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The Interrelationship between Soot and Fuel NO_x Control in Gas Turbine Combustors

The decreased hydrogen content of future fuels will lead to increased formation of soot, while increased organically bound nitrogen in the fuel can result in excessive NO_x emission. Control concepts for these two problems are in conflict: prevention of soot requires leaner operation while control of emissions from fuel nitrogen requires fuel-rich operation. However, recent results of two DOE research programs point to both processes having a major dependence on "hydrocarbon breakthrough." Control of both fuel nitrogen conversion and soot formation can be achieved by primary zone operation at equivalence ratios just below that for hydrocarbon breakthrough. This paper reviews the evidence for the importance of hydrocarbon breakthrough, explains our current understanding of why hydrocarbon breakthrough is important, and offers suggestions of how these results might be applied.

Introduction

With increased emphasis on the utilization of U.S. energy resources for national self-reliance, alternative (synthetic) fuels are expected to play a major role in future energy developments. Future electric power generation with combined cycle gas turbines can make a major contribution to national energy goals if these systems could be made to accept synthetic liquid fuels having minimum upgrading [1-3]. Development of such fuel-flexible gas turbines will encourage the utilization of synthetic fuels as they enter the marketplace, have major impact on future conservation of petroleum supplies, and reduce the cost of power production.

Characteristics of the basic feedstocks from which future liquid fuels for gas turbines will be made are significantly different from typical petroleum properties. Liquid synfuels, especially those derived from coal, are likely to be more aromatic and have low hydrogen content. In the combustion system, these characteristics can be expected to promote the formation of soot. This can result in decreased combustor life due to enhanced flame radiation, increased smoke or visibility of the exhaust plume, increased emission of particulate material, and increased deposit forming tendency. Consequently, it is imperative that the process of soot formation within the combustion system be controlled.

Another significant difference between conventional petroleum and synthetic fuels is nitrogen content. Originally-bound nitrogen is effectively converted to NO_x ¹ in conventional combustion systems. NO_x is also formed thermally by fixation of N_2 and O_2 from the air which participates in the combustion process but, for high nitrogen fuels such as synthetics with minimum upgrading, the NO_x due to fuel nitrogen is usually the dominant contribution. While existing stationary gas turbine standards make some allowance for fuel NO_x

contributions [4], conventional combustors would not be capable of meeting the limitations if high nitrogen synthetic fuels are employed. The extent of fuel nitrogen conversion to NO_x must be reduced.

It is well known that soot production is reduced by operating combustion systems leaner (i.e., with more excess air) in the soot formation zone. In premixed systems or other processes not significantly influenced by droplet burning, the equivalence ratio² at which soot begins to form is greater than 1.0. Since the gas turbine combustion system operates with a low overall equivalence ratio ($\phi \sim 0.3$) it would seem that soot-free operation is routinely achievable. Unfortunately, stabilization of the combustion process requires a portion of the combustor, the primary zone, to be operated at stoichiometric or fuel rich mixture ratios. Further, reduction of fuel nitrogen-to- NO_x conversion requires fuel-rich operation (i.e., $\phi > 1.0$) in the first stage of the combustion process. Consequently, a working knowledge of the interrelationships between the soot formation and fuel nitrogen conversion processes during fuel-rich operation is vital to the development of future combustion systems capable of utilizing the lower hydrogen, higher nitrogen fuels of the future.

This paper presents research results of two organizations conducting independent programs for the U.S. Department of Energy which together provide important practical insight into the interrelationships between the soot formation and fuel nitrogen conversion problems. It has been found that both processes have a major dependence on the presence of hydrocarbons in the combustion process. The sooting limit corresponds to mixture conditions at which hydrocarbons are first observed in the first stage combustion products (the hydrocarbon breakthrough point) and the minimum fuel nitrogen conversion to NO_x occurs at the highest fuel-air ratio prior to the hydrocarbon breakthrough point. Strategies to prevent both soot formation and fuel nitrogen conversion should account for these important phenomena and control concepts might be based on this information.

² Equivalence ratio, ϕ , is the actual fuel-air ratio divided by the stoichiometrically correct fuel-air ratio. Values less than one correspond to lean operation while values greater than one indicate fuel-rich operation.

¹ NO_x is the general symbol which represents the sum of NO and NO_2 emission from a source.

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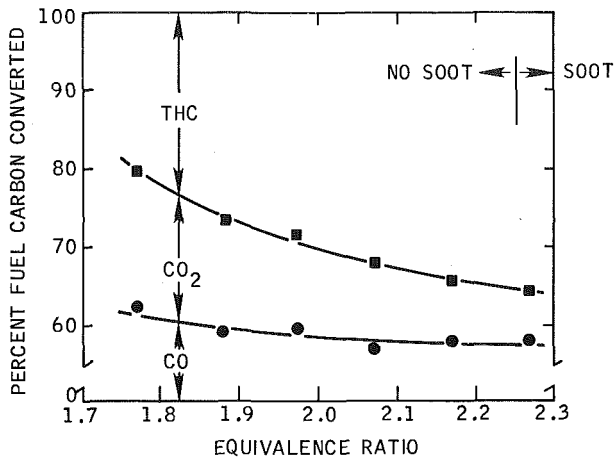


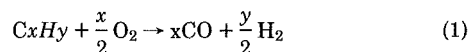
Fig. 1(a) Fraction of fuel carbon converted to each exhaust product for ethylene-air combustion [19]

The balance of this paper is organized into three major sections. The first addresses current evidence that hydrocarbon breakthrough is critical to the soot formation and fuel nitrogen conversion processes. In general, the background work on soot formation was performed at Exxon Research while the fuel nitrogen conversion results were obtained at MIT. The second major section provides our current understanding of why hydrocarbon breakthrough is important to these processes. The third provides some insight on how these results might be applied in a gas turbine system. Use of the information could take the form of guidance for design, explanation of available results, or development of control concepts.

Evidence of Hydrocarbon Importance

Soot Formation. While both carbon formation and carbon consumption processes occur in continuous combustion systems, the latter are very much slower. The optimum approach for preventing hardware distress and avoiding serious environmental consequences is to develop combustion systems which avoid carbon formation while satisfying other system requirements (efficiency, gaseous emissions, hardware reliability, etc.).

The predominance of fundamental research activity has involved laminar premixed flames. Street and Thomas' work published in 1955 is extremely thorough in experimental detail and breadth of hydrocarbons examined [5]; it has become the classic paper in the field. Other publications are references [6-17]. Equilibrium calculations indicate that soot should not be present at fuel-air mixture conditions where the oxygen-to-carbon atomic ratio (O/C) is greater than one. That is, the general chemical equation:



should define a soot formation threshold. However, all experimental results have shown soot formation at O/C substantially in excess of unity, thus proving that the process is kinetically controlled.

The most relevant work to the present interest—soot formation in gas turbine systems—has been recently conducted using a highly-backmixed, experimental combustor [18-20]. As noted above, most previous soot formation research had employed laminar premixed flames. The laminar aerodynamic situation is very different than that in the soot-forming region of continuous combustion devices like the gas turbine where combustion products are usually backmixed with incoming fuel and air in a strong, highly-turbulent recirculation zone. Therefore, soot formation experiments conducted in a highly-backmixed combustion environment are the most relevant here.

The highly backmixed combustion studies of soot formation have been conducted using the Jet Stirred Combustor. The device used was a modification of the Longwell-Weiss reactor [21] with hemispherical geometry. The reaction zone was 5.08 cm in diameter and had 25 radial exhaust ports of 3.2 mm dia. Combustion experiments were conducted

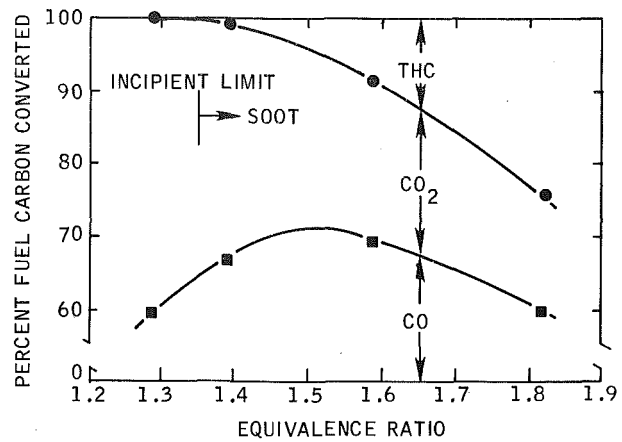


Fig. 1(b) Fraction of fuel carbon converted to each exhaust product for toluene-air combustion (air mass flow = 112.5 gm/min, inlet temperature = 300 °C) [19]

at atmospheric pressure with a range of residence times of 0.6 to 4 ms. Fuel and air were metered separately, preheated to the desired inlet temperature prior to injection (liquid fuels are prevaporized), and injected into the reactor zone through forty small holes or sonic jets which stir the reactor contents and produce a mixture of essentially uniform temperature and composition. Measured quantities included gaseous species concentrations (CO, CO₂, THC³, O₂), the incipient soot equivalence ratio, and soot production (mg/l). A complete description of the experiment can be found in references [18-20].

The previously reported Jet Stirred Combustor results [18-20] included an evaluation of the fuel-rich combustion and soot formation characteristics of a number of pure hydrocarbons. Groups of the hydrocarbons tested were found to behave similarly and three categories of hydrocarbons were defined. The groupings were as follows:

Group 1	Group 2	Group 3
Ethylene	Toluene	1-methyl-naphthalene
Hexane	O-xylene	
Cyclohexane	M-xylene	
N-octane	P-xylene	
Iso-octane	Cumene	
1-octene	Tetralin	
Cyclo-octane	Dicyclopentadiene	
Decalin		

The first group produced large amounts of exhaust hydrocarbons (i.e., many percent based on equivalent flame ionization detector response to methane) without sooting and in no case was significant (i.e., measurable at the mg/l level) soot observed.

The second group produced measurable soot. For these fuels, the leanest mixture ratio at which soot is observed (the incipient soot limit) was found to correspond to the conditions at which significant concentrations of exhaust hydrocarbons were first detected (hydrocarbon breakthrough). In these cases, the measured hydrocarbon concentration was less than one percent at the incipient limit. Figure 1 compares the behavior of ethylene (from Group 1) and toluene (from Group 2). The illustration presents the portions of fuel carbon converted to CO, CO₂ and THC. Hydrocarbon concentrations are very significant at and even below the incipient soot limit in the case of ethylene combustion, but for toluene the soot limit corresponds to the hydrocarbon breakthrough equivalence ratio.

Another commonality in the second group is that the incipient soot limit of these fuels was about 1.4 and the amount of soot produced as fuel-air mixture ratio was increased beyond the incipient sooting limit was similar (within a factor of two) for all fuels in this group. 1-methyl-naphthalene was significantly different in this respect producing much higher soot quantities than those in the second category

³ THC = Total hydrocarbons present in the exhaust products; expressed in volumetric concentration as if their composition was entirely methane.

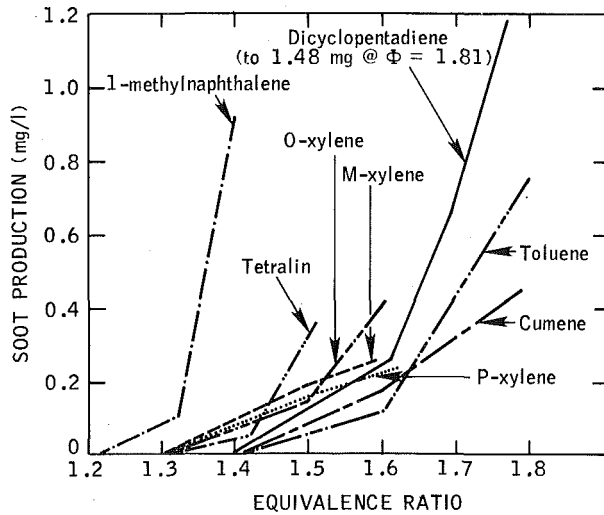


Fig. 2 Soot production for various pure hydrocarbons at 300°C inlet temperature and 112.5 gms/min air flow [19]

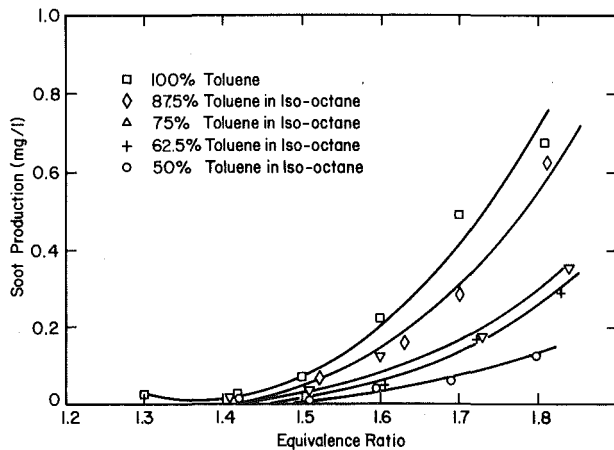


Fig. 3 Soot production versus equivalence ratio for toluene and toluene/iso-octane blends [20]

and having an even lower soot formation equivalence ratio (see Fig. 2). Consequently, this double-ring aromatic represents a third category of hydrocarbon soot forming characteristic.

Blends of iso-octane and toluene were tested to determine the behavior of a two-component mixture with Group 1 and Group 2 hydrocarbons. Results are shown in Fig. 3. Mixtures with 50 or more percent toluene produced soot while a 25 percent toluene blend did not. Clearly, for the mixtures which did soot, increases in the volume percent toluene result in increased soot production at all equivalence ratios.

It was also determined that with less toluene in the blend, the concentration of hydrocarbons at the incipient limit tended to be low for the highly sooting blends but increased sharply for those blends which did not soot (see Table 1). For example, with 50 percent toluene, the hydrocarbon concentration was 2.4 percent at the incipient soot limit, while with 100 percent toluene this value was 0.2 percent. These results indicate a combination of Group 1 and 2 behaviors and imply that a combination of the analytical descriptions for toluene and iso-octane might be a reasonable approach for prediction of the sooting characteristics of such fuel blends.

Taken together, these results allow us to develop the following conclusions concerning soot formation in gas turbines utilizing synthetic liquids:

- Future synfuels having low H-content due to high concentrations of single ring (Group 2) and double ring (Group 3) aromatics are capable of producing substantial quantities of soot.
- The amount of soot produced will be related to the amount of

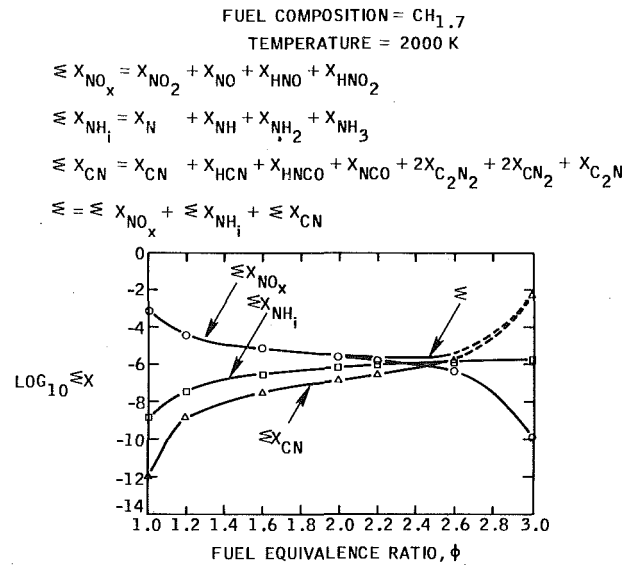


Fig. 4 Equilibrium fixed nitrogen species mole fractions as a function of fuel equivalence ratio. Fuel composition = $\text{CH}_{1.7}$, $T = 2000 \text{ K}$ [22]

Table 1 Combustion product hydrocarbon concentrations in jet stirred combustor experiments

	At Incipient Soot Limit		At Blow-out Point	
	ϕ	% HC	ϕ	% HC
100% Toluene	1.39	0.2	—	—
87.5% Toluene/ 12.5% Isooctane	1.41	0.15	—	—
75% Toluene/ 25% Isooctane	1.40	1.21	—	—
62.5% Toluene/ 37.5% Isooctane	1.49	0.82	—	—
50% Toluene/ 50% Isooctane	1.5	2.4	—	—
25% Toluene/ 75% Isooctane	—	—	1.61	7.12
10% Toluene/ 90% Isooctane	—	—	1.51	7.0

Group 2 and (especially) Group 3 compounds present in the fuel.

- Most importantly, in the case of highly aromatic fuels, the soot limit will correspond to the equivalence ratio at which hydrocarbons become a significant (~1 percent) combustion product.

As stated in the introductory section, the prevention of significant soot production should be accomplished in a combustion process which also minimizes fuel nitrogen conversion. The following subsection presents the evidence of the important influence of hydrocarbon breakthrough on this other process.

Fuel Nitrogen Conversion. It is well recognized that the production of nitric oxide by the combustion of fuels containing organically bound nitrogen can be suppressed by operating the first stage of the combustor fuel rich. The questions of what is the maximum attainable reduction in bound nitrogen conversion and what is the optimum first-stage equivalence ratio needed to achieve the maximum reduction are closely related to the presence of hydrocarbon species during the combustion process, that is, hydrocarbon breakthrough.

Consideration of the effect of increasing equivalence ratio on the equilibrium concentration of bound nitrogen species provides a measure of the constraints on the use of a staged combustion process to reduce NO_x emissions [22]. Representative calculations summarized in Fig. 4 for a flame temperature of 2000K and a fuel with an atomic hydrogen/carbon ratio of 1.7 show that increasing equivalence ratio decreases the concentration of nitrogen oxides ($\sum X_{\text{NO}_x}$) but increases that of amines ($\sum X_{\text{NH}_i}$) and cyanides (X_{CN}). It is vital to design the first stage of the combustion process to minimize amines and cyanides as well as NO_x because, if formed, these species will al-

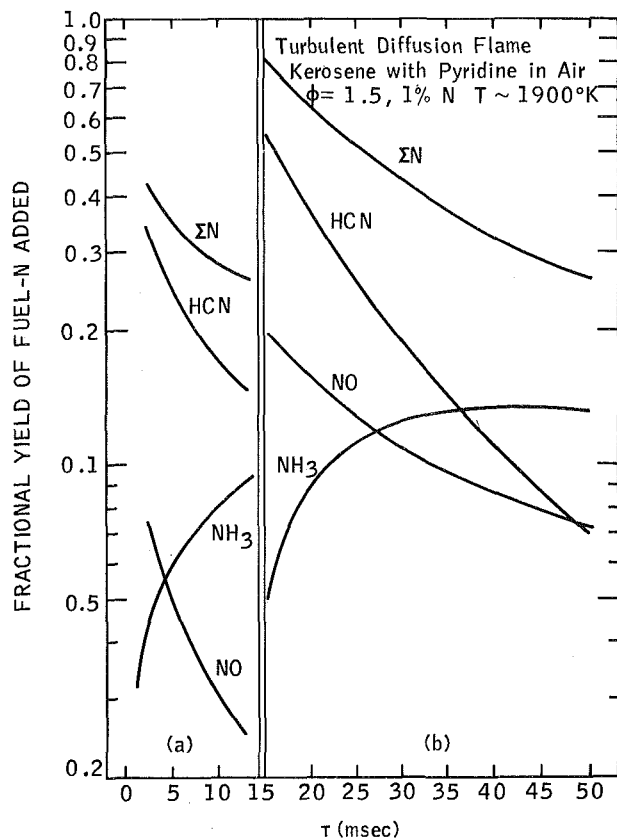


Fig. 5 Joint plot of laminar and turbulence diffusion flame data. (a) flat flame data for $C_2H_4/O_2/He/Ar$ flame at $\phi = 1.6$ with 2.5 percent N as NH_3 . $T < 2120$ K (b) turbulent diffusion flame data for kerosene/air flame at $\phi = 1.5$ with 1.0 percent N as pyridine. $T \sim 1900$ K [23]

most completely convert to NO_x in the fuel lean second stage. The emission of total fixed or bound nitrogen ($\Sigma X_{NO_x} + \Sigma X_{NH_i} + \Sigma X_{CN}$) passes through a minimum at a ϕ of about 2.4.

The equilibrium concentration of bound nitrogen species at the minimum (slightly more than 1 ppm) is, however, not attained in practice. The factors which prevent the attainment of the equilibrium concentration are: (1) the relatively slow rate at which fuel nitrogen species are converted to the thermodynamically-stable and environmentally-preferred molecular nitrogen, (2) the interaction of hydrocarbon species with nitric oxide at higher equivalence ratios to form HCN which reacts even more slowly to N_2 , thus providing an upper bound on the ϕ which can be used in practice, and (3) mixing constraints. Selected results from the program at MIT showing the importance of these three factors are presented below.

The kinetic constraints can be inferred from time-resolved measurement of HCN, NH_3 , and NO obtained in the combustion products of a laminar flat flame of ethylene doped with ammonia (Fig. 5(a)) and the spray combustion of kerosene doped with pyridine (Fig. 5(b)). Several points need to be made. First, although the fuel nitrogen in the premixed flame was added to the flame as NH_3 , most of the bound nitrogen at the first sampling point was in the form of HCN. It is only after the hydrocarbons decay that the ammonia concentration, that NH_3 to be found in the combustion products, begins to increase. Secondly, the rate of decay of the HCN and NO in the post flame gases shows the very slow rate of approach towards equilibrium. Finally, the behavior of the products of combustion for the pyridine-doped kerosene flame is qualitatively similar to that of the ethylene/ NH_3 system, but the time frame is stretched due to the critical additional constraint of mixing in the spray flame.

Examining the effect of equivalence ratio on bound nitrogen species concentrations measured in the premixed flame (Fig. 6) suggests that the optimum value of ϕ is about 1.8. The difference between the experimentally observed ϕ for minimum fixed nitrogen and that calculated from equilibrium considerations (i.e., 1.8 versus 2.4) is at-

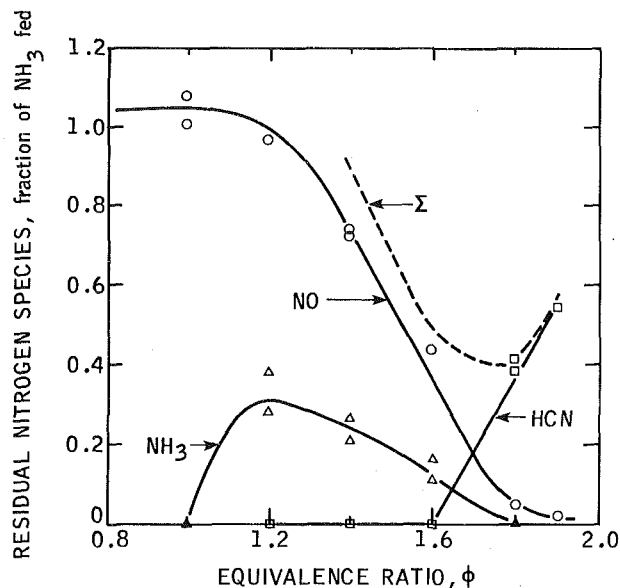


Fig. 6 Residual nitrogen species (dry basis) and temperature profiles as a function of fuel equivalence ratio, at 30 mm above the burner surface. $C_2H_4/O_2/He$ flames doped with NH_3 , $He/O_2 = 6.02$ [28]

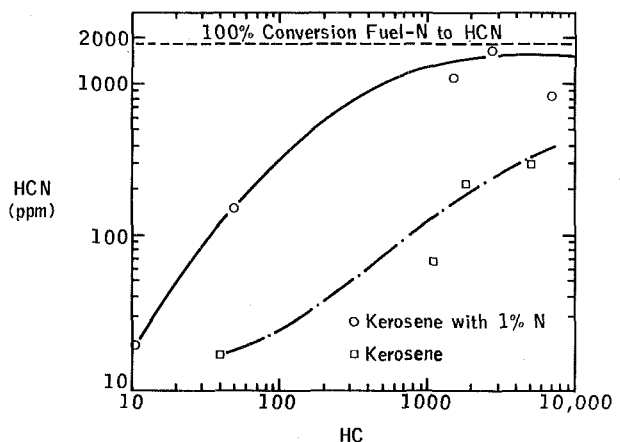


Fig. 7 HCN versus unburned hydrocarbons: $\phi = 1.5$; $T_{inlet} = 600$ K; \circ Kerosene doped with Pyridine to 1 percent N by mass; \square kerosene; $X/D = 5.0$ [23]

tributable to the presence of hydrocarbons beyond $\phi = 1.8$ which allows substantial retention of fixed nitrogen as HCN. At these higher equivalence ratios HCN is by far the dominant species—the minima expresses a boundary where leaner operation is characterized by NO dominance and richer operation results in copious HCN. When at $\phi = 1.8$, this flame is still effective in consuming the initial fuel and no significant hydrocarbon concentrations are observed in the downstream portions of the flame system.

The equivalence ratio for minimum total fixed nitrogen is reduced to an even lower value in the spray flame where hydrocarbons persist at $\phi > 1.5$ due to unmixedness. The influence of hydrocarbons on the emission can be seen from the studies of reference [23] which concern the emissions from both kerosene and pyridine-doped kerosene flames. The values of HCN observed in the combustion products are plotted against the total hydrocarbon content (as measured by a flame ionization detector) in Fig. 7. It is clear that the levels of HCN for both doped and undoped fuels increased with increasing hydrocarbon content. Again it was found that the optimum ϕ for minimizing bound nitrogen emissions is determined by trade-offs between NO and HCN emissions; the optimum ϕ is close to the point at which hydrocarbons breakthrough and HCN shows a corresponding sharp increase at equivalence ratios beyond this point. For the kerosene spray combustor the ϕ for minimum emission of fixed nitrogen was in the range of 1.5.

Current Understanding

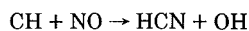
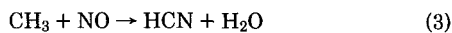
Soot Formation. Many mechanistic models for soot formation have been proposed and a number of references to these have been included. Generally, it is recognized that condensed ring aromatic hydrocarbons can produce soot via a different mechanism than do aliphatic hydrocarbons. A simplified mechanism following Graham, et al. [16,17] is shown in Fig. 8.

Aromatic hydrocarbons can produce soot via two mechanisms: (1) condensation of the aromatic rings into a graphite-like structure, or (2) breakup to small hydrocarbon fragments which then polymerize to form larger, hydrogen-deficient molecules which eventually nucleate and produce soot. Based on his shock tube studies of soot formation, Graham concludes that the condensation route is much faster than the fragmentation/polymerization route. Further, he has proposed that the mechanism by which an aromatic forms soot changes with temperature, below 1800 K the condensation path is favored while above this temperature the fragmentation/polymerization route is followed.

While the aliphatic soot formation process also involves complex reactions of the polynuclear species [15], these influences are far less dominant than for the aromatics. Accordingly, this simple model shows aliphatics producing soot predominantly through the slower fragmentation/polymerization mechanism. As a result, these hydrocarbons do not form the quantities of soot produced by the aromatics. Indeed, during the fuel-rich combustion of a fuel blend composed of aromatics and aliphatics, the aromatic hydrocarbons would produce the major portion of soot. Combustion of the aliphatic portions of the fuel influence temperature and hydrocarbon fragment concentration but soot formation via fragmentation/polymerization is small relative to that of aromatics.

The experimental results are consistent with this model. It has been observed that soot formation with Group 2 fuels commences with the initial presence of hydrocarbons in the exhaust. If we assume that these breakthrough hydrocarbons maintain their aromatic character, this observation may reflect the fast kinetics of the ring-building or condensation reactions. On the other hand, the aromatic molecule may be an effective source of C_2H_2 and high concentrations of acetylene as fuel pyrolysis occurs may be responsible for extensive soot production. Further, the results for 1-methylnaphthalene indicate that a double-ring aromatic provides the most rapid soot formation of the hydrocarbons studied. This observation can also be viewed as consistent with either the ring building view (i.e., the first ring-joining has already occurred) or the polymerization mechanism (i.e., even higher amounts of C_2H_2 present in the pyrolysis zone).

Fuel Nitrogen Conversion. The importance of the reactions of NO and hydrocarbons to form HCN has long been recognized [24–26]. Two of the reactions cited for HCN formation from NO are



These radical fragments will be present during the pyrolysis of most hydrocarbons and the NO-hydrocarbon reaction is therefore expected to be less sensitive to hydrocarbon type than soot formation. More data are needed to establish the extent to which NO-hydrocarbon reaction may be affected by the fuel type.

The conclusions regarding the importance of THC concentrations previously drawn are reinforced by these mechanistic considerations and the message to the combustor designer continues to be to operate a combustor at conditions that minimize hydrocarbons breaking through with the combustion products, i.e., minimize the reactants responsible for soot and HCN formation.

Application of Findings

THC Importance. Acceptable gas turbine combustion performance using low hydrogen, high nitrogen content fuels will require a fuel-rich first stage which promotes conversion of fuel N to N_2 while preventing excessive soot formation. This paper proposes that the first stage be thought of as a well-stirred reactor—a zone which is sufficiently mixed to be nearly homogeneous in temperature and compo-

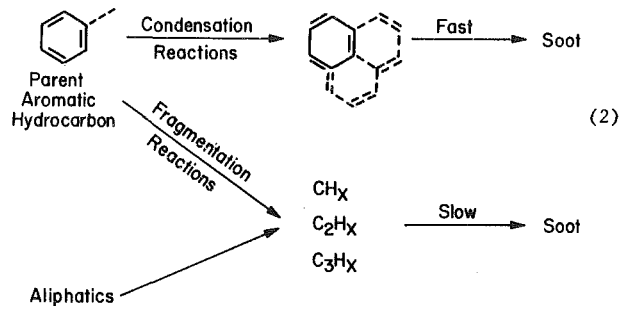


Fig. 8 Equation (2)

sition. The incoming fuel-air mixture is assumed to be instantaneously mixed with the combustion products and the entire reaction zone is represented by one set of composition/temperature conditions. Soot and fuel nitrogen conversion in this system can be viewed as the products of the reaction between these components in the “well stirred pot” at rates determined by the existing temperature conditions.

The distinction between the first stage operating as a plug flow reactor or as a stirred reactor is important. First, previous work has shown that the incipient soot formation limit in the stirred reactor configuration is richer than the plug flow case [27]. A further distinction is added through consideration of fuel nitrogen conversion. In the plug flow case, destruction of fuel nitrogen occurs where large concentrations of hydrocarbon fragments are present and formation of HCN can be extensive; low fixed nitrogen may be achieved by allowing the system to relax back towards equilibrium. On the other hand, at appropriate operating conditions the stirred reactor may allow fuel nitrogen destruction to occur at low hydrocarbon concentrations and the initial formation of HCN may be limited.

Soot will form in this well-stirred combustion zone if the initial fuel contains a substantial amount of single or double-ring aromatics and if the zone is operated in a manner which allows a significant concentration of hydrocarbons (unburned fuel fragments) to be present. Fuel nitrogen is minimized by operating the reaction zone as rich as possible without the presence of hydrocarbons. More oxidizing conditions allow the conversion of fuel N to NO_x to be more effective and the presence of hydrocarbons at richer operating conditions allows the formation of HCN in the first stage which will subsequently be oxidized to NO_x in the second, fuel-lean stage of the combustor. Consequently, these results imply that minimization of both NO_x and soot in gas turbines utilizing future fuels will require a staged combustion process designed for the richest possible operation without substantial hydrocarbon breakthrough. It is recommended that combustor designers utilize this information by analyzing THC concentrations within the fuel-rich first stage during combustor development testing.

The ability to operate fuel rich without soot formation is also influenced by the type of fuel being combusted (i.e., composition in terms of Group 1, 2, or 3). Lesser quantities of single-ring and double-ring compounds in the fuel will increase the incipient sooting ϕ and allow the THC concentration at the limit to increase. However, fuel nitrogen conversion is not likely to be as sensitive to fuel type—fixation of fuel nitrogen as HCN will coincide with the THC breakthrough regardless of the type of hydrocarbons present in the fuel. Consequently, the maximum operating equivalence ratio for fuels with a predominance of Group 1 hydrocarbons may be dictated more by considerations of fuel nitrogen conversion than soot formation.

A point which should be emphasized is that the JSC experiments on which these conclusions are based involves a premixed prevaporized system. The presence of fuel droplets in the first stage would be expected to seriously influence the results. Successful operation will require the pockets of fuel-rich mixture resulting from droplets in the first stage be avoided—otherwise the consequence of hydrocarbon breakthrough (soot formation and fixation of fuel nitrogen) will occur locally. Fuel injection, droplet-air mixing, and droplet vaporization must be accomplished in a manner which allows homogeneous con-

ditions approaching homogeneity to be achieved on a micro-scale within the first stage.

Finally, the second stage combustion process is also critical for achieving low levels of NO_x emission. Large quantities of thermal NO_x emission. Large quantities of thermal NO_x can be produced if the mixing process is too slow and allows regions of near-stoichiometric, high temperature reaction.

Control by THC or Radiative Characteristics. One important concern in the design of low NO_x combustion systems is the impact of load variation on operating characteristics. For example, a reduction in load causes a decrease in fuel-air ratio requirements and perhaps combustor inlet temperature. These changes can cause the system to operate in a manner substantially off the optimum operating point unless adjustments are made to key combustion parameters.

The evidence that THC is a critical indicator of optimum operation suggests that measurement of this parameter might be used to control conditions in the first stage. One can envision a flame ionization detector which monitors first stage gas composition to provide a signal proportional to first stage THC. This, in turn, could control air supplied to the first stage in a manner which assures optimum operation. In essence, this control scheme would attempt to have the combustor always operating at the "knee" of the THC versus equivalence ratio characteristic.

Alternative methods of monitoring THC which do not involve extraction of a physical sample might also be employed. Luminosity is a measure of soot formation but is more indicative of Group 2 and Group 3 hydrocarbon breakthrough than Group 1. It is therefore expected to be a useful measure of when THC breakthrough occurs but could overlook situations in which fuels with a low sooting potential are utilized. Alternatively, a spectroscopic analysis of flame emission or adsorption in a spectral region characteristic of hydrocarbons could be employed as the control signal.

Establishing the best method of sensing hydrocarbon breakthrough and controlling key combustor variables will require additional research and development. The appropriate THC concentration to use as a set point is not known and the ability to design first stage zones with controllable flows must be developed.

Conclusion

The effective use of future synthetic fuels in gas turbines will require the development of two-stage combustion systems which minimize both soot formation and the conversion of fuel-bound nitrogen to NO_x . Recent results show that incipient sooting limits for highly aromatic fuels correspond to mixture conditions at which hydrocarbons are first observed in the combustion products (the hydrocarbon breakthrough point) and that minimization of fuel nitrogen conversion requires operating at the highest fuel-air ratio prior to the hydrocarbon breakthrough point. This paper concludes that the first stage of an advanced combustion system should be operated as a fuel rich stirred reactor. The design of such a system must insure that hydrocarbons are not present in substantial quantities in the first stage and measurements of first stage THC could be an important part of future combustor development programs. This paper also concludes that some form of THC measurement (physical probe, emission, absorption, or luminosity) might be employed as an effective control to maintain optimum combustor performance over the entire range of engine operation.

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