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Factors Affecting NO_x Formation from Nitrogen-Containing Fuels

by

DAVID E. FOSTER*

Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706

and

JAMES C. KECK

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Data from a turbulent diffusion flame burner indicate that the summation of fixed-nitrogen species ($NO + HCN + NH_i$) is a significant measure of a flame's emission potential. Raising the flame temperature by preheating of the inlet air causes a reduction in the summation of fixed-nitrogen species in rich flames. This reduction occurs over only a narrow range of equivalence ratios and only for flame conditions with low concentrations of unburned hydrocarbons at burner exhaust. Therefore, the fuel and air must be intensely mixed at the entrance of the burner. Flames resulting in soot formation heavy enough to turn the flame bright yellow yield high concentrations of unburned hydrocarbons and HCN. For rich flames this results in a high summation of fixed-nitrogen species, because HCN is the dominant nitrogen containing species of these flames. The distribution of fixed-nitrogen species leaving the burner is independent of the form of the nitrogen in the fuel; the reduction of fixed-nitrogen species with increased air preheat occurs at fuel nitrogen concentrations as high as 5%.

INTRODUCTION

The combustion of nitrogen containing fuels gives rise to two sources of NO_x, thermal NO_x and fuel-NO_x. Staged combustion has received considerable attention as a means of controlling NO_x during burning of nitrogen containing fuels [1]. For the staged combustor to yield low NO_x emissions, the fate of the fuel-nitrogen in the rich stage must be known. Sufficient studies have been carried out for rich laminar premixed and diffusion [2-7] flames so that the effect of burner operating conditions on their nitrogen emissions is reasonably well understood. Turbulent diffusion flames are more complicated, however, and have not been studied as extensively [8, 9]. The influence of burner operating parameters on the NO_x emission from practical combustors operating in a two stage mode must be further understood.

Experimental investigations were carried out on a laboratory combustor simulating the fuel-rich stage of a two stage combustor. Synthetic fuels were simulated by use of avaition kerosene doped with pyridine (C_5H_5N) to the desired nitrogen concentration. Selected runs were also made with dodecylamine ($CH_3(CH_2)_{11}NH_2$) added to the fuel instead of pyridine to determine if additive type had any effect. Four burner operating parameters were varied independently:

1. the fuel air equivalence ratio;
2. the amount of nitrogen in the fuel;
3. the inlet air temperature;
4. the mixing intensity of the air and fuel in the burner.

The fixed-nitrogen species NO, HCN, and NH_3 were measured to observe the importance of the different species in accounting for the fuel-nitrogen and the effects of changes in the burner operating parameters on the distribution among these species.

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* Send Correspondence to: D. E. Foster, Department of Mechanical Engineering, University of Wisconsin, 1513 University Avenue, Madison, Wisconsin 53706.

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It was assumed that the fuel-nitrogen left the rich stage as N_2, NH_3, HCN, or NO. The balance of the fuel-nitrogen not accounted for in the data was assumed to be leaving the burner as molecular nitrogen.

EXPERIMENTAL APPARATUS AND PROCEDURE

The burner employed is similar to that used by Heywood et al. [10, 11, 12]. It is basically a cylindrical burner in which the combustion air is supplied at atmospheric pressure at one end through swirler vanes with a 45 degree blade angle. Liquid fuel is supplied through an air assist atomizer on the burner axis. The atomizer air pressure drop is controlled independently of the fuel flow rate. The fuel and air induction system upstream of the swirler vanes is symmetric and contoured to minimize the propagation of flow assymmetries into the burner. Upstream of the burner is an 85 kW air preheater capable of heating the primary combustion air from room temperature (300 K) to 733 K. Independent control of the parameters affecting NO_x emissions is achieved by varying the fuel flow, running fuels with different nitrogen content, using the air preheater, and changing the atomizing pressure of the air assist atomizer [12, 13].

The swirler vanes serve to separate the flow in the burner into two regimes, a recirculation zone and a plug flow region. On the basis of swirl number and geometric similarity, the recirculation zone in this burner was calculated to extend 1.5 to 2.0 burner diameters from the inlet [14]. For the data presented here the swirl number was held constant.

Exhaust samples were drawn continuously into a heated teflon line from a water cooled, quartz tipped probe. A probe tip inner diameter of 3 mm was required to prevent soot clogging during sampling of the rich flames. The sample line was maintained at 150°C while the probe was held at approximately 95°C; both are well above the estimated dew point temperature of the exhaust sample (52°C). The exhaust sample rate was held constant at 2.8 liters/min and was passed through a filter of 0.5 μm porosity. The sample probe and all fittings in the sample line were teflon coated to prevent wall effects from affecting the data [15, 16]. Similarly, only NO was measured in the rich flames to avoid reduction in the NO_2 to NO converter of the chemiluminescent analyzer [17, 18].

The species O_2, CO, CO_2, and NO were continuously monitored with standard commercially available equipment. HCN and NH_3 were measured by means of wet chemical techniques in which samples were obtained by drawing a known volume of gas through a midget impinger which contained an appropriate absorbing solution. HCN was then measured with a cyanide ion electrode; NH_3, by the Nesslerization method. Further details and references on equipment and sampling technique are available in Ref. [19].

The burner was run with constant total air flow in all experiments. The primary air flow, which passes through the swirler vanes, was adjusted so that the total of the atomizing and primary air flows was equal to 56.7 kg/hr. At the highest atomizing pressure (446 kPa (50 psig)) the atomizing air flow accounted for 14% of the total flow. The length required to obtain complete mixing (indicated by uniformity in cross-sectional O_2 profiles during operation of the burner at an equivalence ratio of 1.0) was determined. Under the worst of mixing conditions, (ΔP = 205 kPa (15 psig)) uniform species concentrations (±5% in radial profiles) were obtained within three burner diameters of the nozzle. Except for HCN and NH_3 which were single point center line measurements, the data-gathering procedure involved drawing exhaust samples from six different radial positions at each axial location and then area averaging the readings. Samples taken five burner diameters downstream of the nozzle, x/D = 5.0, referred to as exit samples in the following paragraphs, represent a condition in which the radial profiles are very uniform, ±5% maximum deviation, and a gas resident time of approximately 50 msec. For nonnitrogen-containing fuels they also represent an asymptotic value of the species concentrations. For nitrogen-containing fuels, however, the species concentrations were still changing at burner exit. Comparison of the data for different operating conditions with nitrogen-doped fuels should therefore be viewed as one of equal residence times.

The repeatability of the data for operation at an equivalence ratio of 1.0 was within 3% for the major species (CO_2, CO) and within 10% for the minor (NO, HC). Running the burner under fuel-rich conditions caused a decline in the repeatability of the data. Error bars are presented on the data wherever possible to give an indication of the spread. NH_3 was the most sensitive to fluctuation. For high NH_3 concentration conditions, reproduced data points often differed by 25%. To show that this difference was not due to the sampling technique, two of the midget impingers were run in series to check their collection efficiency. Collection efficiencies of 98% for ammonia at a concentration of 170 ppm and 97.5% at 1600 ppm for HCN were obtained.

RESULTS

Data were taken over a wide range of equivalence ratios to establish an operational region for further investigation.

Table 1 shows the distribution of fixed-nitrogen species at three different equivalence ratios for kerosene flames with 1% nitrogen at high atomizing pressure with room temperature inlet air. A drastic change in the distribution accompanies that from an equivalence ratio of 1.3 to one of 1.5. At an equivalence ratio of 1.3 the majority of the fixed-nitrogen is NO; however, at 1.5 and 1.7, the majority of the fixed-nitrogen is HCN. In the second stage of a two-stage combustor the species HCN and NH_3 would be rapidly converted to NO [20, 21]. Therefore, an important index in evaluating the rich stage performance is the summation of fixed-nitrogen species, HCN + NO + NH_i, as well as the NO concentration.

The effect of preheat on the summation of fixed-nitrogen species was investigated at equivalence ratios of 1.5 and 1.7. At $\phi = 1.7$ the sum of fixed nitrogen was reduced only slightly at higher flame temperatures. The results of the investigation at $\phi = 1.5$ are shown in Figs. 1 through 6. Figs. 1, 2, and 3 show the fixed-nitrogen species for the burner operating on kerosene with no nitrogen added. Figure 1 shows exit concentrations, $x/D = 5.0$, of the species HC, HCN, NO, and NH_3 for different inlet air temperatures at an atomizing pressure of 446 kPa. It is observed that even for nonnitrogen-containing fuels the summation of the fixed-nitrogen species is the important measure of the operating condition's emission potential.

TABLE 1
Effect of Equivalence Ratio on Fixed-Nitrogen Species Distribution[a]

ϕ	NO (ppm)	HNC (ppm)	NH_3 (ppm)	Total
1.3	1200	~20	~18	1238
1.5	30	2000	218	2248
1.7	50	2780	175	3005

[a] Kerosene doped with pyridine to 1% N by weight; in-air temperature, 300°K; atomizing pressure, 446 kPa (50 psig); distance downstream, $x/d = 5.0$.

Figure 2 shows an axial profile of the same species for the 600 K inlet air. The first data points, $X/D = 1.5$, correspond approximately to exit of recirculation zone. All species concentrations decay as the combustion products move down the burner, unburned hydrocarbons and HCN showing the strongest decay.

Figure 3 shows the effect of atomizing pressure (mixing) on the exhaust species. For this condition the change in atomizing pressure had little effect on NO concentrations; however, it had quite a drastic effect on the HCN and unburned hydrocarbon emissions. Changing the atomizing pressure from 204 kPa (15 psig) to 446 kPa (50 psig) caused an order of magnitude decrease in the HCN concentrations and almost two orders of magnitude decrease in the unburned hydrocarbons. It is the change in HCN concentrations that is principally responsible for the decrease in the summation of fixed-nitrogen species.

Figures 4, 5, and 6 represent the same sequence of data as in the previous three figures, except that nitrogen has been added to the fuel in the form of pyridine to a concentration of 1% nitrogen by mass. The data show that raising the inlet air temperature increased the NO concentration while the HCN and unburned hydrocarbon concentrations decreased by approximately one order of magnitude. In this case the ammonia concentration also appeared to decrease; however, because of the uncertainty of the NH_3 measurements, the decrease would have to be called qualitative.

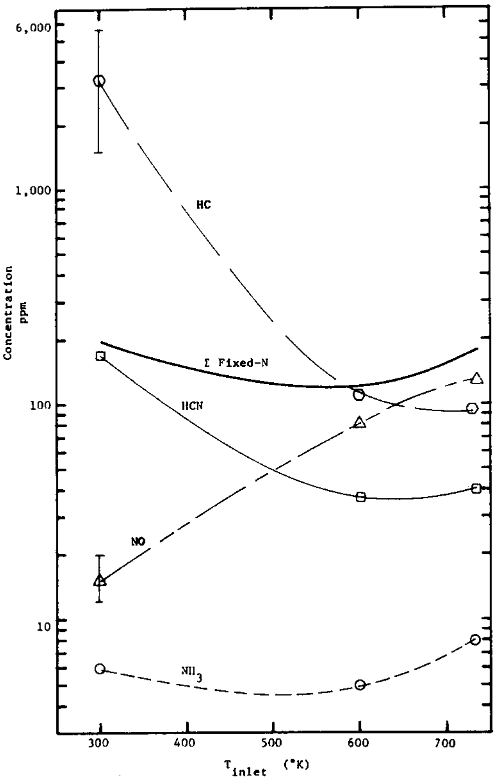

Fig. 1. Effect of temperature on species concentration: kerosene, ΔP = 446 kPa, X/D = 5.0, ϕ = 1.5.

Figure 5 shows axial profiles of the different species for the case of 600 K inlet air. The behavior of the species is similar to that shown in Fig. 2 and to that observed in laminar flat flames by Fenimore [5], Haynes [7] and, most recently, Taylor [22]. In the laminar flames, however, there were no hydrocarbons. The appearance of unburned hydrocarbons and their subsequent behavior is specific to the turbulent diffusion flame.

The effect of atomizing pressure on the different species concentrations at burner exit, with an inlet air temperature of 600 K and equivalence ratio of 1.5, is shown in Fig. 6. There is no counterpart to this data in the premixed laminar flames. Note that when the atomizing pressure was changed from 274 kPa to 446 kPa the HCN concentration changed from approximately 90% of the added nitrogen to 5%. The unburned hydrocarbons also showed a decrease of over an order of magnitude. The NO and NH_3 changed with atomizing pressure too, but their impact on the summation of fixed-nitrogen species was secondary compared with that of the change in the HCN concentrations. Also shown in Fig. 6 is a curve labeled lumunosity. This curve is a measure of the brightness of the flame at the different atomizing pressures and has an interesting correlation with the summation of fixed-nitrogen species in the flames studied. A more detailed discussion of the flame luminosity and the resultant emissions is presented later.

Previous investigators [5, 6, 7] have found that the form of the nitrogen additives does not affect the results in premixed laminar flames. Similar tests were run for the turbulent diffusion flames studied here. Figure 7 is analogous to Fig. 4; the only difference is that the nitrogen has been added to the fuel as dodecylamine, ($CH_3(CH_2)_{11}NH_2$), instead of pyridine. Some difficulty was encountered in operating the burner with dodecylamine as the doping compound: the dodecylamine tended to deposit on the inner walls of the fuel line, necessitating constant adjustment of the fuel metering valve. Consequently this data should be

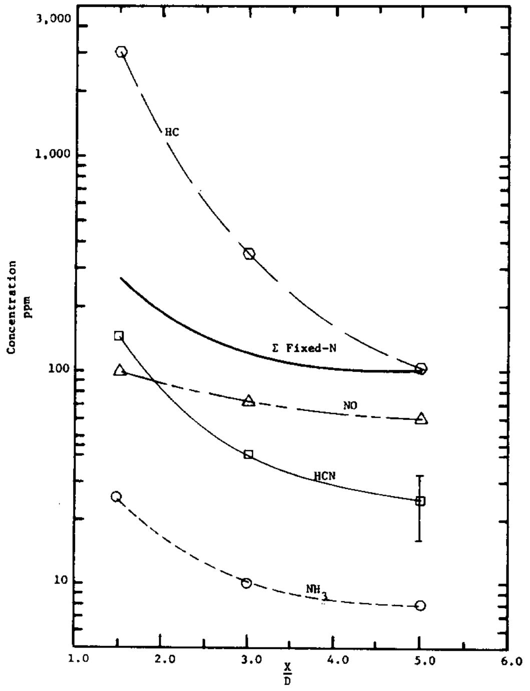

Fig. 2. Species concentration at different axial locations: kerosene, ϕ = 1.5, T_{inlet} = 600°K, ΔP = 446 kPa.

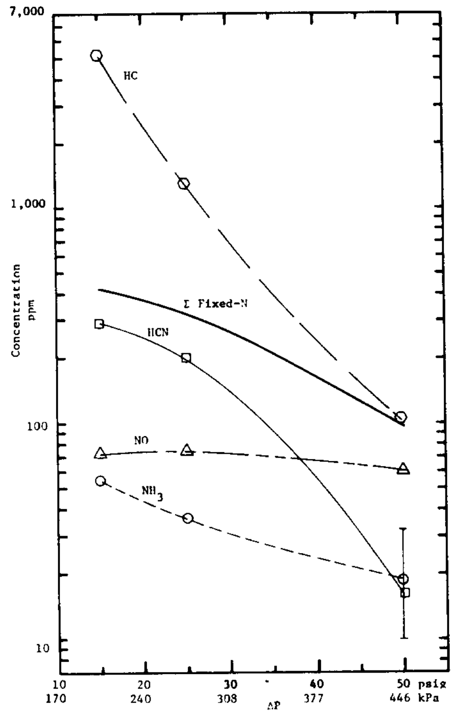

Fig. 3. Effect of mixing on fixed-nitrogen species: kerosene, $\phi = 1.5$, $T_{\text{inlet}} = 600°\text{K}$, $X/D = 5.0$.

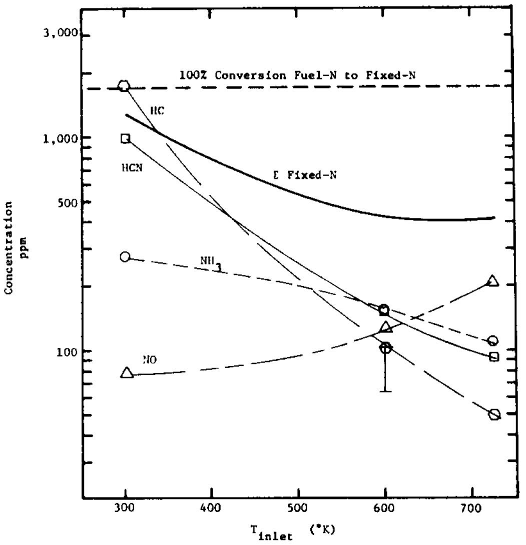

Fig. 4. Effect of temperature on species concentration: kerosene with pyridine in 1% nitrogen by mass, ΔP = 446 kPa, $X/D = 5.0$, $\phi = 1.5$.

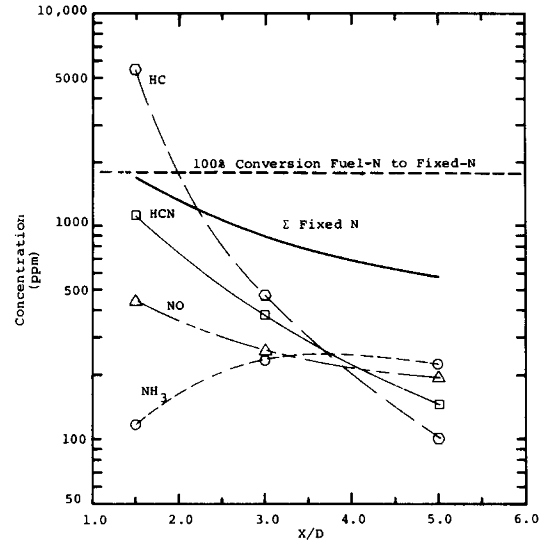

Fig. 5. Species concentrations at different axial locations: kerosene with pyridine to 1% nitrogen by mass, T_{inlet} = 600°K, ΔP = 446 kPa, $\phi = 1.5$.

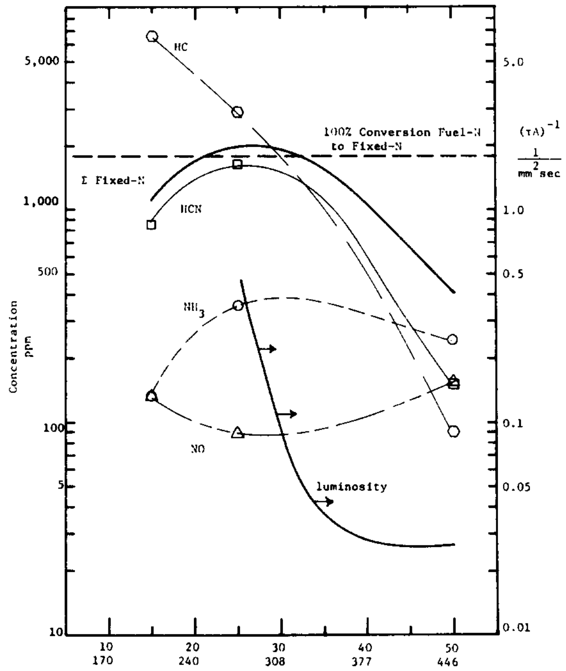

Fig. 6. Effect of mixing on fixed-nitrogen species: kerosene with 1% nitrogen as pyridine, $\phi = 1.5$, $T_{\text{inlet}} = 600°\text{K}$, $X/D = 5.0$.

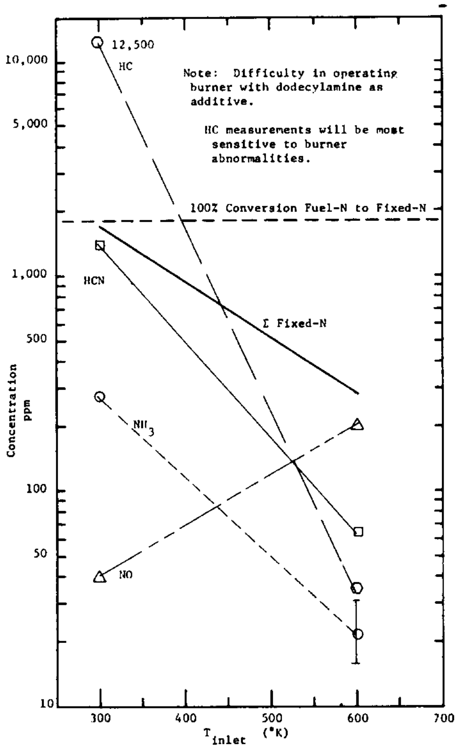

Fig. 7. Effect of temperature on species concentration: kerosene with dodecylamine to 1% nitrogen by mass, ΔP = 446 kPa, X/D = 5.0, ϕ = 1.5.

viewed as qualitative. Note that the behavior of the fixed-nitrogen species and unburned hydrocarbons with increasing inlet air temperature is similar to that exhibited by the pyridine-doped flames. The measured NH_3 concentrations are the same or less than the corresponding NH_3 concentration for the pyridine-doped flame. The large HCN concentrations at the burner exit indicate that the HCN observed in the pyridine-doped flames is not unoxidized pyridine and that the form of the nitrogen additive is not a significant factor in turbulent diffusion flames.

Fenimore [2] showed that the concentration of NO in rich flames approaches an asymptote as the level of nitrogen in the fuel increases. Initial experimental runs with different additive concentrations showed this also to be true in turbulent diffusion flames. However, the effect of additive concentration on the remaining nitrogen species in a turbulent diffusion flame had not been investigated. Figures 8 and 9 are the results of such an investigation. Exhaust concentrations were taken at an equivalence ratio of 1.5 with an atomizing pressure of 446 kPa at different inlet air temperatures for nitrogen concentrations of 0, 1, and 5%. Figure 8 shows the resultant species concentrations with room temperature inlet air. The NO concentration increased and then leveled off, within the accuracy of the measurements, as the nitrogen concentration went from 0 to 1 to 5%. The ammonia concentration showed a similar trend, at first a sharp increase and then a leveling off. The HCN concentration underwent a steady increase as the nitrogen concentration was increased. The concentration of HCN for a 5% nitrogen concentration was approximately five times that at 1% nitrogen.

Figure 9 is for the same operating conditions as that for Fig. 8, but with an inlet air temperature of 600 K. In both cases the same behavior was observed for NO and NH_3. However, the increased inlet air temperature resulted in an order of magnitude reduction in the HCN concentrations, and also in the summation of fixed-nitrogen species, even at nitrogen concentrations of 5%.

DISCUSSION

During the course of the measurements it was observed that the appearance of the flame changed drastically between certain burner operating conditions. In particular, flames that resulted in a low summation of fixed-nitrogen species at the burner exit (ϕ = 1.5, ΔP = 446 kPa, T_{in} = 600 K) were blue and of low luminosity. Those that had a high summation of fixed-nitrogen species (ϕ = 1.5, ΔP = 446 kPa, T_{in} = 300 K and ϕ = 1.5, ΔP = 274 kPa, T_{in} = 600 K) were a very bright luminous yellow. This suggests that the appearance of the flame might be an indication of its emission potential.

Shown in Fig. 10 is a series of flame photographs for different atomizing pressures and equivalence ratios for an inlet air temperature of 600 K. The picture in the top right-hand corner, ΔP = 446 kPa, ϕ = 1.5, corresponds to the flame with a low summation of fixed-nitrogen species, that in the bottom right-hand corner, ΔP = 273 kPa, ϕ = 1.5, corresponds to a flame with a high summation.

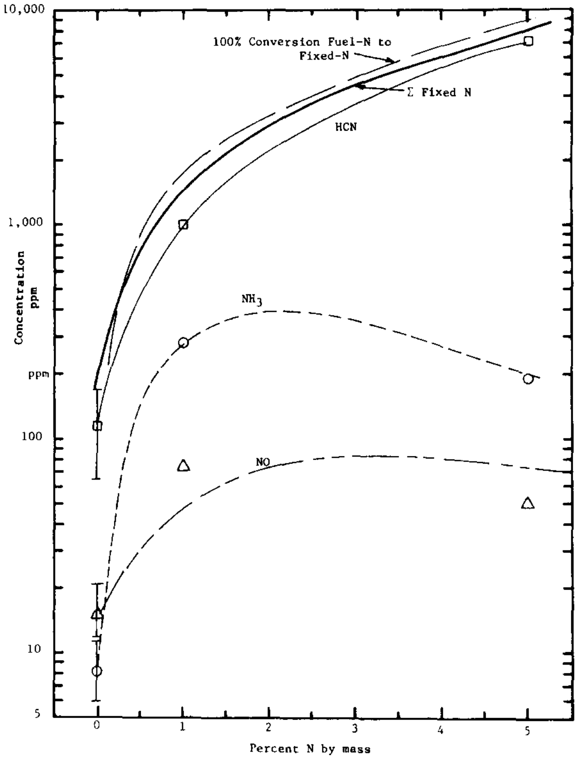

Fig. 8. Effect of pyridine concentration on species concentration: base fuel is kerosene, 300°K inlet air, ΔP = 446 kPa (50 psig), X/D = 5.0, ϕ = 1.5.

The data suggest that for this burner a low summation of fixed-nitrogen species can be obtained under only those operating conditions that yield a blue flame. Not all points in the blue flame region will be satisfactory, either. As the flame becomes leaner, moving from right to left on Fig. 10, the increase in oxygen available for reaction will result in higher NO emissions.

Attempts were made to minimize the summation of fixed-nitrogen by operating at equivalence ratios closer to unity with lower atomizing pressure (ΔP = 273 kPa, ϕ = 1.3) to keep NO concentration low [10, 11, 12]. The concentrations of HCN and NH$_3$ in these flames increased; it was felt that they would be dependent on the nitrogen concentration in the fuel [19], whereas the more intensely mixed richer flames showed a minimum of fixed-nitrogen essentially independent of fuel-nitrogen concentration, as shown in Fig. 9. In this experiment it was possible to define a narrow region in the ϕ, ΔP, T_{in} operational space in which the summation of fixed-nitrogen species was minimized [19].

The appearance of the luminous yellow flame is a strong indication of soot. All the data showed a correspondence among the appearance of soot, high unburned hydrocarbon, and HCN concentrations. If the luminosity of the flame is taken as a measure of soot concentration, then it can be superimposed on the species concentration graphs as if it were a concentration measurement itself. The number of τA appearing under each picture in Fig. 10 is the product of the shutter speed and aperture of the camera lens required to obtain pictures of constant exposure. It is therefore inversely proportional to the luminous intensity or soot concentration of the flame. The luminosity, $(\tau A)^{-1}$, has also been plotted on Fig. 6. It exhibits a "threshold" type of behavior very similar to that of soot formation as cited in the literature [23] and in equilibrium calculations of solid carbon formation [24].

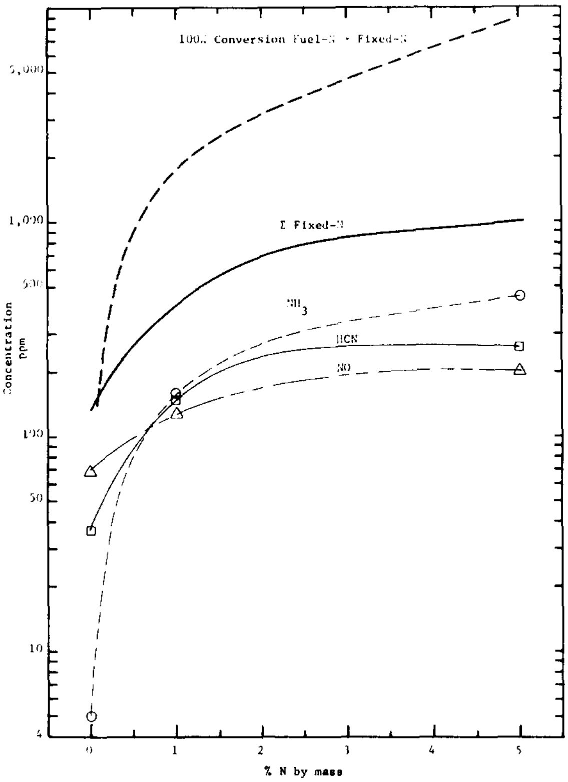

Fig. 9. Effect of pyridine concentration on species concentration: base fuel kerosene, 600°K inlet air, ΔP = 446 kPa (50 psig), X/D = 5.0, ϕ = 1.5.

The shape of the luminosity curve suggests an alternative shape for the HCN and HC curves: a plateau at the high levels of HCN and HC between atomizing pressures of 204 and 274 kPa, then a very rapid decrease parallel to the luminosity curve to a lower plateau at an atomizing pressure of 446 kPa. Because the summation of fixed-nitrogen species is basically controlled by the HCN concentration in this case, it too would exhibit this sharp decline between a plateau of approximately 100% of the fuel-nitrogen to one of approximately 22% of the total fuel-nitrogen. The transition of the sooting high HC flame to the low HC blue flame would represent an equally sharp transition from a condition of high fixed-nitrogen to one of low fixed-nitrogen.

The nature of the combustion in the turbulent diffusion flame studied here is such that it cannot be used for direct evaluation of specific kinetic reactions. In the recirculation zone, hot combustion products are brought back into contact with the incoming reactants, and because it is a diffusion flame, there will be a distribution of fuel air mixtures about the mean equivalence ratio. Examination of the data does, however, offer some insight as to the general applicability of the kinetic schemes appearing in the literature [4-7].

Even though investigators disagree as to the importance of the different individual species in the fuel-nitrogen chemistry, there is universal agreement on the basic reaction path in the premixed flames, namely:

$$\text{Fuel N} \rightarrow \text{HCN} \rightarrow NH_i \begin{array}{l} \nearrow NO \\ \searrow N_2 \end{array}$$

The data that have been presented also support this scheme for turbulent diffusion flames of the condition shown in Fig. 5. What cannot be explained, however, is the persistence of high HCN concentrations in rich flames, which were luminous

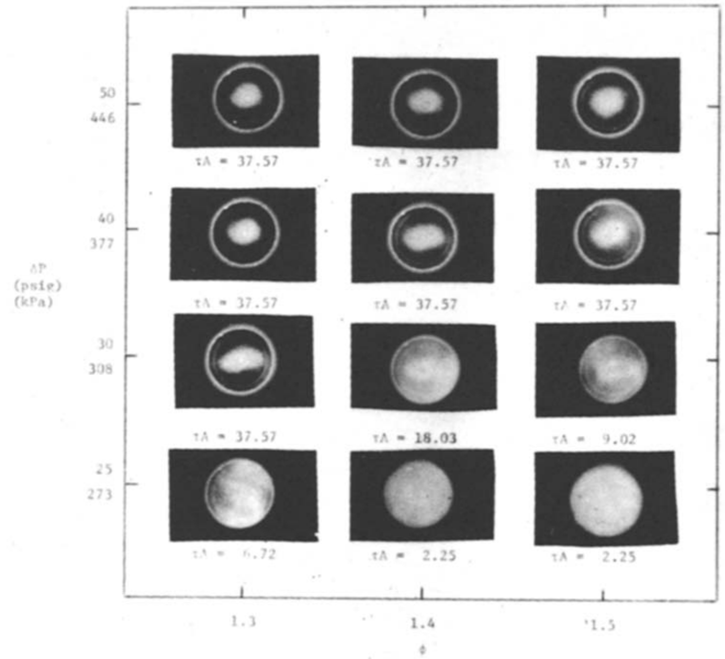

Fig. 10. Flame photographs: τA = shutter speed × aperture area, kerosene, T_{inlet} = 600°K.

yellow. In the laminar flames, which were all low luminosity blue with hydrocarbon free products, the general trend was for large concentrations of HCN to leave the flame zone and then decay as the combustion products traveled downstream. Raising the flame temperature increased the rate of decay. Under no conditions did any investigator observe the persistence of large concentrations of HCN downstream in a premixed laminar flame. The persistence of high HCN concentrations in turbulent flames has been observed by other researchers as well as by the authors [8, 9]. The data also suggest that persistence of unburned hydrocarbons and HCN are synonymous. This has recently been supported by the work of Ogasawara et al. [21].

Reactions between unburned hydrocarbons and NO, N, and NH_i have been speculated [25, 26, 27, 28], but no conclusive findings have been published. Ogasawara et al. [21] believed that the reaction:

$$3.27 \text{ kcal gmole}^{-1} + CH + N_2 \rightarrow HCN + N$$

was important to the production of HCN in their combustion products. In the data just presented this reaction was ruled out as the primary source of HCN by comparison of doped and undoped flames of similar conditions. There was a consistent order of magnitude difference between HCN concentrations from doped and undoped flames of the same unburned hydrocarbon concentrations. The large HCN concentrations observed in these experiments are attributable to the nitrogen in the fuel.

One possible explanation for these large concentrations is that HCN persists in rich regions because the removal rate is low due to low OH concentrations. If the unburned hydrocarbons were to inhibit the oxidation of HCN in the post flame gases, HCN would then be "frozen" in the exhaust gases and subsequently exhausted. The most likely oxidant in the rich flame is the OH radical. If reactions such as:

$$CH + OH \rightarrow C + H_2O + 38.3 \text{ kcal gmole}^{-1} \qquad (3)$$

$$CH_2 + OH \rightarrow CH + H_2O + 17.30\ \text{kcal gmole}^{-1} \quad (4)$$

were to suppress the OH concentration below its equilibrium value, there might be insufficient oxidant left, so that the HCN would be "frozen in." Before modeling efforts can be undertaken, the interaction among unburned hydrocarbons, HCN, and possibly soot must be considered.

The difficulties of measuring the temperature of the sooting inhomogeneous, turbulent flame were not addressed. Estimates of the flame temperature were made by means of measuring the burner wall temperatures and doing an energy balance on the system. At the highest inlet air temperature, 733 K, it was estimated that the flame was only slightly hotter than the adiabatic flame temperature for ambient conditions. Therefore, the present results might also have been obtained through better insulation of the burner. However, it is believed that even with perfect insulation the use of air preheat to raise the flame temperature higher than the adiabatic flame temperature would be useful. The NO concentrations from an adiabatic flame are superequilibrium by an order of magnitude or more [22]. Raising the flame temperature higher than that of the adiabatic flame might attenuate the kinetic constraints and further reduce the NO concentration.

SUMMARY

Measurements were taken at the exit and along the axis of a rich turbulent diffusion flame. The results indicate that the summation of fixed-nitrogen species ($HCN + NH_i + NO$) serves as the significant measure for evaluating the emission potential of a burner operating condition. If only NO were used as the measure, the possible oxidation of the other single nitrogen-containing species (HCN and NH_i) in the second stage of the combustor where excess oxygen is present would be ignored..

For room temperature inlet air, changing the equivalence ratio changed the distribution of fixed-nitrogen species from 97% NO at $\phi = 1.3$ to 89% HCN at $\phi = 1.5$. For still richer flames, $\phi = 1.7$, HCN remained the dominant fixed-nitrogen species, at 93%. Raising the inlet air temperature to 600 K produced an increase in NO and a decrease in HCN for all equivalence ratios. For an equivalence ratio of 1.5 the decrease in HCN resulted in an 80% decrease in the summation of fixed-nitrogen species. The reduction of fixed-nitrogen species with preheated inlet air occurred only over a narrow range of equivalence ratios; at an equivalence ratio of 1.7 the reduction was only 50%.

Intense mixing, $\Delta P = 446$ kPa (50 psig), was required at an equivalence ratio of 1.5 to obtain the lowest summation of fixed-nitrogen. Lowering the atomizing pressure to 274 kPa (25 psig) resulted in a larger summation of fixed-nitrogen species; at the lower pressure 90% of the fuel-nitrogen was measured as HCN. The optimal operating point for this burner was $\phi = 1.5$, $\Delta P = 446$ kPa and $T_{\text{in}} = 600$ K.

Axial profiles of the burner under different operating conditions demonstrated that at equivalence ratios of 1.5 and greater, HCN is the dominant species leaving the recirculation or reaction zone.

It was observed that the fixed-nitrogen species profiles were independent of the specific doping compound used (pyridine or dodecylamine). With room temperature inlet air and at an equivalence ratio of 1.5, increasing the concentration of pyridine from 0 to 1 to 5% resulted in a leveling off of the NO concentration and a proportional increase in the HCN concentrations. Raising the inlet air temperature to 600 K resulted in over an order of magnitude reduction in the fixed-nitrogen species, even at a 5% nitrogen concentration.

It was also observed that the occurrence of a luminous yellow flame coincided with high concentrations of unburned hydrocarbons and HCN. Blue, low luminosity flames had low concentrations of unburned hydrocarbons and HCN. For $\phi = 1.5$, where HCN was the dominate fixed-nitrogen species, this meant a low summation of fixed-nitrogen species at the burner exit. Attributing the flame luminosity to soot implies a possible link among the soot loading of the burner, the unburned hydrocarbon concentration, and the HCN concentration; for rich flame ($\phi = 1.5$, 1.7) this would also indicate the summation of fixed-nitrogen species.

This result is worthy of further investigation. Gerhold, Fenimore and Dederick [29], as well as Takagi, Tatsumi, and Ogasawara [21] have found a similar relationship between the HCN and unburned hydrocarbon concentrations. Gerhold et al., however, found that the unburned hydrocarbon and the smoke of the burner were not related.

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