AMMONIA COMBUSTION PROPERTIES AND PERFORMANCE IN GAS-TURBINE BURNERS

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Experimental studies were conducted to determine the minimum ignition energy, quenching distance, flame-stability limits, and gas-turbine-burner performance of ammonia–air mixtures. The minimum ignition energy of ammonia was 8 millijoules compared to less than 0.5 millijoules for propane. At stoichiometric conditions, the quenching distance for ammonia–air was 0.275 in. The corresponding reported value for propane–air is 0.08 in. In the flame stability experiments, ammonia would burn at only one-half the air-flow velocity possible with hydrocarbon fuels and the range of equivalence ratios for stable flame was much narrower than for hydrocarbon fuels. These characteristics were essentially substantiated in gas-turbine-burner testing. It was concluded that neat ammonia cannot be used as a substitute fuel for hydrocarbons in conventional gas-turbine burners unless the ignition-system energy is increased, the combustion liner diameter is increased by a factor of approximately 2, and the ammonia injected in the gaseous state.

Two approaches were investigated for improving the combustion properties of ammonia. These were to use additives or to partially pre-dissociate the ammonia. Additives were tested in the flame-stability apparatus in concentrations of 5% by volume of the total fuel. At this concentration, none of the additives improved the flame-stability properties to the extent required. The minimum ignition energy, quenching distance, and flame-stability properties of 28% dissociated ammonia were approximately equal to these same properties of methane. Partially dissociated ammonia was also tested in the gas-turbine burner. It was concluded that 28% dissociated ammonia could be used as a substitute fuel in gas-turbine-combustion systems optimally sized for hydrocarbon fuels.

Introduction

The supply of fuels to military operations in the field constitutes a severe logistics problem. An Energy Depot System is a possible solution in some operations. This approach uses energy from a mobile nuclear reactor to synthesize a fuel in the field from environmental materials. The product must be usable as a primary or substitute fuel in existing or specially designed vehicular powerplants.

Although several fuels could potentially be produced,[1] studies indicated that the most feasible approach was ammonia. The ammonia would be synthesized from nitrogen and hydrogen obtained from fractionation of air and electrolysis of water. One problem was the anticipated poor combustion performance of ammonia fuel in vehicular powerplants. As shown in Table I, ammonia has a low heat of combustion, low flame speed, narrow flammability limits, and high heat of vaporization. The reported minimum ignition energy of ammonia[2] was 680 millijoules compared to less than 0.5 mJ for hydrocarbons. Previously, ammonia had been used only in limited emergencies, such as in Belgium during World War II when it was used in engines for powering buses.[3] Therefore, additional combustion data was required before reliable performance or design predictions could be made concerning its use in spark ignition, compression ignition, or gas-turbine engines. Of primary concern in this study was the performance of ammonia in gas-turbine-combustion systems. The combustion data desired for neat ammonia–air was: (1) ignition energy, (2) quenching distance, (3) flame stability, and (4) gas-turbine-combustion performance.

Based on the available combustion properties, it was predicted that neat ammonia could not be used as a substitute fuel in gas-turbine powerplants as required for Energy Depot operation. Therefore, means for improving the combustion properties were to be investigated. Additives and partial dissociation of the ammonia prior to injection were considered. The additives examined were hydrazine, acetylene, carbon monoxide, and nitrogen oxides. All were tested at 5% by volume of the total fuel flow. The method for evaluating their effect was to compare their flame stability limits with those for hydrocarbon fuels and neat ammonia–air.

TABLE I

Comparison of JP–4, ammonia, and hydrogen combustion properties

Combustion property	JP–4	Ammonia	Hydrogen
Stoichiometric fuel–air ratio by weight	0.0674	0.1753	0.0292
Net heat of combustion (liquid fuel):			
Btu/lb	18,400 (min.)	7,470	49,900
Btu/gal	118,700	38,500	28,100
Flammability limits (downward propagation at 1 atm and 300°F):			
Percent by volume of stoichiometric fuel–air ratio	54 to 410	77 to 133	24 to 266
Fuel equivalence ratio range	0.55 to 4.24	0.724 to 1.46	0.182 to 8.84
Laminar burning velocity at 300°F, 1 atm, and stoichiometric, ft/sec	2.04	0.492	11.5
Theoretical stoichiometric combustion temperature at 1 atm, and reactants at 77°F, °F	3700	3064	3660
Spontaneous ignition temperture, °F	502	1204	1060
Minimum ignition energy, mJ	0.3	(680[2])	0.18
Quenching distance at stoichiometric, in.	0.08	0.275*	0.025
Heat of vaporization, Btu/lb	155	508.6	193
Critical temperature, °F	642	270.3	−399.8

* Values obtained in this study.

The products of partial ammonia dissociation are nitrogen, hydrogen, and ammonia. Hydrogen has significantly better combustion properties than ammonia or hydrocarbon fuels, as shown in Table I. Therefore, partial dissociation should improve the combustion properties. The effects of dissociation were determined on the following ammonia combustion characteristics: (1) ignition energy, (2) quenching distance, (3) flame stability, and (4) gas-turbine-burner performance.

Minimum Ignition Energy and Quenching Distance Experiments

Minimum ignition energy is the smallest spark-discharge energy which will ignite a flammable mixture at a given fuel–air ratio, pressure, and temperature. Quenching distance is the minimum distance between two surfaces through which a flame will propagate. There are several classical methods for determining the quenching distance. Our approach was to use the same system to determine both the minimum ignition energy and quenching distance.[4] To determine quenching distance, glass flanges were added to the tips of the electrodes used in the minimum ignition energy experiments.

The experimental system was designed to develop minimum ignition energy and quenching distance data for ammonia–air and partially dissociated ammonia–air. Propane–air tests provided base-line data for correlation with previous experiments. Dissociated ammonia was simulated in the tests by using appropriate mixtures of ammonia–hydrogen–nitrogen.

The test apparatus followed the approach described by Blanc et al.[5] and modified by Metzler.[6] The system consisted essentially of the gas-supply system, test chamber, ignition system, and ignition-energy-measurement equipment. The desired proportions of the fuel mixture and dry air were prepared by partial pressure addition and the mixtures were subsequently analyzed by gas chromatography. The configuration of the ignition test chamber was similar to that used by Metzler.[6] The electrodes meet at the center of the test chamber. One electrode can be withdrawn and the gap length adjusted by a built-in micrometer. Ports permit visual observation of spark discharge and charge ignition characteristics.

The ignition system circuity consisted of a 25,000 V power supply to charge a capacitor, which was then discharged across the spark gap. A dual beam oscilloscope incorporating a Polaroid camera provided time history traces of the voltage and current discharged across the gap. The power ($E \times \dot{I}$) was plotted versus time and the total energy discharged obtained by graphical integration. The photographic traces were read by means of an oscillograph scanner and reader (OSCAR) and the calculations performed by an IBM 7090 computer program.

For a test, the thoroughly evacuated ignition bomb was charged to 1 atm from the supply chamber. Step increases were made in the applied voltage until an ignition was obtained. Ignition was defined as the propagation of a visible flame throughout the volume. The bomb was then evacuated and the test repeated until a minimum ignition value was determined upon a charge not previously sparked more than once. Several tests were required before a satisfactory ignition point was obtained. The electrode-gap spacing was then changed and the test repeated until the spark gap producing a minimum ignition energy was ascertained. With the glass-shrouded electrodes used in quenching distance tests, a high emf was applied and the gap increased until an ignition was obtained on the initial sample. The previously described procedure was then followed to determine the minimum ignition point and to veryify the quenching distance value.

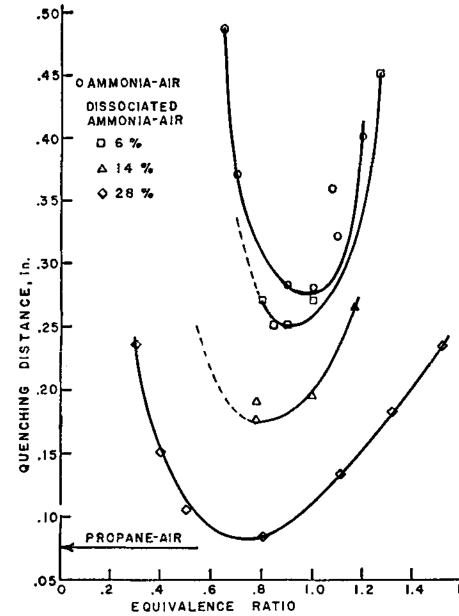

FIG. 2. Quenching distance of ammonia and partially dissociated ammonia at ambient temperature and 760 mm Hg pressure.

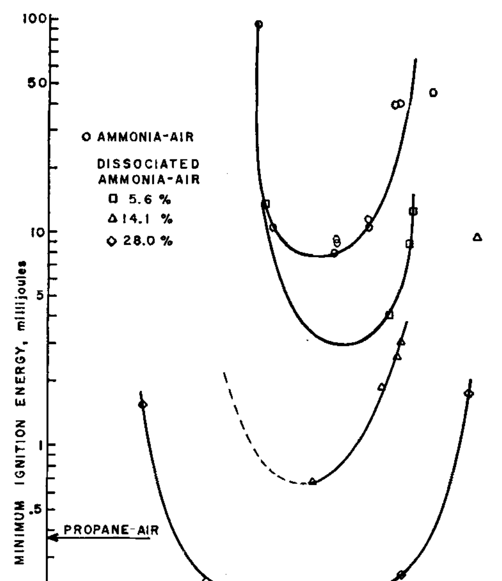

FIG. 1. Ignition-energy requirements for ammonia and partially dissociated ammonia at ambient temperature and 760 mm Hg pressure.

Base-line tests were conducted with propane–air to establish correlation of our ignition energy measurements with previous data. At 0.97 equivalence ratio, the minimum ignition energy of propane–air was 0.37 mJ compared to a literature value of 0.41 mJ[7] for a near-stoichiometric mixture. This correlation established confidence in the experimental equipment and techniques.

The minimum ignition energy curves for ammonia–air and 5.6%, 14.1%, and 28% dissociated ammonia–air are presented in Fig. 1. The minimum ignition energy of ammonia–air is approximately 8 mJ at an equivalence ratio of 0.9.

Partial decomposition of ammonia reduced the energy required for ignition. When 28% is dissociated, the minimum ignition energy is less than that for propane–air. Another significant observation from Fig. 1 is that a low ignition energy is obtained over a wider equivalence ratio as the ammonia dissociation is increased.

Quenching-distance data, obtained for ammonia–air and 6%, 14%, and 28% cracked ammonia–air, is presented in Fig. 2. For ammonia–air, the minimum quenching distance was 0.275 in. at one equivalence ratio. For the 28% cracked ammonia–air, the minimum quenching distance was 0.083 in. at 0.807 equivalence ratio. An equivalent value for propane–air is 0.075 in.[8]

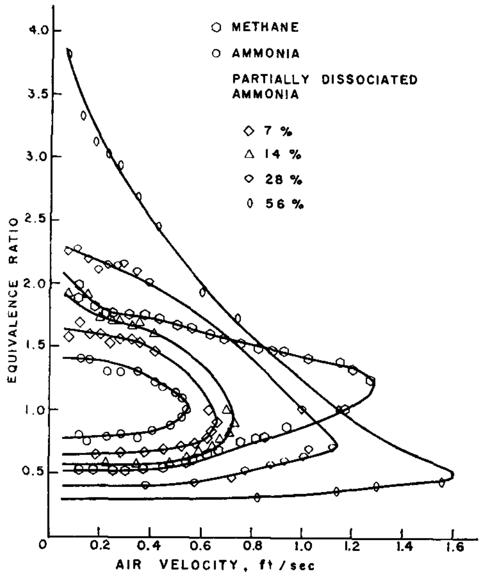

FIG. 3. Comparative flame-stability properties of methane–air, ammonia–air, and partially dissociated ammonia–air at ambient temperature and pressure.

Flame-Stability Experiments

Flame-stability diagrams are plots of fuel equivalence ratio versus flow velocity at blowout. The values obtained are a function of the burner geometry, but the comparative results for various fuels can be used to predict the relative stable burning limits of the fuels in gas-turbine combustors.

A laboratory burner, similar to a Powling flat-flame burner,[9] was designed to develop flame-stability diagrams for: (1) methane–air, (2) ammonia–air, (3) partially dissociated ammonia–air, and (4) additive-enriched ammonia-air. Methane was used to provide hydrocarbon fuel base-line data. Ammonia dissociation of 7%, 14%, 28%, and 56% was simulated by nitrogen–hydrogen–ammonia mixtures. The additives examined were hydrazine, acetylene, carbon monoxide, nitric oxide, nitrogen dioxide, and nitrous oxide at concentrations of 5% by volume of the total fuel.

To obtain a blow-out, stable burning was established at a selected fuel and additive flow rate and the air flow increased or decreased until blow-out occurred. For single-component fuels, a constant air-flow rate was established and the fuel-flow rate increased or decreased to blow-out. The blow-out points were normally distinct and reproducible, except at maximum blow-out limits. At these high-velocity conditions, limited tests were conducted with premixed fuel–air mixtures.

The flame stability diagrams obtained for methane–air, ammonia–air, and partially dissociated ammonia–air are presented in Fig. 3. The methane burned stably at flow velocities approximately twice that of ammonia and over a much wider fuel–air ratio range. The maximum burning limit for ammonia–air mixtures at 300°F inlet temperatures was 1.45 times that for ammonia–air at ambient temperature.

Comparison of the data obtained for 7%, 14%, 28%, and 56% dissociated ammonia–air shows that partial cracking significantly improves the ammonia flame-stability properties. With 28% dissociated ammonia, the flammability limits approach the limits of methane–air.

Various degrees of improvement in the flame stability of ammonia was accomplished by additives in 5% by volume concentrations. However, hydrazine offered no apparent improvement. Results obtained with the other additives are summarized in Fig. 4. The base line (zero improvement factor) is for ammonia–air and the improvement factor curves show the increases obtained as compared to ammonia–air. While acetylene and nitric oxide were the most

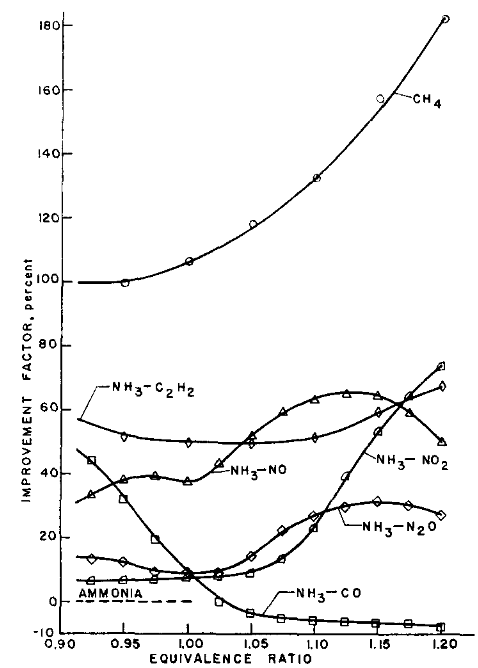

FIG. 4. Effect of additives on improving the flame-stability properties of ammonia–air.

effective additives tested, none appeared as promising as partial pre-dissociation of the ammonia.

Gas-Turbine-Burner Experiments

The performance of ammonia, injected in liquid, gaseous, and simulated dissociated states, was determined in a T63-A-3 gas-turbine burner at engine air-flow conditions. This burner is 10.6 in. long and its diameter is 5.5 in. in the primary combustion-zone area. The approximate air-flow distribution in the burner is: dome, 13%; first row primary, 11.9%; second row primary, 11.9%; secondary, 36.9%; and coolant, 26.3%. Air-flow conditions at the burner inlet for idle power are 220°F, 62 in. Hg abs, and 1.1 lb/sec, which represents a burner reference velocity of 34 ft/sec. At maximum power, the burner inlet air conditions are 521°F, 195 in. Hg abs, and 3.16 lb/sec, which is equal to reference velocity of 44.9 ft/sec. The burner outlet temperature is 1525°F for idle power and 1720°F for maximum power conditions.

Combustion efficiency and blowout velocity were the two principal parameters for evaluating the burner performance and stability with the ammonia fuels. These data were then correlated with inlet air conditions and equivalence ratio. Combustion efficiency was expressed as the actual temperature rise/ideal temperature rise. Actual temperature rise was determined from the measured inlet temperature and the average outlet temperature of the burner.

Liquid Ammonia Experiments

Seven fuel-injector and combustion-liner combinations were tested with liquid ammonia. The basic liner used was the T63-A-3, but wide variations in the total inlet-hole area and primary–secondary air distribution were investigated. Three different pressure atomizing fuel nozzles were tested: a dual orifice injector, a 4 gpm simplex nozzle, and a standard T63-A-5 injector. The air-inlet conditions to the burner were varied as follows for these tests: (a) temperature, 89° to 460°F; (b) pressure, 30.5 to 140 in. Hg abs; (c) air flow, 0.0675 to 2.5 lb/sec; (d) reference velocity, 3.4 to 39.3 ft/sec.

The maximum burner-outlet temperature obtainable with liquid ammonia injection was 850°F. Blow-out occurred in all tests when the torch ignitier was shut off. The results were attributed to the combined effect of:

The high heat of vaporization of ammonia (508 Btu/lb);

The endothermic characteristics of its decomposition;

The low energy release and flame speed of the ammonia–air reaction

Gaseous Ammonia Experiments

Thirty-three combustion system configurations were tested with gaseous ammonia. These included various combinations of fuel injectors, combustion liners, fuel deflectors, air deflectors, and flameholders. Two basic liners were used but their air-distribution characteristics were varied during the testing. One was the standard T63-A-3 liner. The second also had a 5.5 in. diameter, but its length was increased by 4 in. Based on actual hole area, the combustion-zone air was varied from 25.2% to 41.75% for the long liner and from 20.4% to 49.5% for the short liner. The predicted percentage of combustion zone air required for stable burning of ammonia at T63 conditions was 25% to 36%. The four types of injectors tested were: axial distribution, radial distribution, center point, and air aspirators. Various modifications to these injectors were also examined. Two fuel deflectors, flat plate and cone, were tested with the center-point injectors and one air deflector, designed to increase the fuel–air mixing in the combustion zone, was evaluated. Two flameholders were also tested.

The gaseous ammonia was injected at approximately 300°F inlet temperature. Combustion performance data were obtained over the following ranges of inlet-air conditions: (a) temperature, 80° to 569°F; (b) pressure, 34 to 182 in. Hg abs; (c) flow rate, 0.17 to 2.18 lb/sec; and (d) reference velocity, 5.25 to 39 ft/sec. The over-all equivalence ratio was varied from 0.0936 to 0.468.

The blow-out data obtained emphasized that gaseous ammonia would not burn at air-flow velocities feasible with hydrocarbon fuels. Blowout generally occurred at approximately 40% of the velocity at which hydrocarbon fuels burned stably. These results essentially agreed with the predictions previously made in the flame-stability tests. Stability limits obtained with gaseous ammonia are summarized in Fig. 5. The stability parameter used is that proposed by Noreen and Martin.[10] As shown, gaseous ammonia could not be used as a substitute fuel for hydrocarbons, even with continuous ignition, unless the burner diameter is increased by approximately a factor of 2.

Gaseous ammonia combustion-stability limits were significantly reduced as burner-inlet-air temperature decreased. At inlet temperatures below approximately 100°F, burning was es-

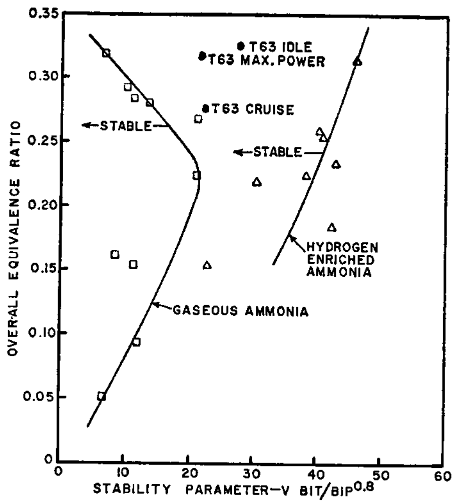

FIG. 5. Gas-turbine-burner stability limits of ammonia and hydrogen-enriched ammonia (H_2/NH_3, 2% to 6% by weight).

sentially impossible. Similar results were observed in laboratory tests by us and elsewhere.[11]

High combustion efficiencies were attainable with gaseous ammonia injection. One typical combustion system demonstrated an average combustion efficiency of 97% at the equivalence ratio for cruise power.

The effects of inlet-air conditions on the gaseous ammonia combustion efficiency were combined into an efficiency parameter (Fig. 6). The combustion efficiency decreased rapidly at air-inlet conditions much less severe than those suitable for hydrocarbon fuel operation.

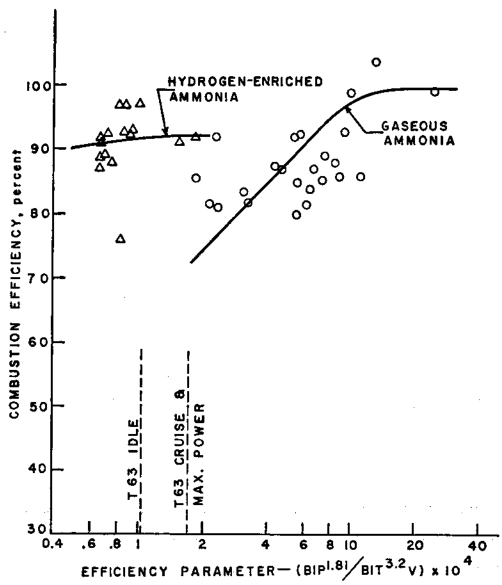

FIG. 6. Correlation of gas-turbine-burner combustion efficiency and inlet conditions for ammonia and hydrogen-enriched ammonia.

Partially Dissociated Ammonia Experiments

Partially dissociated ammonia, simulated by hydrogen-enriched ammonia mixtures, was tested in one of the combustion system configurations previously evaluated with gaseous ammonia. The configuration was a standard size T63-A-3 liner with a modified hole pattern, a center-point-type fuel injector and a 2-in-diameter fuel deflector. The modified liner had the following hole-area distribution: (a) dome, 12.6%; (b) primary, 26.2%; (c) secondary, 35.7%; and (d) coolant, 25.5%. The center-point-type fuel injector had six 0.089-in.-diameter orifices.

The amounts of hydrogen addition examined varied from 2.17% to 19.8% hydrogen to ammonia by weight. This would be equivalent to cracking 10.1% to 53% of the ammonia. Data was obtained over the following range of inlet air conditions: (a) temperature, 200° to 420°F; (b) pressure, 59 to 142 in. Hg abs; (c) flow rates, 1.10 to 2.545 lb/sec; and (d) reference velocities, 34.6 to 53.4 ft/sec. These inlet air conditions essentially spanned the required operating conditions of the T63 burner.

Efficient and stable combustion was obtained with hydrogen-enriched ammonia at design inlet-air conditions and volumetric flow rates, and far exceeded the range possible with uncracked gaseous ammonia fuel. As predicted from the basic combustion experiments, ammonia can be used as a substitute fuel if partially cracked prior to injection. Comparative stability limits of partially cracked ammonia and neat gaseous ammonia are shown in Fig. 5. This data also illustrates that the stability limits obtained exceed the limits required for use in the T63 engine.

The combustion efficiency of hydrogen-enriched ammonia was fairly constant over the range of conditions investigated. As shown in Fig. 6, the efficiency was approximately 92% at T63 operating conditions. From analysis of the stability and performance data obtained, it was predicted that a gas-turbine burner designed for hydrocarbon fuels can attain comparable performance with 28% cracked ammonia.

Conclusions

1. The minimum ignition energy for ammonia-air is approximately 8 mJ, which is greater than

that of hydrocarbon fuels (less than 0.5 mJ), but much below a previous literature value. An increase in ignition-system-energy capacity appears necessary in order to use ammonia fuel in a system optimized for hydrocarbon fuels.

2. Partial decomposition of ammonia reduced the energy required for ignition. When 28% was dissociated, the energy requirements were reduced to the range associated with hydrocarbon fuels which indicates that 28% dissociated ammonia could be used in an engine with a conventional ignition system.

3. Quenching distance was a minimum of 0.275 in. for ammonia–air and 0.08 in. for 28% dissociated ammonia–air as compared to approximately 0.075 in. for propane–air.

4. Due to the low flame-stability limits of ammonia–air, it was predicted and demonstrated that neat ammonia cannot be used as a substitute fuel in gas-turbine burners optimally sized for hydrocarbon fuels.

5. Dissociation of ammonia, prior to injection, significantly improved the flame-stability properties of ammonia. Experiments demonstrated that approximately 28% of the ammonia must be dissociated to obtain flame-stability performance comparable to that of hydrocarbon fuels. If 28% is dissociated, ammonia appears usable as a substitute fuel in gas turbine burners sized for hydrocarbon fuels.

6. None of the additives tested in concentrations of 5% by volume of the fuel increased the ammonia–air flame propagation velocity to the extent obtained by dissociating 28% of the ammonia. Nitric oxide and acetylene were found to be the most effective for improving the flame-propagation rate over the equivalence ratio range of 0.9 to 1.2.

ACKNOWLEDGMENTS

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COMMENTS

Dr. R. M. Fristrom (APL, The Johns Hopkins University): Would the authors care to comment on the possibility that the low value of ignition energy obtained for NH_3-air might be due to H_2 contamination from previous sparks. The technique is described as increasing the spark energy while ignition is obtained. A spark which does not ignite a mixture still will dissociate some H_2.

Mr. F. J. Verkamp: The possibility of contamination from previous sparks was reduced by using the following iterative experimental procedure.

1. A preliminary minimum ignition energy value was obtained by step increases in the discharge energy until an ignition was obtained.
2. Repeated tests were made with fresh fuel–air charges until the minimum ignition energy values reported in this paper were obtained on a charge which had not been previously sparked more than once.

The optimum experimental procedure would have been to use a fresh fuel-air charge for each spark.

Dr. R. M. Fristrom: Do the ignition energy and other combustion processes in partially decomposed mixtures correspond to a simple mixture law, i.e., an average of the properties of NH_3 and H_2?

Mr. F. J. Verkamp: The following approximate correlations were obtained over the indicated ranges of ammonia dissociation:

(a) Quenching distance for 0% to 28% dissociated ammonia:

$$\text{Q.D.} = 0.275 - 0.0052(X),$$

where X = mole per cent of hydrogen to total fuel ($H_2 + NH_3$), and Q.D. = quenching distance, in.

(b) Minimum ignition energy for 0% to 14% dissociated ammonia:

$$\text{M.I.E.} = 8/[\exp 0.121(X)],$$

where M.I.E. = minimum ignition energy, millijoules; and X = mole per cent of hydrogen to total fuel ($H_2 + NH_3$).

A. C. Nixon (Shell Development Company): I am interested in the system outlined for the conversion of ammonia to hydrogen and nitrogen, utilizing the exhaust heat from the engine. I would like to know if the properties of the conversion system have been worked out, i.e., have the size of the heat exchanger required been studied and the type of catalyst, the temperature levels, pressure and space velocities possible in the proposed system either theoretically or experimentally?

Mr. F. J. Verkamp: An experimental investigation of the catalytic decomposition of ammonia was conducted in the Allison Research Laboratory.

Experimental ammonia dissociation data was obtained for various catalysts such as: (a) triply promoted iron; (b) nickel on alumina; (c) iron on silica; and (d) platinum on alumina. Empirical ammonia dissociation-rate equations were developed incorporating the ammonia temperature and pressure, amount and configuration of catalyst, and ammonia flow rate.

This empirical data was applied to the design of an ammonia dissociator for an engine which utilized the engine-exhaust heat to vaporize the ammonia and to provide the thermal energy for the dissociation. The ammonia dissociator for the engine was tested and satisfactory dissociation, at the rate predicted, was obtained.