EFFECT OF HYDROGEN INJECTION ON STABILITY AND EMISSIONS OF AN EXPERIMENTAL PREMIXED PREVAPORIZED PROPANE BURNER

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16. Abstract

Hydrogen in quantities up to 5 percent by weight of the total fuel flow was injected into a pre-mixed propane burner. The hydrogen was either premixed with the propane and air upstream of the burner or introduced as a torch at the flameholder. Emissions of total nitrogen oxides, carbon monoxide, and unburned hydrocarbon are reported as are combustion efficiencies and lean blowout limits. To maintain at least 99 percent combustion efficiency at a 700 K inlet mixture temperature with no hydrogen added, it was necessary to burn with a propane equivalence ratio of 0.525. When 4 percent hydrogen was premixed with the propane and air, a combustion efficiency greater than 99 percent was recorded at a propane equivalence ratio of 0.425. The total nitrogen oxides (NO_x) emissions corresponding to these two conditions were 0.8 g NO_2/kg equivalent propane and 0.44 g NO_2/kg equivalent propane, respectively. The hydrogen torch did not reduce NO_x emissions.

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EXPERIMENTAL PREMIXED PREVAPORIZED PROPANE BURNER

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SUMMARY

Hydrogen was injected into a premixed prevaporized propane-air burner to deter-mine the effect on lean stability and nitrogen oxides (NO_x) emissions. Inlet mixture temperatures of 600 and 700 K, a pressure of 5.6×10^5 newtons per square meter, and a residence time of 2 milliseconds were studied. Hydrogen flow was varied from 0 to 5 percent by weight of the total fuel flow. In one set of experiments hydrogen was added upstream of the flameholder to premix with the propane and air. In the second set hy-drogen was added as a torch at the flameholder. Propane equivalence ratios were varied from lean blowout to 0.64.

At the 700 K inlet mixture temperature, propane equivalence ratios less than 0.525 produced combustion efficiencies less than 99 percent when no hydrogen was added. The premixing of 4 percent hydrogen with the propane and air permitted data to be taken at propane equivalence ratios as lean as 0.425 with combustion efficiencies greater than 99 percent. The NO_x levels at these equivalence ratios were 0.8 and 0.44 gram NO_2 per kilogram equivalent propane, respectively. For both cases carbon monoxide was near equilibrium and unburned hydrocarbons were about 1 gram per kilogram. The lean flammability limit decreased from a propane equivalence ratio of 0.48 with no hydrogen to 0.4 with 4 percent premixed hydrogen.

The use of a hydrogen torch permitted even leaner propane equivalence ratios before blowout, but with poor combustion efficiency. Nitrogen oxides emissions were generally not reduced with the addition of torch hydrogen, probably due to the high NO_x concentra-tion produced by burning at the torch.

INTRODUCTION

Experiments reported here were performed to determine if hydrogen could be used effectively in small quantities to stabilize premixed hydrocarbon flames at lean equivalence ratios.

A number of studies have been made to determine the total nitrogen oxides (NO_x) emissions that are produced by burning premixed, prevaporized fuel and air (refs. 1 to 3). Because NO_x production increases exponentially with flame temperature, it is desirable to burn with a flame as lean as possible. Nitrogen oxides emissions of about 0.7 gram NO_2 per kilogram fuel were measured in a flame tube at an 800 K inlet mixture temperature, a 5.6×10^5-newton-per-square-meter pressure, and a 0.45 equivalence ratio. The combustion efficiency was greater than 99 percent, and the residence time was 2 milliseconds (ref. 3). The NO_x emission indexes reported in reference 3 were as low as 0.3 gram NO_2 per kilogram fuel when equivalence ratio was reduced to 0.4 with other residence times. It was shown that NO_x is only weakly dependent on residence time at such lean equivalence ratios. To achieve lower NO_x levels, still leaner equivalence ratios (cooler flames) are required. However, cooler flames result in instability, poor combustion efficiency, and, eventually, blowout.

Hydrogen flames have a lower flame temperature at blowout than do hydrocarbon flames. For this reason the lean limit of hydrocarbon fuels might be extended if small quantities of hydrogen are injected. Norgren and Ingebo (ref. 4) injected up to 4 percent hydrogen by weight of total fuel flow into an experimental combustor designed for operation with liquid Jet A fuel. Because the combustor design did not provide a uniform fuel-air mixture in the primary zone, little effect of hydrogen injection on NO_x emissions was observed.

The present study used the premixing, prevaporizing apparatus described in reference 3. This configuration provided a nearly homogeneous fuel-air mixture at the burner flameholder. Gaseous propane was used as the primary fuel with up to 5 percent hydrogen by weight of total fuel added. Two series of experiments were performed to determine what effect hydrogen addition has on NO_x emissions and on the lean flammability limit. In the first series hydrogen was injected upstream to permit it to premix with the propane and air. For the second series hydrogen was fed into the premixed propane and air mixture at the flameholder to serve as a local torch.

Inlet mixture temperatures of 600 and 700 K were tested. Inlet pressure was maintained at 5.6×10^5 newtons per square meter and reference velocity was 25 meters per second. A moveable gas sampling probe was positioned to sample the burner exhaust products after about 2 milliseconds of combustion.

APPARATUS AND PROCEDURE

Details of the apparatus are given in figure 1. Air entering the test section was indirectly preheated for all tests. Gaseous propane fuel was introduced through a fuel tube located 2.6 meters upstream of the flameholder to allow sufficient time for thorough mixing of propane and air. A small swirler was located on the end of the propane fuel tube to give some initial mixing.

Small quantities of hydrogen were admitted in either one of two locations. The first was upstream near the propane fuel tube. This location was used to provide a homogeneous propane-hydrogen-air mixture to the burner. Alternatively, a hydrogen torch was obtained by introducing hydrogen flow in a small jet at the flameholder. These optional hydrogen injection points are indicated in figure 1.

The flameholder was made by welding 61 tubes of 0.635 centimeter inside diameter between two 0.476-centimeter-thick stainless-steel plates as shown in figure 2. This arrangement permitted cooling with water to prevent burning the flameholder during operation at high temperatures. The flameholder blockage was 75 percent, which resulted in a pressure drop of 3 to 5 percent of the upstream total pressure. The flameholder shown in figure 2(a) was used for the first test series, which employed upstream hydrogen injection. The design was nearly identical to that used in the study of reference 3.

This same flameholder was also used for the hydrogen torch experiments. However, a ring containing the hydrogen fuel tube was placed just upstream of the flameholder to allow the hydrogen fuel tube to slip through one of the holes in the flameholder as shown in figure 2(b).

The water-cooled burner was 10.25 centimeters in diameter, the same as the inlet duct, and 31 centimeters long (see fig. 1). At the downstream end, quench water was sprayed into the gas stream to cool the exhaust to about 370 K. This mixture of combustion products and water passed through a remotely operated back-pressure valve for control of rig pressure.

Rakes for inlet instrumentation were avoided to eliminate any possible flameholders in the inlet duct. Instead, static pressure was measured at the wall 8.9 centimeters upstream of the flameholder, and a single Chromel-Alumel thermocouple was inserted to a depth of about 2 centimeters into the flow at a location 12.7 centimeters upstream of the flameholder. Downstream static pressure was measured at a tap 43 centimeters downstream of the flameholder. ASME standard orifices were used to measure air and fuel flows.

Details of the water-cooled stainless-steel gas-sampling probe are also shown in figure 1. The single-point probe had a 0.635 centimeter outside diameter with a 0.159-centimeter-diameter center sampling tube. The probe could be traversed axially along the burner centerline. Each time test conditions were changed the probe was

repositioned so that sampling always occurred after 2 milliseconds of combustion residence time.

Stainless-steel tubing (0.95-cm diam) connected the gas sample probe with the exhaust gas analyzers. To prevent condensation of unburned hydrocarbons, this sample-line tubing was electrically heated to maintain the sample gas temperature between 410 and 450 K. The sample line was approximately 18 meters long.

Gas analysis equipment included a model 402 Beckman flame ionization detector for measuring unburned hydrocarbons, model 315B Beckman nondispersive infrared analyzers for measuring concentrations of carbon monoxide (CO) and carbon dioxide (CO_2), and a model 10A Thermo-Electron chemiluminescent instrument for nitric oxide (NO) and total NO_x concentration.

Calibration of the instruments with standard calibration gases was performed at the beginning of each day's testing and whenever a range change was made.

Inlet air humidity was measured with an EG & G model 137 Vapor Mate II humidity meter with a model S3 sensor. Although measurements of CO, CO_2, NO, and NO_x were made after water vapor was removed from the sample, the values reported for all constituents are on a wet basis. Inlet air humidity was essentially zero for all tests.

Commercial grade gaseous propane was used for all tests (see table I). Propane has a heating value near that of jet fuels so that combustion characteristics, especially NO_x production, are similar. The properties of hydrogen are also shown in table I.

DATA ACCURACY

Heat Losses

Both the burner walls and the flameholder were water cooled. Measurements made in the study of reference 3 showed that heat losses due to wall cooling were consistently about 10 percent of the total enthalpy increase resulting from fuel burning. Because sampling of combustion products takes place only at the burner centerline, it should be possible to assume that side wall effects are negligible.

The possible influence of flameholder cooling on emissions was also studied in reference 3, and no measurable effect was found. Thus, since neither burner wall nor flameholder cooling should affect emissions measurements, the emissions reported here should be indicative of what might be expected from an adiabatic burner. Combustion efficiencies were determined from the emissions measurements; thus, they too should be similar to adiabatic results. Blowout data may not be as meaningful, however, because of the heat losses.

Sample Validity

It should not be necessary to sample the exhaust gases of a uniform mixture at more than one location in the combustor to get a representative measurement, assuming no wall effects. In this study a single-point gas sampling probe was used. To determine if this single-point sample was adequate, an equivalence ratio based on the measured carbon concentrations was compared with that from fuel and air flow measurements. The agreement was always within the ±15 percent suggested in reference 5 as necessary for good sample validity. The carbon-balance equivalence ratio was generally about 0.9 of the equivalence ratio based on flow measurements. The carbon-balance equivalence ratio was used in computations and in the presentation of data throughout this report.

Although a carbon balance was also made for each test with hydrogen injection, it had meaning only with respect to the distribution of hydrocarbons. The uniformity of hydrogen concentration could not be determined with the instrumentation available; however, with upstream hydrogen injection it is assumed that a homogeneous mixture was achieved. For the hydrogen torch series the sample from the single-point probe was probably not representative of the average burner emissions. Measured NO_x emissions might be expected to be lower than average, and carbon monoxide (CO) and total unburned hydrocarbon (THC) are probably measured to be higher than average. General qualitative conclusions concerning the effect of the hydrogen torch on blowout and combustion efficiency trends should be valid.

CALCULATIONS

Emission index. - The emission index (g pollutant/kg fuel) used in this report was based on an equivalent weight of propane fuel to permit comparison between the data when different amounts of hydrogen were added to the propane-air flame. This emission index was determined from pollutant concentrations as follows:

$$EI_x = \left(\frac{M_x}{M}\right)\left(\frac{1 + f_{C_3H_8} - \alpha}{f_{C_3H_8}}\right)\left(\frac{1}{1 + 2.81\,\alpha - \alpha}\right) C_x \times 10^{-3}$$

where

EI_x emission index of pollutant x, g pollutant/kg equivalent propane

M_x molecular weight of pollutant x

M molecular weight of combustion products

$f_{C_3H_8}$ mass flow ratio, $\dot{m}_{C_3H_8}/\dot{m}_{air}$

α $\dot{m}_{H_2}/\left(\dot{m}_{C_3H_8} + \dot{m}_{H_2}\right)$

C_x concentration of pollutant x, ppm

$\dot{m}_{C_3H_8}$ mass flow rate of propane, kg/sec

$\dot{m}_{H_2}$ mass flow rate of hydrogen, kg/sec

$\dot{m}_{air}$ mass flow rate of air, kg/sec

The factor 2.81 which appears in this expression is the ratio of the heat of combustion per kilogram of hydrogen to that of propane. Effectively, the expression multiplies the emission index based on the propane-hydrogen mixture flow by the ratio of the heating value of propane to that of the propane-hydrogen mixture (see ref. 4). Thus, the emission index is based on the propane flow that would be required to give the same adiabatic flame temperature as the propane-hydrogen mixture.

Hydrogen mass flow. - In the presentation of results the hydrogen mass flow is expressed as a percentage of the total hydrogen-plus-propane mass flow.

Theoretical calculations. - The well-stirred-reactor computer program described in reference 6 was used to determine NO_x concentrations for comparison and verification of experimental measurements. The concentrations of 13 different inlet species, including nitrogen and oxygen (air) and H_2 can be specified along with that of any one of 10 different hydrocarbon fuels (including propane). Thus, it was possible to run calculations for different concentrations of hydrogen mixed with the propane and air, as well as for varying propane equivalence ratios. The reactor was assumed to be adiabatic for these calculations.

An equilibrium computer program (described in ref. 7) was also used. This program permits the calculation of adiabatic equilibrium compositions and flame temperatures for any mixture of inlet oxidants and fuels. In using this program the appropriate mixtures of propane and hydrogen were input as fuel with air as the oxidant.

RESULTS AND DISCUSSION

Flashback of Flame

One of the major problems with premixed systems is the hazard of flame stabilization upstream of the burner. In this event NO_x emissions become high because of the very long residence times that result and the fact that diffusion burning occurs with local regions at temperatures well above the mean flame temperature. In addition, hardware damage is likely.

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In this study no objective tests were made to determine the effect of hydrogen addition on flashback. It was observed, however, that with a 600 K inlet mixture temperature and no hydrogen injection, propane equivalence ratios less than 0.6 gave noisy and somewhat unstable burning. Under these conditions flashback often occurred. When even 1 percent hydrogen was added the flame became more stable, less noisy, and flashback no longer occurred.

At higher inlet temperatures and equivalence ratios, however, the higher flame speed of hydrogen compared with propane makes flashback more likely. At a 700 K inlet mixture temperature with 4 percent hydrogen added upstream, flashback occurred often when the propane equivalence ratio was greater than about 0.6. Data were therefore taken at somewhat leaner equivalence ratios.

Nitrogen Oxides Emissions

Measured total nitrogen oxides emissions are shown in figure 3 as a function of the propane equivalence ratio. This equivalence ratio was determined from a carbon balance of the exhaust gases. Data were taken with upstream hydrogen injection at inlet mixture temperatures of 600 and 700 K (figs. 3(a) and (b)) and with the hydrogen torch at 700 K (fig. 3(c)). The residence time was determined by the position of the gas-sampling probe. For the data reported here the probe position was adjusted to maintain a residence time of approximately 2 milliseconds. The inlet pressure was 5.6×10^5 newtons per square meter. Only data that showed combustion efficiencies greater than 99 percent are presented in figure 3.

Also shown for comparison are the NO_x emissions predicted by the well-stirred reactor computer program of reference 6. Reasonable agreement is obtained between the measured and predicted values for the upstream injection data of figures 3(a) and (b). Figure 3(c), the hydrogen-torch case, shows considerable deviation from theory, especially at higher concentrations of hydrogen. This deviation may be due to a large contribution of NO_x from the locally rich hydrogen torch.

With combustion efficiency greater than 99 percent, minimum NO_x emissions were measured to be on the order of 1 gram NO_2 per kilogram equivalent propane for all concentrations of hydrogen injected upstream at the 600 K inlet mixture temperature (fig. 3(a)). Emissions were as low as 0.45 gram NO_2 per kilogram equivalent propane when 4 percent hydrogen was injected upstream at the 700 K inlet mixture temperature (fig. 3(b)). This was about half the minimum value obtained with no hydrogen. The hydrogen torch produced minimum emissions near 1 gram NO_2 per kilogram equivalent propane at 700 K, independent of hydrogen concentration (fig. 3(c)).

The experimentally observed lean blowout limit is also shown in figures 3(a) and (b) plotted as a lower limit to the predicted (well stirred reactor) NO_x emissions. No NO_x

emissions were measured at the blowout limit; however, this limit indicates the NO_x values that would be predicted at the experimental blowout equivalence ratio. No blowout data were obtained with the hydrogen-torch case of figure 3(c). The blowout data will be discussed in greater detail later, but it is apparent that as hydrogen concentration increases, the predicted NO_x level at blowout decreases.

At a constant propane equivalence ratio, NO_x emissions increase as hydrogen is added. To determine if this is due only to the increased flame temperature which results, NO_x concentrations (in ppm) were plotted as a function of flame temperature in figure 4. The adiabatic flame temperatures used in figure 4 were obtained from the equilibrium computer program of reference 7. Inlet temperatures of 600 and 700 K, hydrogen concentrations from 0 to 4 percent by weight, and both hydrogen torch and upstream injection data for which combustion efficiency was greater than 99 percent are shown. Again, the well-stirred-reactor model is used for comparison.

Within experimental scatter the hydrogen-propane-air premix data agree with the predicted values and show that, for this range of temperatures and at constant pressure and residence time, NO_x concentration is nearly exponentially dependent on flame temperature. Nitrogen oxides data correlate well with flame temperature alone; inlet temperature and hydrogen concentration have an effect on NO_x emissions only through their influence on flame temperature. Hydrogen-torch data tends to be somewhat higher than the predicted and measured premixed values because of the high NO_x concentration contributed by the locally rich torch.

The well-stirred reactor model predicted the lack of the effect of hydrogen concentration but suggested a very minimal effect of inlet temperature on NO_x concentration at constant flame temperature.

Carbon Monoxide Emissions

The measured carbon monoxide emissions at 5.6×10^5 newtons per square meter and 2 milliseconds are presented in figure 5. Also shown, for reference, are the equilibrium values of CO determined from the computer program of reference 7. Figure 5(a) shows data taken with an inlet temperature of 600 K and an upstream injection of 0 to 3 percent hydrogen. Although equilibrium CO tends to increase with both propane equivalence ratio and the quantity of hydrogen added, the measured values show the opposite trends.

The extent to which the CO oxidation reaction has gone to completion is suggested by the difference between the measured and equilibrium values of emission index. For propane fuel a CO emission index difference of 50 grams CO per kilogram fuel indicates that 1 percent of the energy in the fuel is not released due to incomplete CO oxidation to CO_2.

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Figure 5(a) shows clearly that combustion is incomplete at 2 milliseconds with low values of either hydrogen addition or propane equivalence ratio at the 600 K inlet mixture temperature. As either parameter is increased independently of the other, combustion proceeds further to completion and CO approaches the appropriate equilibrium curve.

The 700 K upstream-injection data (fig. 5(b)) indicates that CO is very near the equilibrium values for all propane equivalence ratios and hydrogen concentrations. This result is due to the higher rates of reaction at the higher temperature.

Carbon monoxide measured from the 700 K hydrogen-torch operation (fig. 5(c)) was higher than equilibrium for lean propane equivalence ratios, but approached equilibrium values above an equivalence ratio of 0.5.

Unburned Hydrocarbons

Figure 6 gives the emissions of total unburned hydrocarbons. Measured hydrocarbon emissions during operation with upstream hydrogen injection at 600 K are shown in figure 6(a). For complete combustion, hydrocarbons should be essentially zero. A hydrocarbon emission index of 10 indicates that 1 percent of the available energy of the fuel has not been released. Increasing either propane equivalence ratio or hydrogen concentration reduces the unburned hydrocarbon emissions.

At the 700 K inlet mixture temperature with upstream hydrogen injection (fig. 6(b)) there was little unburned hydrocarbon measured. Nearly all the data fell below 1 gram hydrocarbon per kilogram equivalent propane.

In figure 6(c) the emissions with hydrogen-torch operation at 700 K can be seen. Emissions were high due to the poor combustion of the propane-air flame in regions far from the hydrogen torch. Again, increases in hydrogen concentration or propane equivalence ratio resulted in decreases in unburned hydrocarbon emissions.

Combustion Efficiency

One of the objectives of this study was to determine if the addition of hydrogen, either premixed with the propane and air or as a torch, would permit lean burning with good combustion efficiency. Subjectively, it was apparent that hydrogen injection did improve combustion. At the 600 K inlet mixture temperature, some combustion rumble was apparent when running on propane alone. When hydrogen was added, operation became quieter, until with 4 percent hydrogen no combustion noise was noticed. The combustion efficiency determined from the measured CO and unburned hydrocarbons is plotted in figure 7.

The 600 K inlet mixture temperature data of figure 7(a) were taken with upstream hydrogen injection. It is apparent that even small concentrations of hydrogen permit the lowering of the propane equivalence ratio while maintaining constant combustion efficiency. For example, with 0 to 1 percent hydrogen, a propane equivalence ratio of 0.57 gives 99 percent combustion efficiency. For leaner equivalence ratios combustion efficiency decreases unless hydrogen concentration is increased. With 3 to 4 percent hydrogen, the equivalence ratio can be decreased to 0.51 before combustion efficiency drops below 99 percent. These minimum equivalence ratios for 99 percent combustion efficiency allow predictions to be made of the minimum NO_x for 99 percent combustion efficiency. Thus, from figure 3(a) with no hydrogen injection, the well-stirred reactor predicts a NO_x emission index of 0.66 gram NO_2 per kilogram equivalent propane at an equivalence ratio of 0.57. With 4 percent hydrogen a NO_x level of 0.65 gram NO_2 per kilogram equivalent propane is predicted at an equivalence ratio of 0.51. Thus, although the propane equivalence ratio can be decreased as increasing amounts of hydrogen are injected, there is virtually no decrease in the minimum NO_x emissions for 99 percent combustion efficiency at 600 K.

When the inlet mixture temperature is raised to 700 K, the measured combustion efficiency improves. Figure 7(b) gives the data taken with upstream hydrogen injection. When hydrogen concentrations were greater than 1 percent of the total weight of fuel, combustion efficiency was always nearly 100 percent. Lean blowout tended to occur suddenly and without the warning of gradually decreasing combustion efficiency.

The use of a hydrogen torch at the 700 K inlet mixture temperature permitted leaner burning than resulted with premixed, upstream-injected hydrogen. The data of figure 7(c) show that combustion efficiency decreased almost linearly with decreasing propane equivalence ratio. To obtain 99 percent combustion efficiency, propane equivalence ratio could be reduced from 0.51 with 0 percent hydrogen to 0.4 with 4 percent hydrogen. Predicted NO_x would decrease from 0.6 to 0.15 gram NO_2 per kilogram equivalent propane (see fig. 3(c)). However, because of the torch contribution to NO_x the actual decrease in NO_x would probably be much less. The data of figure 3(c), in fact, suggests that NO_x might not be reduced at all

Blowout

Experimental blowout data were obtained by gradually decreasing the propane flow while adjusting the hydrogen flow to maintain a constant percentage of total fuel flow. Airflow, inlet temperature and pressure were also kept constant. It was not possible to record all conditions at blowout, although the propane flow rate at blowout was noted.

The blowout data are given in figure 8 for the upstream hydrogen injection case. No data were obtained for the hydrogen torch tests because it was possible to reduce

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propane flows to such low values that accurate measurement was not possible. Qualitatively, however, blowout was observed at much lower equivalence ratios in the torch tests than when hydrogen was injected upstream.

The effect of increasing hydrogen concentration on the propane equivalence ratio at blowout is indicated in figure 8(a) for both the 600 and 700 K inlet mixture temperatures. It is not surprising that the trend is to leaner equivalence ratios as hydrogen is added. The scatter in data is probably due to unsteady flow effects at blowout, which made precise identification of the blowout point difficult.

The effect of hydrogen injection on blowout flame temperature is shown in figure 8(b). The differences between the results for the 600 K and 700 K inlet mixture temperatures are probably due only to inaccuracies in the measurement of the blowout point. The mean data line shown represents an average fit for all data irrespective of the inlet temperature.

The trend suggests that the addition of hydrogen lowers the blowout temperature from an average of 1830 K with premixed propane and air only to 1755 K when a mixture of 96 percent propane, 4 percent hydrogen is burned in air. Due to the difficulty in determining the exact blowout point and the possible inaccuracies resulting from cooling losses, the effect of hydrogen injection on blowout shown here should be considered to be only qualitative.

CONCLUDING REMARKS

Previous laboratory studies (ref. 3) have measured NO_x emissions from lean premixed combustion as low as 0.7 gram NO_2 per kilogram propane with greater than 99 percent combustion efficiency and a 2-millisecond residence time. The present work has shown that, by premixing 4 percent hydrogen with the propane and air, still leaner burning is possible and a level of 0.45 gram NO_2 per kilogram equivalent propane was measured.

As a result of a large contribution of NO_x from locally rich burning at the torch, operation with a hydrogen torch produced no reduction in NO_x emissions compared with the use of premixed propane-air alone. The use of a premixed lean hydrogen-air torch might well allow further reductions in both NO_x emissions and blowout temperatures, however.

Premixed hydrogen injection was shown to improve combustion efficiency at all operating conditions. The minimum flame temperature at which it is possible to burn was reduced by 75 K when 4 percent hydrogen was premixed with propane and air.

Measured NO_x concentrations were shown to be nearly logarithmically dependent on flame temperature alone for both the 600 and 700 K inlet mixture temperatures and hydrogen concentrations ranging from 0 to 4 percent by weight of total fuel flow.

Although the benefits of hydrogen injection have been clearly demonstrated in this laboratory study, it is not evident that the complexity that would be involved in the practical use of hydrogen injection for a premixed prevaporized combustor would be warranted by these benefits.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, July 25, 1975,
            505-03.

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TABLE I. - PROPERTIES OF FUELS USED

(a) Commercial grade propane

Analysis:	
Propane (C_3H_8), percent	92
Ethylene (C_2H_6), percent.	1 - 2
Propylene (C_3H_6), percent	4 - 6
Butane (C_4H_{10}), percent	1 - 2
Volatile sulfur, g/m^3	0.09 - 0.14
Dew point, K.	244
Heat content, J/g	49 800
Vapor pressure at 310 K, N/m^2	12.1×10^5
Specific gravity	0.508

(b) Hydrogen

Analysis:	
Hydrogen, percent	99.94
Oxygen, ppm	5
Carbon monoxide, ppm	5
Carbon dioxide, ppm	5
Methane, ppm.	5
Water vapor, ppm	1.5
Organic chlorides, ppm	1.0
Nitrogen.	Balance
Heat content, J/g	141 000
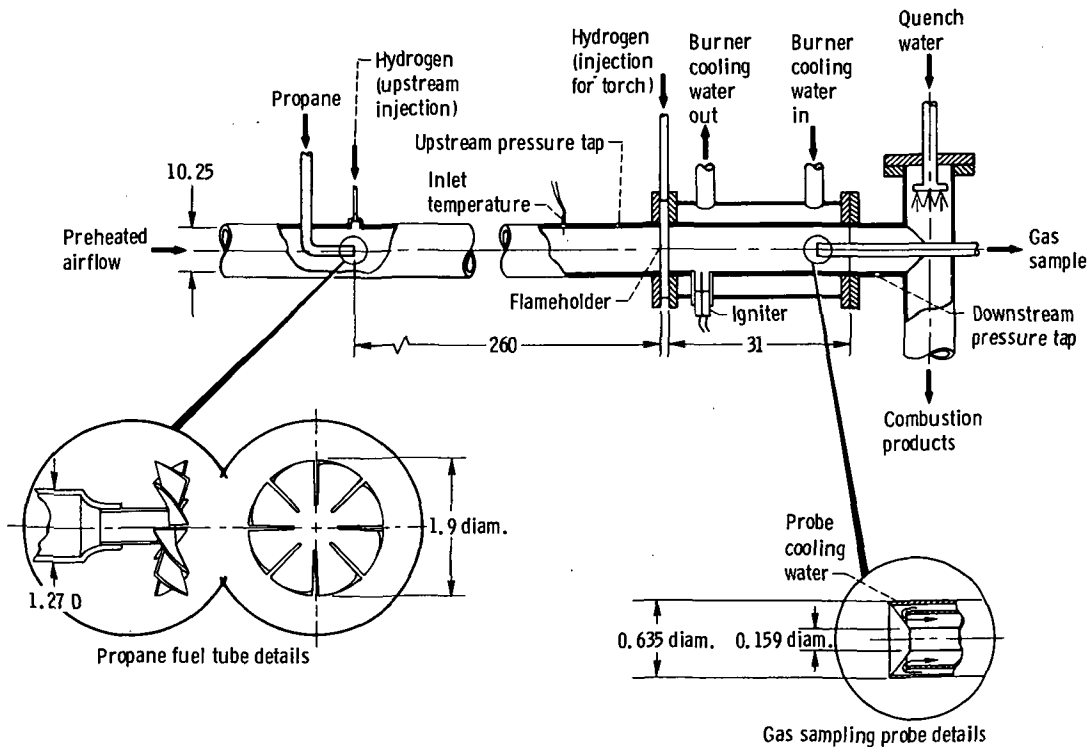
Figure 1. - Propane burner rig. (Dimensions are in cm.)

CD-11872-14

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Cooling water in

Holes around
circumference
for cooling
water discharge

0.953 o.d. by
0.635 i.d. tube
(61 tubes)

9.7 diam.

0.476

1.92
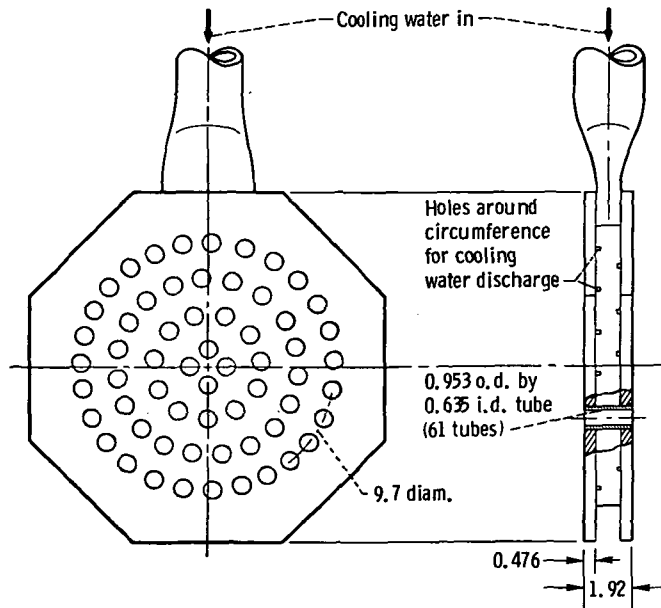
(a) Without hydrogen-torch fuel tube (upstream hydrogen injection
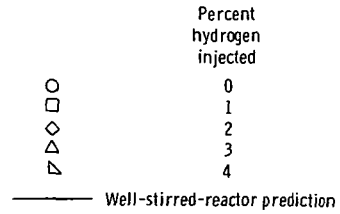configuration).

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Hydrogen

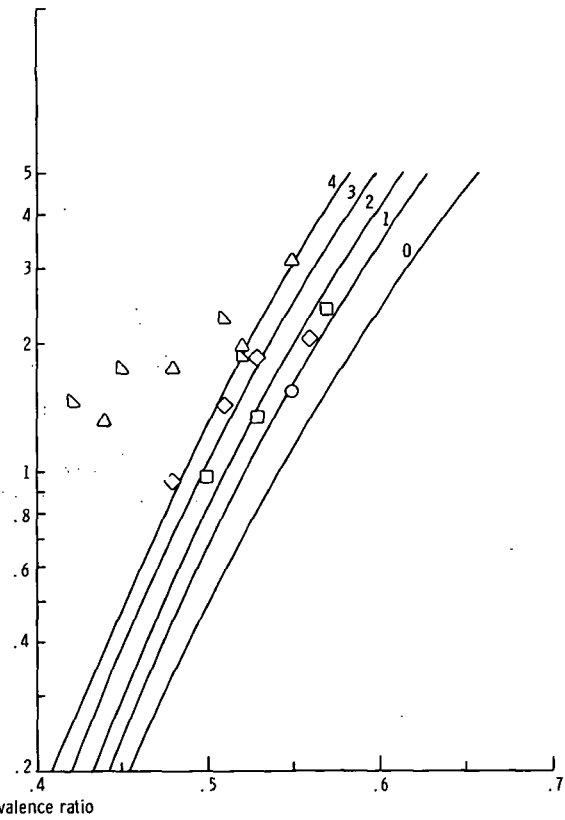Gasket
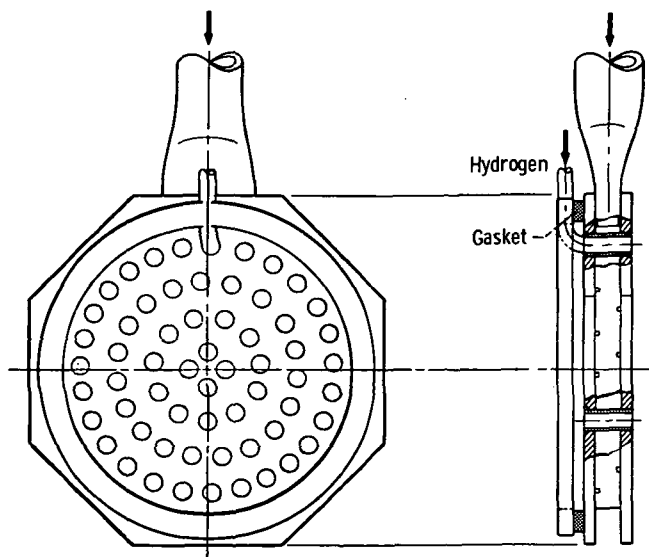
(b) Showing location of hydrogen-torch fuel tube.

Figure 2. - Flameholder. (Dimensions are in cm.)
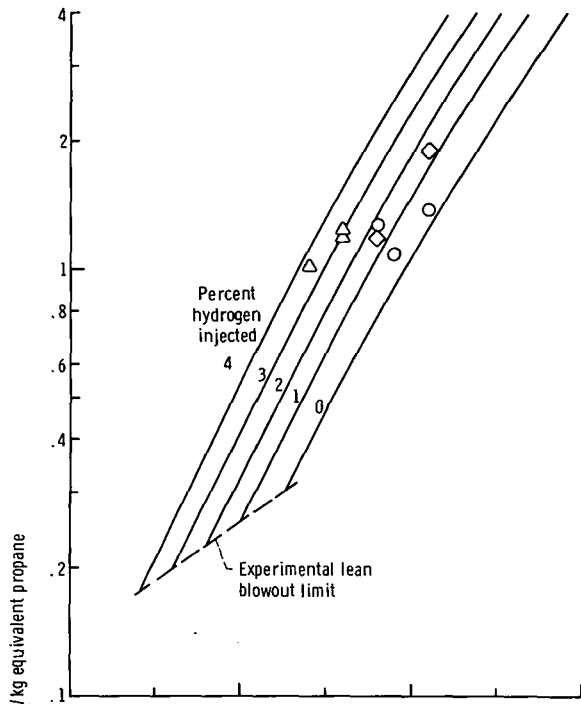
(a) Premixed hydrogen; inlet mixture temperature, 600 K.
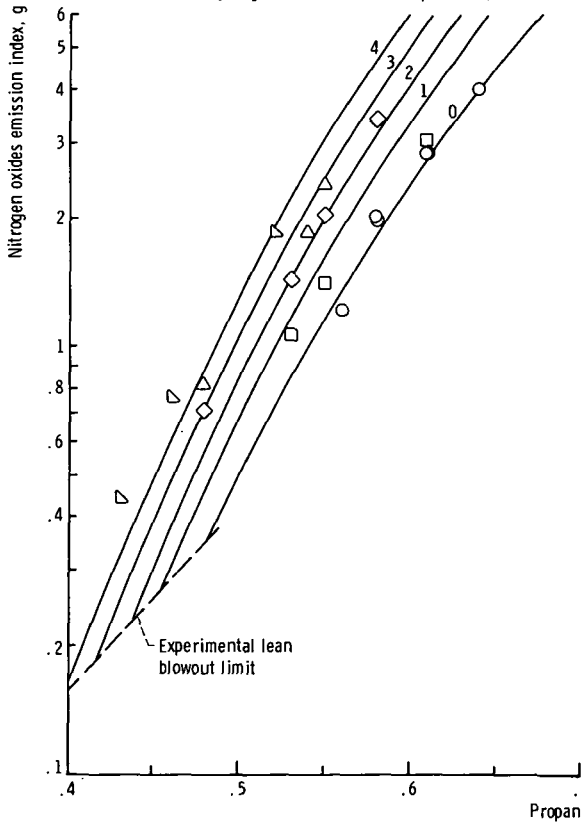
(b) Premixed hydrogen; inlet mixture temperature, 700 K.
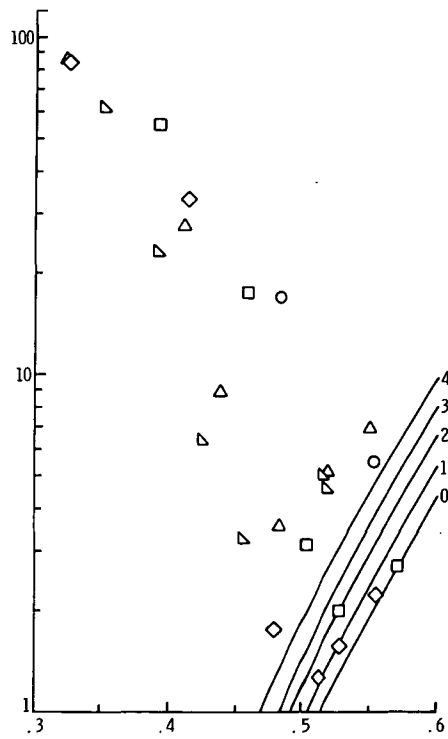
(c) Hydrogen torch; inlet mixture temperature, 700 K.

Figure 3. - Total nitrogen oxides emissions. Combustion efficiency, >99 percent; pressure, 5.6x10^5 newtons per square meter; residence time, 2 milliseconds; reference velocity, 25 meters per second.
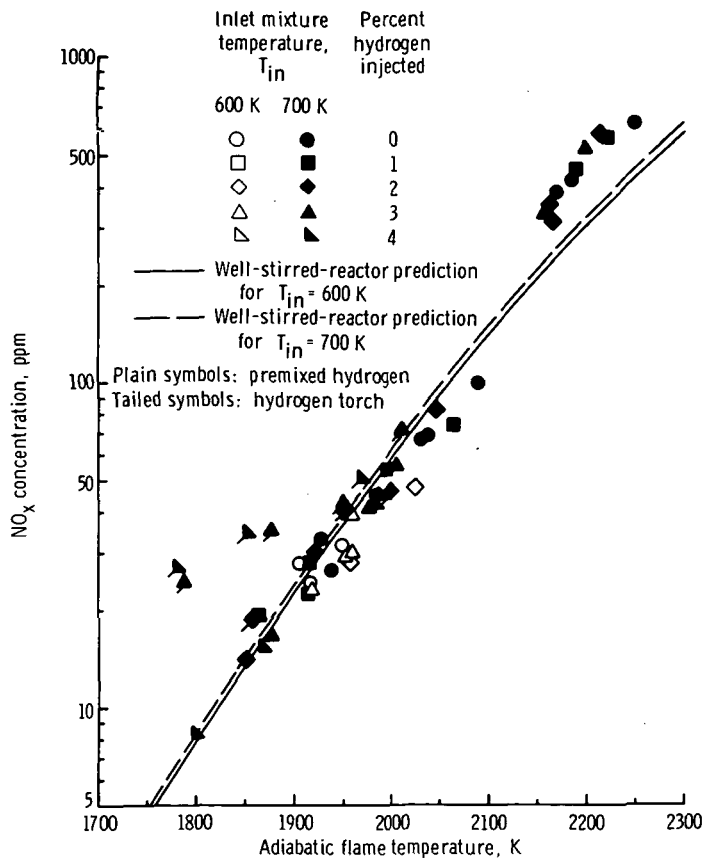
Figure 4. - Total nitrogen oxides concentration. Combustion efficiency, >99 percent; pressure, 5.6x10^5 newtons per square meter; residence time, 2 milliseconds; reference velocity, 25 meters per second.
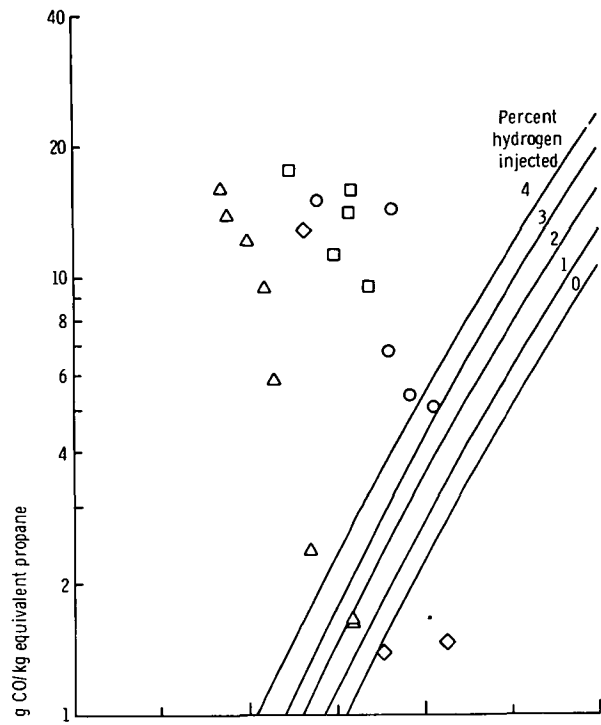
(a) Premixed hydrogen; inlet mixture temperature, 600 K.
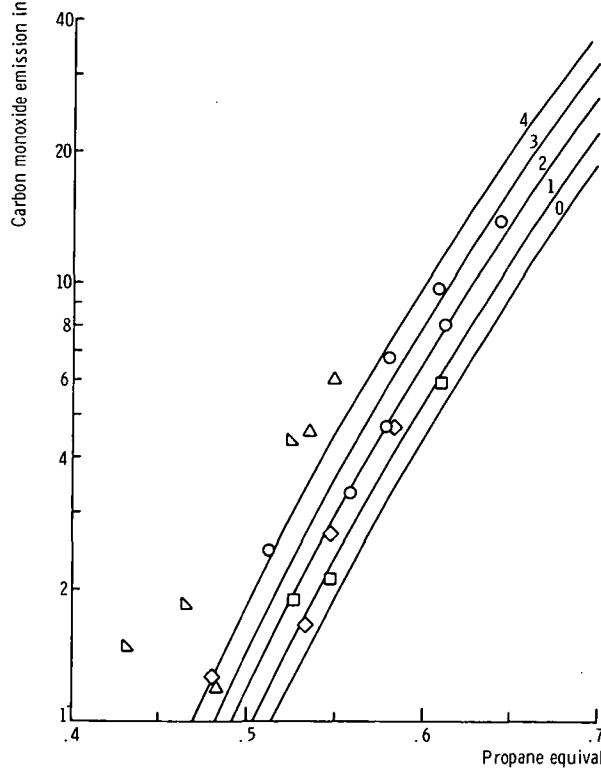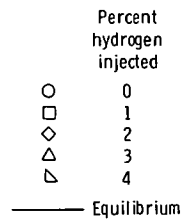
(b) Premixed hydrogen; inlet mixture temperature, 700 K.

(c) Hydrogen torch; inlet mixture temperature, 700 K.

Figure 5. - Carbon monoxide emissions. Pressure, 5.6×10^5 newtons per square meter; residence time, 2 milliseconds; reference velocity, 25 meters per second.
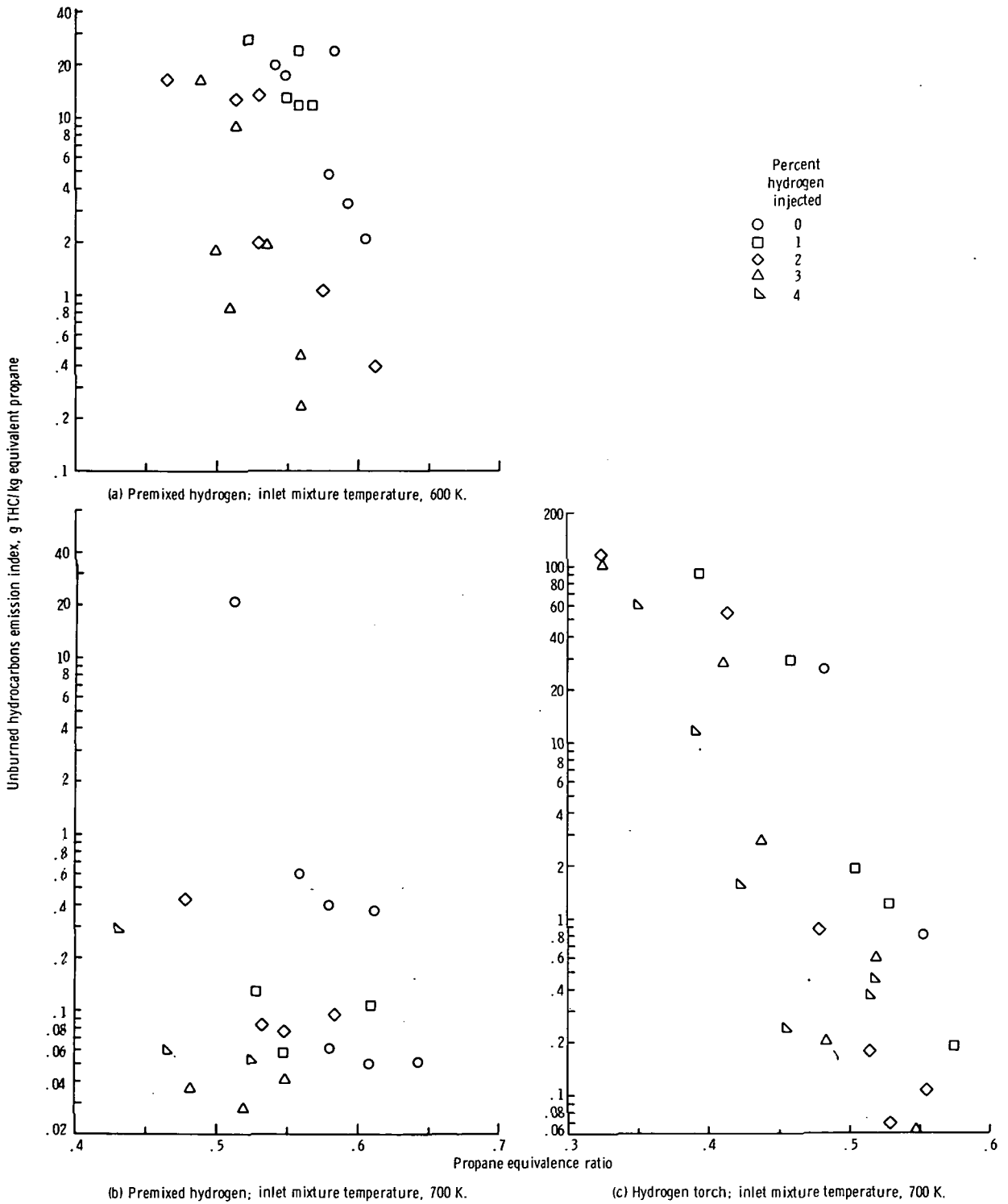
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Figure 6. – Unburned hydrocarbons emissions. Pressure, 5.6×10^5 newtons per square meter; residence time, 2 milliseconds; reference velocity, 25 meters per second.
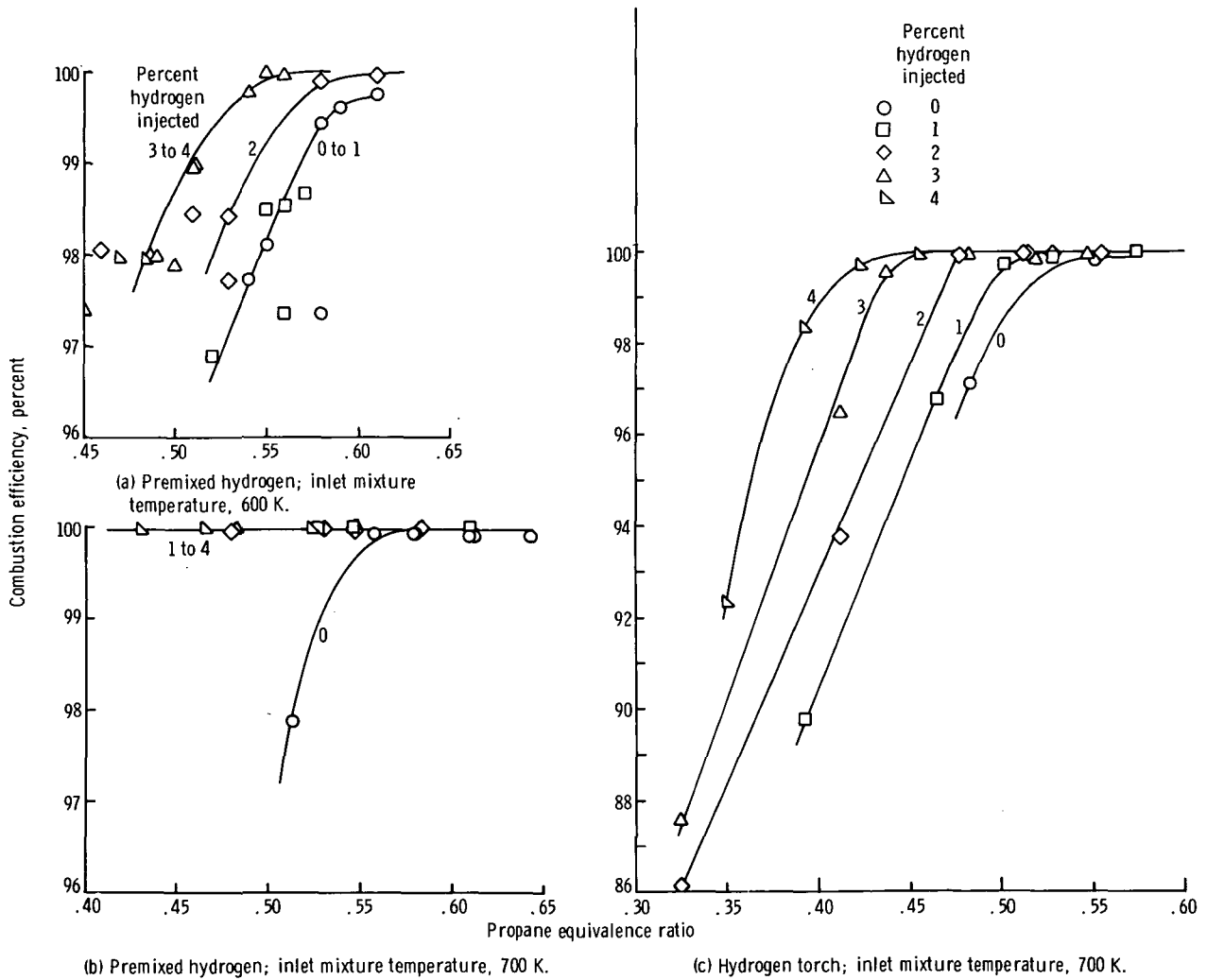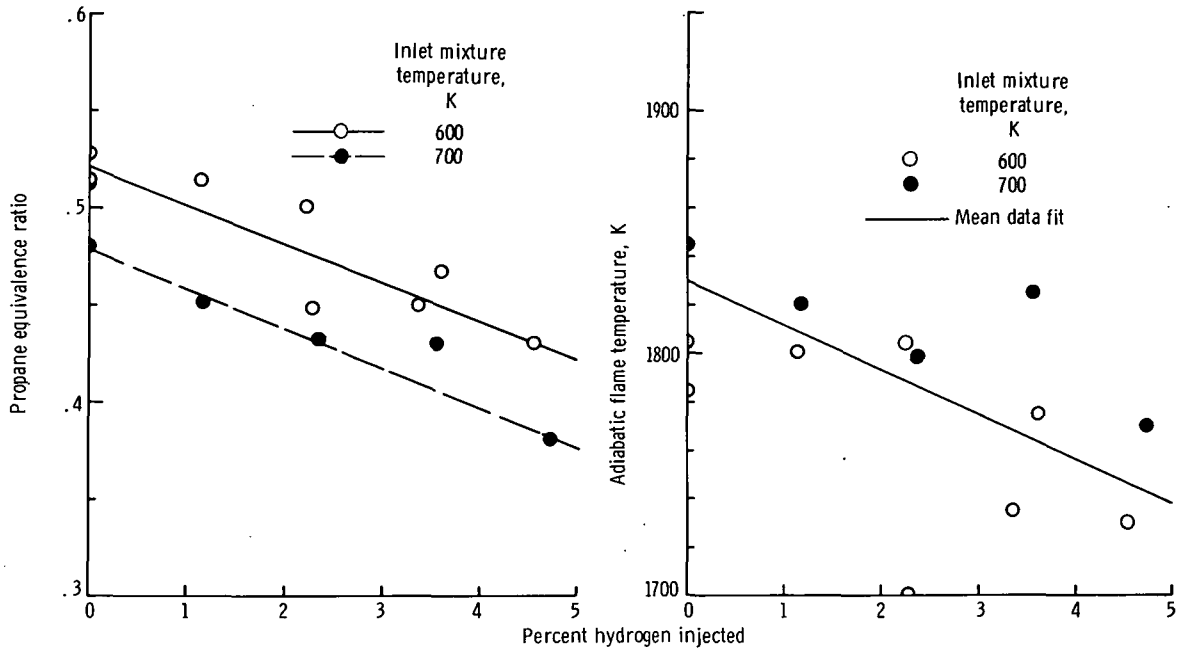
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Figure 7. – Combustion efficiency. Pressure, 5.6×10^5 newtons per square meter; residence time, 2 milliseconds; reference velocity, 25 meters.

(a) Propane equivalence ratio at blowout.

(b) Flame temperature at blowout.

Figure 8. – Lean blowout limit. Pressure, 5.6×10^5 newtons per square meter; reference velocity, 25 meters per second.

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