynolds numbers, μ_a and μ_f are the air and fuel viscosities. When V_a is equal to zero, Eq. 4 simply reduces to the scaling for the flame length of a simple jet used by Hawthorne et al. [13] which indicates that the flame length becomes independent of the fuel velocity. This condition, therefore, was used to determine the constant C_1 which was

Figure 8. Flame length normalized by nozzle diameter, L_f/d_n , as a function of $Re,a/Re,f$ (+: measurements; the solid line was calculated using Eq. 4 with $C_1 = 23.648$ and $C_2 = 0.15$)

about 23.648 based on our data on the maximum normalized flame length (L_f/d_f). Figure 8 shows the measured and calculated data on L_f/d_f as a function of the ratio of the air-to-fuel Reynolds numbers. The calculations, with $C_2 = 0.15$ obtained by curve fitting, produced results that agreed very well with the measured data.

Equation 4 also explains several other trends observed in the present work. For a fixed fuel-flow rate, Eq. 4 shows that the flame length should become shorter as the air velocity increases. This agrees with the data presented in Fig. 6. For a fixed air-flow rate, Eq. 4 indicates that the effect of the air shroud on the flame shortening becomes weaker when fuel-flow rate increases. Thus, the flame should be longer and eventually levels off at a constant value. This agrees with the data presented in Fig. 7 where the normalized flame length (L_f/d_f) increased and leveled off when the fuel-flow rate was increased above about 300 cm³/s. Thus, the flame length of a jet flame surrounded by a shroud of combustion air follows a different scaling law than does the flame length of a simple-jet flame.

3.3. *NO_x Emissions*

To investigate the effect of the injection air on NO_x emissions, measurements were carried out for a wide range of fuel and air flow conditions. Four different fuel flow rates (40.0, 78.33, 138.33, and 166.6 cm³/s), air flow rates up to 2500 cm³/s, and four air injector diameters

(0.079 cm, 0.158 cm, 0.237 cm, and 0.316 cm) were used. For such a variety of flow conditions, the present data showed NO_x emissions ranging from 5 ppm to 64 ppm and a significant dependence of NO_x emissions on fuel-flow rates, air velocity, and mass flow rates. As shown in Fig. 9, for a fixed fuel-flow rate, as the air-flow velocity increased, the NO_x emissions significantly decreased and leveled off at a constant value, which was from 5 ppm to about 15 ppm depending on the fuel mass-flow rate. Such a substantial decrease in NO_x emissions also occurred by lowering the fuel-flow rate while keeping air-velocity constant.

The effect of the air mass-flow rate on NO_x reduction can be investigated using Fig. 10, which shows data on NO_x emissions versus the air velocity at three different air injector diameters. It is clear that the reduction of NO_x also occurred by increasing the air mass-flow rate while both fuel-flow rate and air injection mass-flow rate were kept constant. However, the effect of the air mass-flow rate on NO_x emissions was much less significant than the effect of air velocity or fuel mass-flow rate.

The decrease in the NO_x emissions can be attributed to the reduction of the flame length caused by the shroud of combustion air. The reason is that the flame is forced to exist closer to the nozzle tip where the velocities are larger, which reduces the local residence time

Figure 9. NO_x emissions as a function of air velocity: Effects of fuel flow rate ($d_a = 0.158$ cm; $d_r = 0.158$ cm; fuel flow rate: ■: 38.33 cm³/s; +: 78.83 cm³/s; *: 138.33 cm³/s; □: 166.6 cm³/s)

Figure 10. NO_x emissions as a function of air velocity:
 Effects of air mass flow rate ($d_f = 0.158$ cm;
 fuel flow rate: $78.83 \text{ cm}^3/\text{s}$; $+$: $d_a = 0.158$ cm; $*$:
 $d_a = 0.237$ cm; $\square$: $d_a = 0.316$ cm)

as well as the reaction zone volume. The other effect is caused by the recirculation of the combustion products into the flame, which lowers the flame temperature. Thus, NO_x emissions are reduced as a result of the lowering of the local residence time and the flame temperature.

3.4. NO_x Emissions Scaling

In practice, it is of interest to relate NO_x emissions to both the fuel and air flow conditions to obtain a NO_x scaling relationship that could be useful for burner design. For industrial flames, the NO_x scaling is difficult because of the complex shape of the air and fuel nozzle of the burner. Available data, however, show that NO_x emissions decrease when air velocity increases [10-12]. The present data confirm this behavior, as shown in Figs. 9 and 11 where a significant decrease in NO_x emissions occurred with V_a/V_f increasing for V_a/V_f less than 1 and, for larger values of the air-to-fuel velocity ratio, the reduction of NO_x was much less significant.

For a simple jet-diffusion flame in a quiescent air, Peters and Donnerhack [8] reported that the amount of NO_x emissions relate to the fuel-gas Reynolds and Froude numbers. They assumed that the emission index of NO_x (EINOX), which is defined as the grams of NO_x per kilogram of fuel, depends on the reaction volume, the local residence time, and NO_x kinetics. They showed that EINOX is proportional to L_f^3 and to the volume integral of $d(\text{NO})/dt$, which depends on fuel type.

Figure 11. Effect of V_a/V_f on NO_x emissions

When the influence of the nozzle diameter was considered, a $Fr^{0.33}Re^{-0.88}$ dependence was obtained. Chen and Driscoll [9] added the effect of the strain rate, the degree of flame area change due to wrinkling, and the reaction-zone thickness to Peters' analysis. They obtained an expression for EINOX that is proportional to L_f^3 , and Reynolds and Damkohler numbers. For hydrogen-coaxial air flame, they found that coaxial-air causes EINOX and L_f^3 to decrease by the same factor. For methane with coaxial-air flow, however, EINOX was reported to increase with V_a/V_f for V_a/V_f up to 0.15. Prompt NO_x formation was suggested by the authors to be the reason why methane-air flames do not scale with L_f^3 as proposed.

Such an increase of the NO_x index was also observed in the present experiments, as shown in Fig. 12. The measured NO_x index (grams of NO_x /kg of fuel) was obtained by the following relation as in ref. [9]

$$EINOX = 0.001X_{NOX} \left(\frac{M_{NOX}}{M_p} \right) \left(1 + \frac{m_a}{m_f} \right) \quad (5)$$

where X_{NOX} is the measured concentration of NO_x in ppm, M is the molecular weight, and m is the mass flow rate; subscripts p, a, and f are the product, air, and fuel. Because an increase in the air velocity increases the air mass-flow rate, from Eq. 5 one notes that an increase

Figure 12. Effects of V_a/V_f on the NO_x index ($m_f = 40$ cm^3/s ; $d_f = 0.158$ cm; +: $d_a = 0.158$ cm; *: $d_a = 0.237$ cm; □: $d_a = 0.316$ cm)

in the measured EINOX is possible after the decrease in the measured concentration of NO_x is offset by the increased air velocity. Therefore, to see if EINOX for methane-air flames still scales with the flame length, both the fuel and air flow rates must be kept constant and the increase of the air velocity is obtained by decreasing the size of the air injector. The present data on EINOX versus the ratio of the air-to-fuel flow rate for three values of the air-injector diameters are shown in Fig. 13. It is clear that for fixed air and fuel-flow rates, EINOX behaved like X_{NOX} and decreased when the air velocity increased.

The data presented above showed that the shroud of combustion air causes the flame length and NO_x emissions to decrease in a similar manner. Thus, one can conclude that NO_x emissions follow a similar scaling law as does the flame length. The present data on NO_x emissions versus the ratio of the air-to-fuel Reynolds numbers (Re_a/Re_f) are shown in Fig. 14. The solid line was calculated using Eq. 4 with $C_1 = 4.982$ ppm and $C_2 = 1.25$. The measured data agreed very well with the computed data. Thus, an excellent correlation clearly exists between NO_x emissions and the ratio of the air Reynolds number to the fuel Reynolds number.

Figure 13. Effects of Q_a/Q_r on the NO_x index ($m_f = 40$ cm³/s; $d_f = 0.158$ cm; +: $d_a = 0.158$ cm; *: $d_a = 0.237$ cm; □: $d_a = 0.316$ cm)

Figure 14. Effects of Re_a/Re_f on NO_x emissions ($\square$: measured; the solid line was calculated from Eq. 4 with $C_1 = 4.982$ ppm and $C_2 = 1.25$)

3.5. *Unburned Hydrocarbon Emissions*

Because the properties of a diffusion flame depend strongly on both the fuel and air-flow conditions, the reduction of NO_x by increasing the air velocity or by lowering the fuel flow velocity may also affect the emissions of other unwanted species such as unburned hydrocarbons. Thus, it is important to investigate the emissions of the unburned hydrocarbons for a variety of flow conditions to identify a crossover condition at which both NO_x and THC emissions are low.

Data in Figs. 15 to 18 showed the total unburned hydrocarbons in the exhaust gases for a variety of fuel and air-flow conditions. It is clear that for a fixed-fuel velocity, the unburned hydrocarbon emissions increased substantially as the air velocity increased. For a given air velocity, a substantial increase of the total unburned hydrocarbon emissions also occurred when the fuel velocity decreased. This behavior is different from the behavior of NO_x emissions discussed above.

For a given fuel velocity, if the air velocity is not high enough to form a stagnation contour on top of the flow, the flame is long and intense and air rapidly entrains into the flame along its axis. As a result, the flame temperature is high, which leads to high NO_x emissions. Since the flame is long, the fuel has enough time to burn, resulting in high CO_2 and low THC emissions. For example, at air velocity of 2396 cm/s, an increase of the fuel velocity from 6909 cm/s to

Figure 15. THC emissions as a function of air velocity: Effects of fuel flow rate ($d_a = 0.158$ cm; $d_f = 0.158$ cm; fuel flow rate: ■: 38.33 cm³/s; +: 78.83 cm³/s; *: 138.33 cm³/s; □: 166.6 cm³/s)

Figure 16. THC emissions as a function of V_a/V_f

8425 cm/s resulted in an increase of NO_x emissions from 34 ppm to 46 ppm and a decrease in unburned hydrocarbons from 7 to 1 ppm. The decrease of the THC emissions indicated that more fuel was burned in the combustion zone as indicated by the increase of the CO_2 concentration in the exhaust gases from 4.2% to 5.1% and the decrease of oxygen concentration from 13% to 11%, respectively.

If the air velocity is high enough, a stagnation contour is formed, which creates a strong recirculation zone near the nozzle tip where fresh fuel and air intensely mix with the combustion products. As a result, the flame temperature is low and NO_x emissions are reduced. Because the flame length is short and the jet flame is forced to exist closer to the nozzle where the velocities are larger (which reduces the local residence time as well as the reaction zone), there may exist a situation where the combustible mixture slips over the combustion zone before it has enough time to burn completely. Thus, high levels of unburned hydrocarbons exist in the exhaust gases. For example, at a fuel velocity of 1938 cm/s, an increase of the air velocity up to 9973 cm/s led to a decrease in the NO_x emissions from 44 ppm to less than 2 ppm while the total unburned hydrocarbons increased from 8 to 750 ppm.

The above results indicate that the shroud of the combustion air has a strong effect on the flame length, NO_x formation, and total unburned hydrocarbon emissions. The reduction of NO_x always is

Figure 17. THC emissions as a function of Re_a/Re_f

Figure 18. THC emissions as a function of m_s/m_r

associated with the increase in the unburned hydrocarbons. A crossover condition that reduces both NO_x and unburned hydrocarbon emissions must be identified. Under the conditions used in the present work it was found that NO_x and unburned hydrocarbon emissions were both less than 20 ppm at a ratio of air-to-fuel velocity of about 1.

4. CONCLUSIONS

An experimental apparatus was set up to study the combustion characteristics of a steady-jet flame surrounded by a shroud of combustion air. From these preliminary observations, it is clear that the shroud of combustion air has a strong effect on the flame length, NO_x formation, and the total unburned hydrocarbon emissions. It was observed that, for a fixed fuel flow rate, the flame length and NO_x emissions decrease substantially as the air velocity increases. Such a substantial decrease also occurs by lowering the fuel-flow rate while keeping air flow rate constant. Both the flame length and the NO_x emissions were found to follow the same scaling law, which is proportional to $1/[(\rho_a/\rho_f) + C_2(\mu_a \text{Re}_a/\mu_f \text{Re}_f)^2]^{1/2}$.

The reduction of NO_x always is associated with the increase in unburned hydrocarbons. The emission of the total hydrocarbons was found to increase with increased air velocity or decreased fuel-flow rate. With the conditions in the present work, it was found that NO_x and unburned hydrocarbon emissions were both less than 20 ppm at the

ratio of air-to-fuel velocity of about 1.

NOMENCLATURES

C_1	: constant
C_2	: constant
Fr	: Froude number
d_a	: air injection diameter (cm)
d_f	: nozzle diameter (cm)
L_f	: flame length (cm)
M	: molecular weight (g/gmole)
m	: mass flow rate (g/s)
Q_a	: air flow rate (cm ³ /s)
Q_f	: fuel flow rate (cm ³ /s)
Re	: Reynolds number
r_s	: stoichiometric ratio
V	: velocity (cm/s)
V_c	: characteristic mixing velocity (cm/s)
V_{RZ}	: tangential velocity of vortex (cm/s)
W	: circumference of the toroid center, $W=2\pi\delta$ (cm)
X	: mole fraction

Greek Symbols

δ	: characteristic radial-mixing distance (cm)
μ	: viscosity (g/cm-s)

ρ : gas density (g/cm^3)

Subscripts

a : air

f : fuel

NOX : NO_x

p : products

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