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Final Report

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Introduction

Lean premixed combustion is used in stationary gas turbine engines for highly efficient, low emission power generation from natural gas. Good fuel/air mixing coupled with ultra lean operation allows for a reduced flame temperature, which in turn minimizes the formation of NO_x. Due to rising environmental concerns world wide, governments are imposing tighter restrictions on NO_x emissions. In order to help decrease these emissions, it has been a trend to reduce flame temperature even further. Presently, gas turbine manufacturers are developing ultra-low NO_x turbines that are operating just about at their lean stability limit. Taking the flame temperature any lower will lead to serious flame stability issues. In order to stabilize the flame at lower equivalence ratios/flame temperatures, hydrogen could be mixed into the natural gas to increase the lean blow out limits of hydrocarbon fuels [1,2,3,4].

Since hydrogen is not naturally occurring in its pure form, coupled with the fact that there is no supporting delivery infrastructure, it is unrealistic to develop engines to run on pure H_2; however, a portion of the natural gas stream could be reformed into H_2 and this stream could be doped into the main or pilot fuel stream [1]. It is expected that discrete injection into either the pilot or main fuel stream will have a positive effect on the lean blow out, LBO, limit of a natural gas fired combustor. In addition to having a higher flame speed, H_2 has the potential to enhance local reaction rates via a local increase in both radical concentration and temperature. When diatomic hydrogen comes into contact with the O_2 molecule, it readily oxidizes to form a hydroperoxy radical (HO_2) and hydrogen radical (H), which provides the essential initiation step to develop a radical pool of OH, O, and more H radicals via the chain branching reactions:

$$\mathrm{H} + \mathrm{O_2} \rightarrow \mathrm{O} + \mathrm{OH}$$

$$\mathrm{O} + \mathrm{H_2} \rightarrow \mathrm{H} + \mathrm{OH}$$

$$\mathrm{H_2} + \mathrm{OH} \rightarrow \mathrm{H_2O} + \mathrm{H}$$

$$\mathrm{H} + \mathrm{O_2} \rightarrow \mathrm{O} + \mathrm{OH} \ [5].$$

This radical pool will help contribute to the pyrolysis of the carbon containing species; thus, promoting more radical growth and faster reaction rates. Due to the possibility of incomplete mixing of the of the fuel and air, hydrogen injection into these lean pockets will create a larger radical pool and help to stabilize a reaction in local lean zones that would not be able to otherwise sustain a reaction. Both the increase in local flame temperature and larger OH radical pool is also thought to help completion of CO oxidation to CO_2 [6]. It is known that small concentrations of hydrogen containing compounds help to catalyze CO-O_2 kinetics via the following chain branching reactions:

$$\mathrm{CO_2} + \mathrm{O_2} \rightarrow \mathrm{CO_2} + 2\mathrm{O}$$

$$\mathrm{O} + \mathrm{H_2O} \rightarrow 2\mathrm{OH}$$

$$\mathrm{CO} + \mathrm{OH} \rightarrow \mathrm{CO_2} + \mathrm{H}$$

$$\mathrm{H} + \mathrm{O_2} \rightarrow \mathrm{O} + \mathrm{OH}$$

$$\mathrm{O} + \mathrm{H_2} \rightarrow \mathrm{OH} + \mathrm{H}$$

$$\mathrm{OH} + \mathrm{H_2} \rightarrow \mathrm{H_2O} + \mathrm{H} \ [5].$$

Experimental Setup

In these experiments a variable geometry LPP injector is used to inject fuel and air mixtures into an 8-inch diameter quartz tube at atmospheric conditions as shown below in Figure 1.

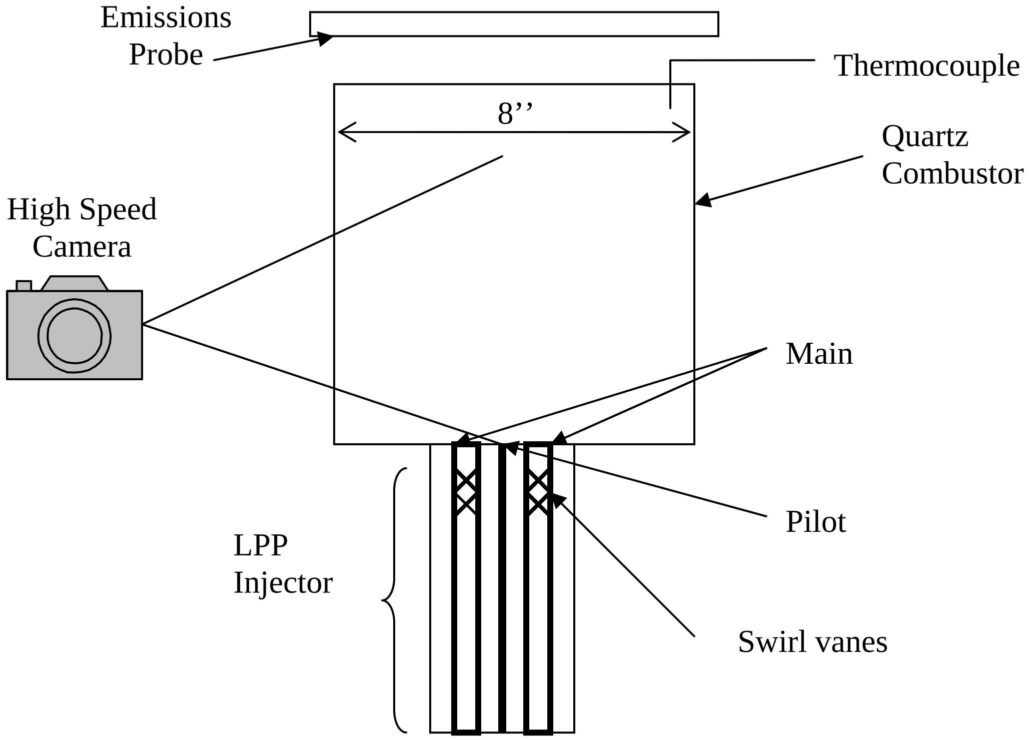


Figure 1: Schematic of the quartz combustor facility.

Since it is the goal of this research to study the effect of doping small amounts of hydrogen into either the main or the pilot flame, a relatively small mass flow controller is employed having a maximum flow rate of 5 slpm, or about 0.1 lb/hr. A larger controller should definitely be purchased if a higher percentage of hydrogen is to be mixed into the fuel stream, or if high-pressure tests are to be conducted.

A variety of injectors could have been selected for testing in this experimental rig. In fact, future experiments should be conducted with different injectors, because lean blow out limit is also a function of the geometry of the injection device [3]. The test injector is selected because the effective area of the main swirler can be adjusted between 0.85 and 1.76 in^2. This adjustable geometry allows one to flow hydrogen concentrations up to about 10% by volume of the fuel to be injected corresponding to the smallest injector opening. Each of these injectors is designed to operate with a pressure drop of about 4%.

Other larger injectors were considered for testing; however, the air flow rates would be so large, that in order to sustain a flame barely 2% of the fuel flow will be composed of hydrogen. Figure 2 displays the maximum composition of hydrogen that can be injected into the fuel stream at atmospheric conditions with a 4% pressure drop, preheat temperature of 600ºF, and a flame temperature of 2400ºF.

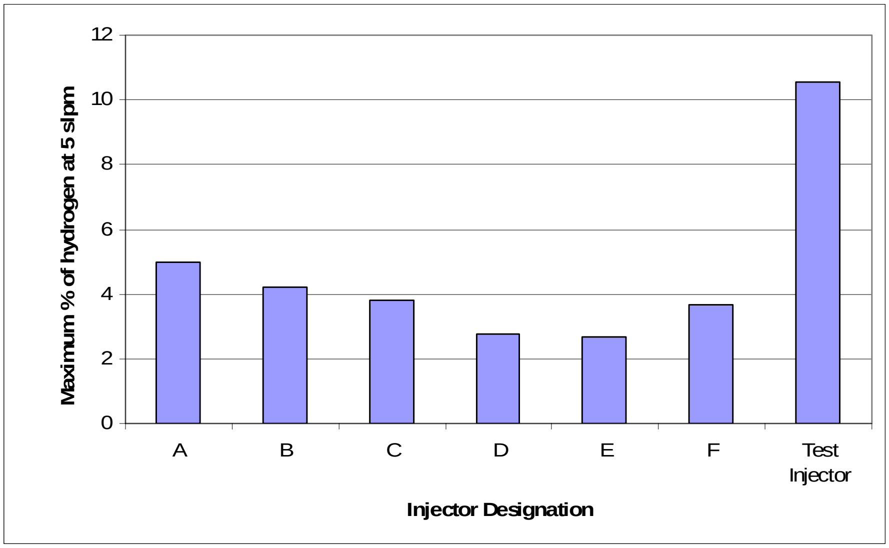


Figure 2: Maximum percent composition that the current hydrogen MFC can flow to obtain a flame temperature of 2400°F at 4% pressure drop, T1 = 600°F, operating at atmospheric conditions.

In order to mix 10% hydrogen by volume into the fuel stream of the largest injector operating at the same conditions, the mass flow controller would have to be sized to flow at least 21 slpm. If high-pressure tests are carried out in the future, a new controller would definitely need to be purchased; for, the required flow rates would be far larger. For each of the above injectors operating at the same inlet temperature, percent pressure drop, and 200 psig, the hydrogen controller would have to be sized according to the flow rates shown in Figure 3 to obtain a flame temperature of 2400°F and have 10% H_2 by volume.

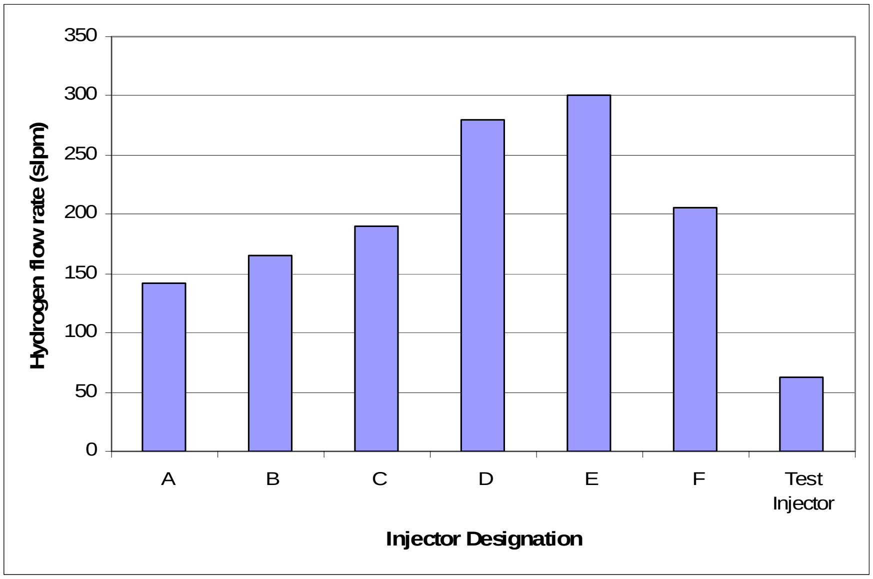


Figure 3: Required size of hydrogen MFC to provide 10% of the fuel composition for a flame temperature of 2400°F, T1 = 600°F, operating at 200 psig.

Design of Experiment was used to determine the most important parameters affecting the lean blow out limit of the test injector. The original parameter space included: the inlet temperature, percent pressure drop, mass percent of pilot, % hydrogen, and dopant location. The preliminary experiments were run and the data were analyzed. After analyzing the results from these preliminary tests, it became obvious that too many parameters were being adjusted and effects of the hydrogen injection were overshadowed by the interrelations between the other parameters. Not one parameter made an impact with a high level of statistical significance. For example, the nozzle velocity will change with both inlet temperature and % pressure drop. A changing nozzle velocity will greatly influence the fluid dynamics of the reacting jet and in turn the blow out temperature. In addition, the hydrogen composition of the fuel stream also will change with varying inlet temperature, % pressure drop, and % pilot.

It is actually found that for the test injector, higher flow rates (pressure drop) actually promoted a more stable flame near blow out conditions. Higher inlet temperature and % pilot by mass also appeared to extend lean blow out; however, the correlations were not determined at a high confidence interval. In addition, the results showed that an increase in H_2 content actually had a negative effect on lean blow out. In order to remove extra effects that inlet temperature and pressure drop have on the lean blow out limit, these parameters are set as constants. Percent pilot is not kept constant since it does not have the same meaning if the fuel stream is made up of multiple constituents since the molecular weights of the fuels are different. Instead, it is decided to run the first two sets of experimental tests with a calculated pilot flame temperature of 3000ºF with natural gas making up the remainder of the fuel composition when hydrogen is doped into the pilot, and natural gas making up the entire pilot fuel composition when hydrogen is doped into the main. Running at a constant flame temperature is similar to running at constant mass % pilot when the pilot fuel is natural gas, only now the fuel flow rates are normalized on an energy basis rather than a mass basis. The third set of tests is at the same % pressure drop, and inlet temperature, but now only hydrogen is sent through the pilot with no natural gas making up the extra energy required to keep the pilot flame temperature at 3000°F. The revised test matrix is shown in Table 1 where only hydrogen composition and injection location is varied. Four different levels of hydrogen are injected at equal inlet temperatures, pilot flame temperatures, and airflow rates into both the pilot and the main flame.

Table 1: Experimental Test matrix.

Test #	H_2 doping location	% of hydrogen maximum flow	Inlet Temperature (°F)	% Pressure drop	Pilot Flame Temperature (°F)
1-5	Main	0%, 25%, 50%, 75%, 100%	650	5	3000
6-10	Pilot	0%, 25%, 50%, 75%, 100%	650	5	3000
11-15	Pilot, no natural gas	0%, 25%, 50%, 75%, 100%	650	5	3000

Results and Discussion

Lean Blow out Flame Temperature

As expected, doping hydrogen into the fuel stream extends the lean blow out of the test injector regardless of location. As shown in Figure 4, doping the hydrogen in the pilot results in the furthest extension of lean blow out followed closely by doping the hydrogen in the main. Blow out is below the data points with a stable reaction occurring at flame temperatures above these points. Notice that the amount of hydrogen in the fuel stream is reported as the percent energy the hydrogen comprises in relation to the total amount of energy in the fuel stream based on the lower heating values of the fuel.

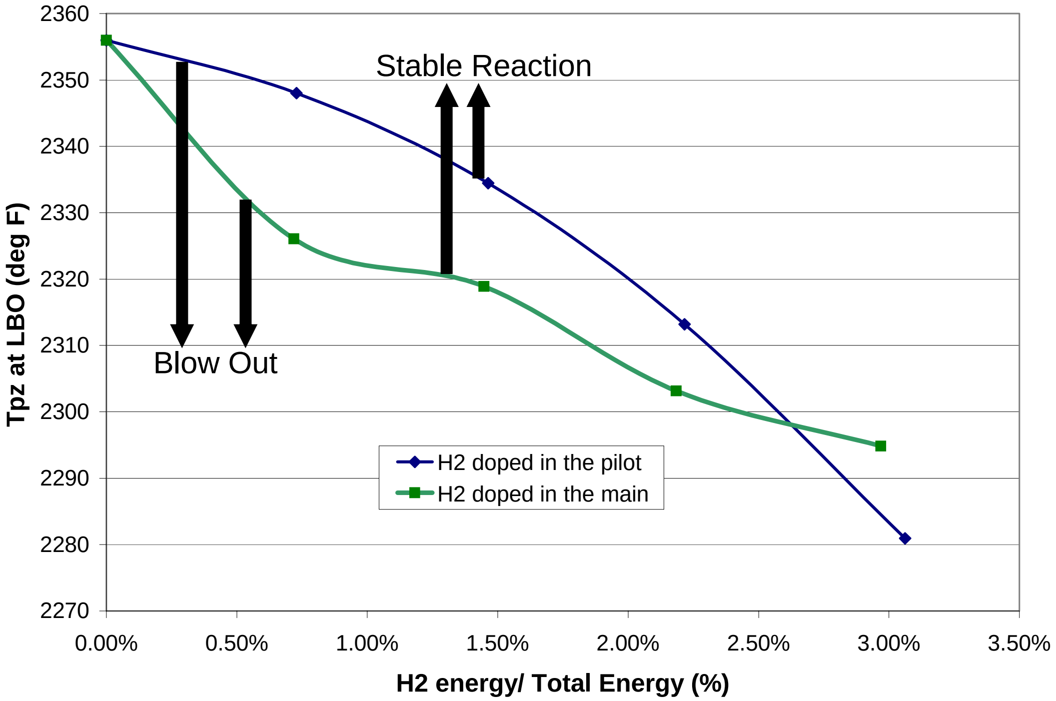


Figure 4: Lean blow out at various compositions of hydrogen for the 2 different injection locations.

The above plot suggests that it may be marginally better to inject the hydrogen in the pilot than in the main, meaning that the pilot provides more of a stabilization anchor, and when hydrogen is added to it, the stabilization effect becomes more pronounced. One important point to note is that even though doping the pilot results in the largest extension of blow out, doping the main results in a larger effect at very low H_2 flows, and may be a more stable reaction and cleaner flame at temperatures just above lean blow out. This will be discussed in more detail below in the discussion of flame structure.

Flame Structure

The flame shown in Figure 5, is indicative of the test injector running with natural gas only and reacting at a stable flame temperature of 2500°F. There are three main components to take note of in this flame:

1. The pilot flame is sent up through the center of the injector. Its function is to stabilize the flame by burning out any fuel that is recirculated by the primary recirculation zone.
2. The primary recirculation zone is composed of the fuel/air mixture that is sent up through the injector main. Any unreacted fuel will complete its reaction when it comes into contact with the pilot.
3. The secondary recirculation zone is also composed of the fuel/air mixture sent up through the injector main, but it recirculates back towards the injector in a downward swirl. Most likely this flow is entrained back into the main or pilot and is eventually consumed when it comes back into contact with the pilot or reacting gases in the primary recirculation zone.

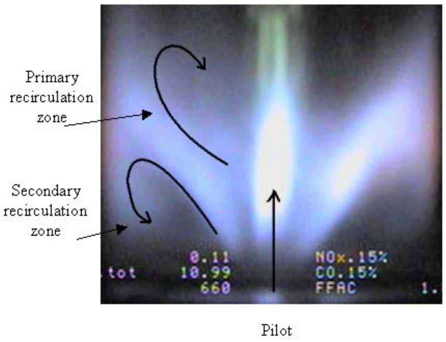
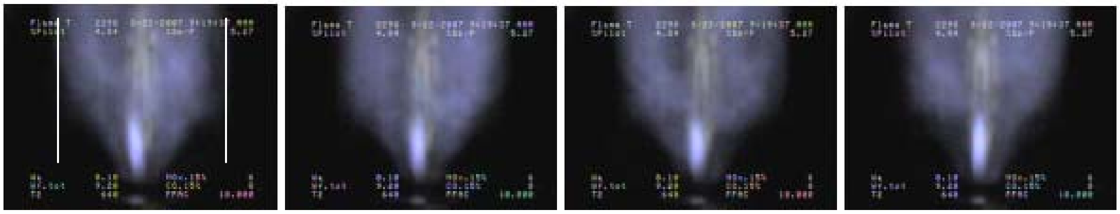


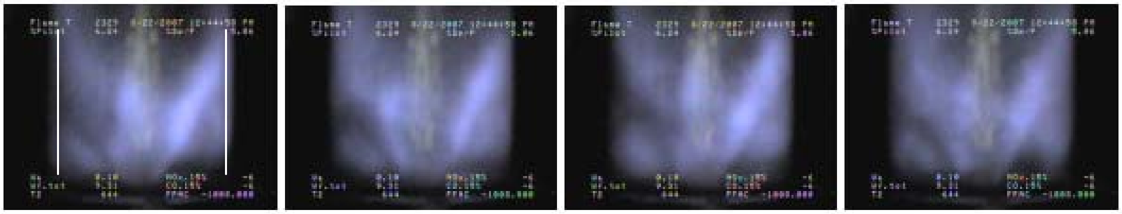
Figure 5: The pilot, primary, and secondary recirculation zones for a Natural Gas flame, operating at a flame temperature of 2500°F.

The effect that the hydrogen injection location has on flame structure is further illustrated in Figure 6. Each of the sequences of photographs in Figures 6a through 6c, is taken with a high speed camera at a rate of 30 frames per second; thus each image is separated by about 33 ms. As shown, injection location has a significant effect on flame structure. The inlet temperature, the airflow rate and the pilot flame temperature are equal for each of the three cases. Shown in Figure 7, the calculated flame temperatures are nearly equal; however the flames doped with hydrogen are 40 to 50 degrees above blow out; where as the undoped flame is hovering at the verge of blow out.

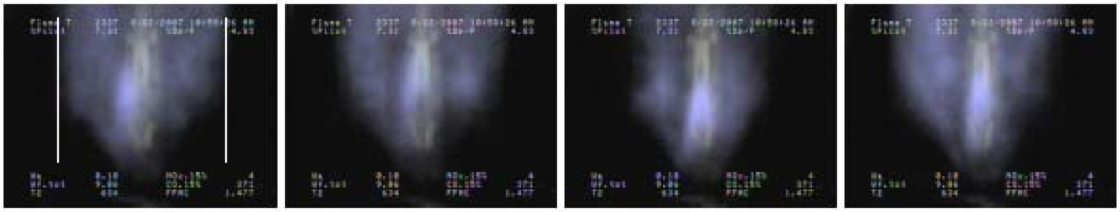
The first point to take note of is the different pilot in each of the three cases. In Figure 6a, hydrogen is injected into the pilot, and in Figures 6b and 6c there is no hydrogen in the pilot. The hydrogen in the pilot causes the pilot flame to be shorter, thinner, and more luminous, as opposed to the natural gas pilot flames that are thicker, more dispersed and duller in overall luminosity. Another point to make in regards to the pilot is the fact that the hydrogen doped pilot flame does not appear to move around as it is anchored better. The natural gas pilots appear to blow around, and are lifted off from the injector slightly more. The H_2 is doped into the injector main in Figure 6b. Figure 6c shows the flame with no H_2 injection. There is an obvious effect here shown in the secondary recirculation zone. In Figures 6a and 6c, the secondary recirculation zone has all but disappeared at these low flame temperatures; however, there appears to be a significant sustained reaction in this area shown in Figure 6b. Looking at Figure 6c, it is obvious that this flame is on the edge of extinction. It shows some characteristics of local extinction and reignition shown in the third and fourth flames of Figure 6c. The flames in Figures 6a and 6b are at flame temperatures about 15°F lower than the flame in Figure 6c; however, they appear to be still quite stable, or at least unchanging, while the flame in Figure 6c is quite close to blow out, as mentioned above.



a) Hydrogen is doped into the pilot, Tpz = 2337°F, T1 = 650°F, %DP = 5, pilot Tpz = 3000°F



b) Hydrogen is doped into the main, Tpz = 2340°F, T1 = 650°F, %DP = 5, pilot Tpz = 3000°F



c) There is no hydrogen in the flame, Tpz = 2354°F, T1 = 650°F, %DP = 5, pilot Tpz = 3000°F

Figure 6: The effect that H_2 doping location has on flame structure at similar flame temperatures, T_1 = 650°F, 5% pressure drop, and pilot Tpz = 3000°F.

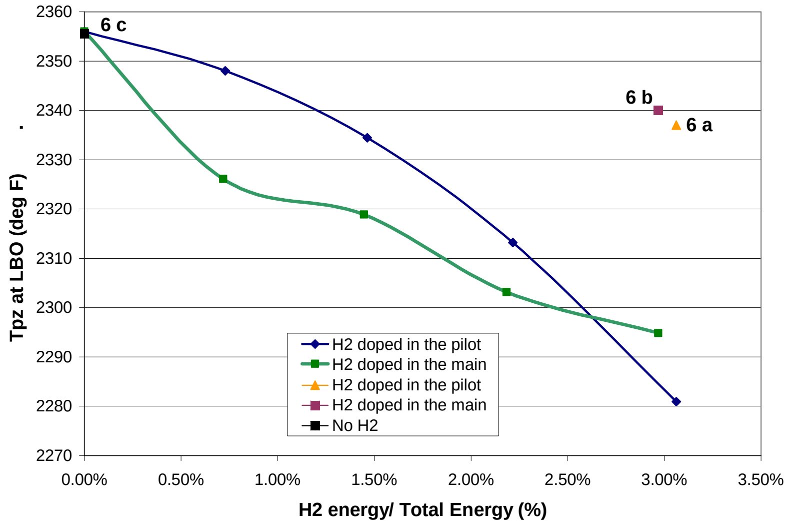


Figure 7: Locations of the flames in Figure 6 with respect to flame temperature and H_2 composition.

While the hydrogen doped pilot flame seems to have a wider range of blow out limits as suggested in Figure 4, the flame is not nearly as robust at low temperatures as the flames with hydrogen doped in the main. The flame in Figure 6a is still about 60°F above its lean blow out limit; however, it does not touch the sides of the quartz combustor anymore as shown in the first snaps of Figures 6a, b, and c. Eventually, the flame will reduce to essentially a pilot flame with high levels of unburned hydrocarbons escaping around the sides as shown in Figure 8.

Figure 8: Photograph of the hydrogen doped pilot near blow out conditions at a flame temperature of 2280°F.

It definitely seems that this flame in Figure 8 would be unacceptable in a gas turbine combustor, and the large amounts of unburned hydrocarbons and CO it is producing would be certainly be intolerable from an emissions standpoint. For the purposes of this experiment, lean blow out was defined as the point in which the flame extinguishes itself. The large concentration of hydrogen in a small area allows this flame to stay lit, although most of the main flow is escaping out the sides of the combustor unreacted.

To further illustrate this point, the temperature at the exit of the combustor was measured as shown in Figure 9.

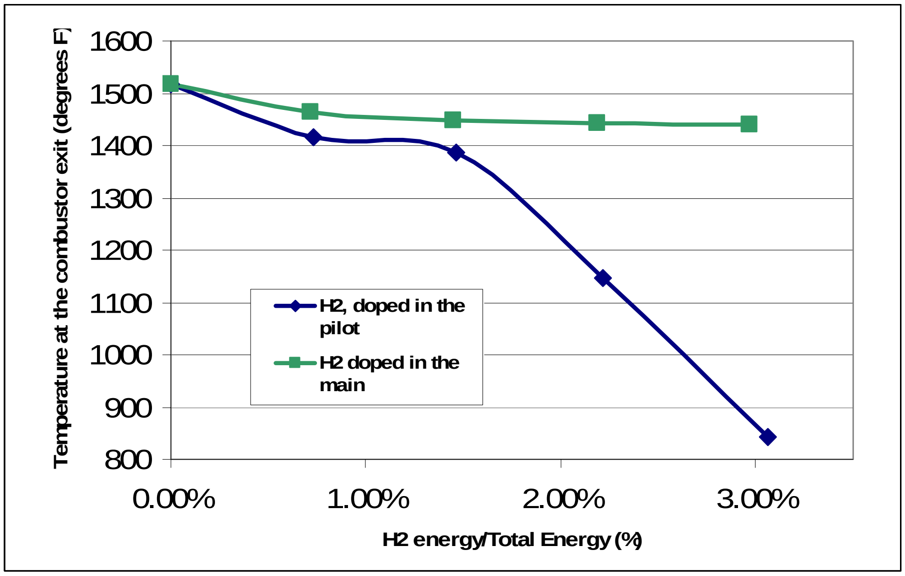


Figure 9: Temperature at the exit plane of the quartz combustor at blow out.

The position of the thermocouple is shown in Figure 1. As it is not measuring the actual flame temperature of the reaction, it does indicate a relative robustness of the flame. As shown in the plot, the exit plane temperature of the combustor at flame blow out starts out at about 1510 °F for no hydrogen doping. As more hydrogen is added and the blow out flame temperature is decreased for both injection locations, the exit plane temperature for the condition where hydrogen is injected into the pilot decreases rapidly; whereas, the exit plane temperature remains nearly constant when hydrogen is injected into the main. Both due to a more stable exit temperature and the weak flame structure at blow out for pilot injection, suggests that it is better to inject hydrogen into the main, even though a lower blow out flame temperature was achieved when H_2 is injected into the pilot.

Emissions

As stated above, larger OH radical pools should help to oxidize CO to CO_2. In addition to decreasing CO emissions, it is suggested that for a given flame temperature a larger OH radical pool also will increase NO_x [4]. Although more NO_x production is expected at equal flame temperatures with hydrogen addition, hydrogen and effectively a larger OH radical pool allows for a stable flame at lower flame temperatures. Thus, ultimately lower levels of NO_x can be achieved.

Since it is common knowledge that lower flame temperatures produce less NO_x, it is not tested to see whether or not this is the case. In addition to this, the emissions analyzer in the test facility goes offline if HC levels rise above 200 ppm to prevent damage to the analyzers. At very low equivalence ratios/flame temperatures the HC levels were always above this point, so emissions data near blow out were not collected. Instead, emissions measurements were collected at equal flame temperatures of about 2400°F, for various concentrations of hydrogen doped into both the pilot and the main. Literature suggests that at equal flame temperatures, there should be higher NO_x and lower CO concentrations corresponding to larger levels of OH radical in the reaction zone. As shown in Figure 10, this is the case for hydrogen doped into the injector main; however for the case where hydrogen is doped into the pilot, the NO_x falls and the CO rises slightly as the amount of hydrogen is increased.

The levels of both pollutant emissions are so low that any changes are beyond the accuracy of the analyzer to quantify. In addition, controlling the natural gas flow rate in the test stand is quite difficult; thus, maintaining precisely 2400°F is quite difficult. However, assuming that the analyzer is accurate and the flame temperatures are completely equal, these phenomena could be explained by looking back at Figures 6a and 6b. Both of these flames are nearly equal in temperature, but the hydrogen doped pilot flame (Figure 6a) is thinner and does not quite touch the outer walls of the combustor. The hydrogen doped main flame (Figure 6b), appears more robust and has a more homogenous look to it, which suggests that the hydrogen is spread out more evenly in the reaction zone, which leads to a better spread of the OH radical pool; thus achieving emissions trends that have been reported in the literature.

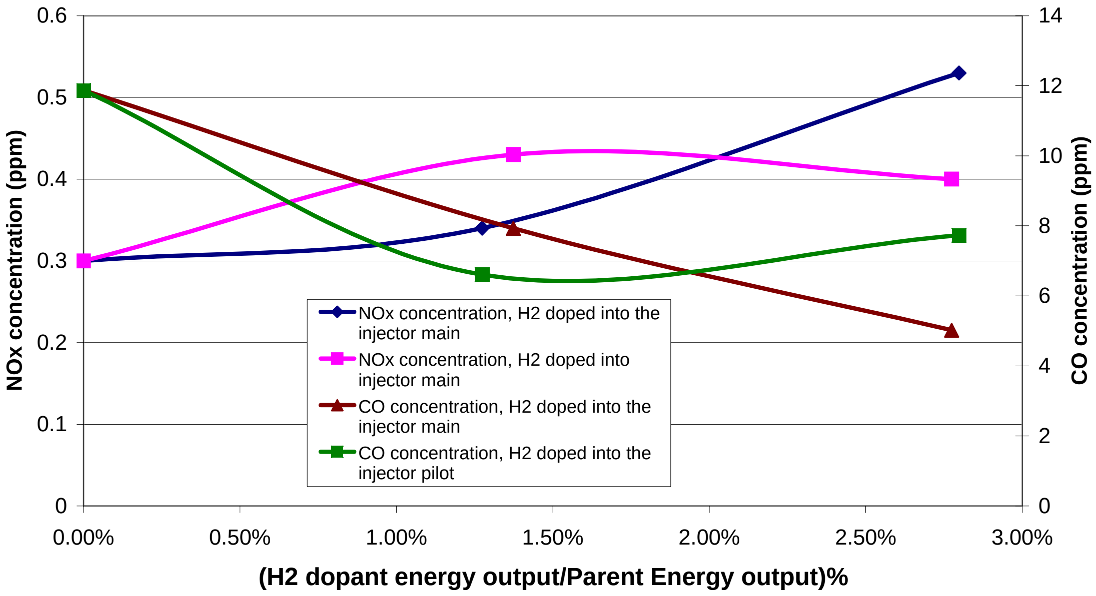


Figure 10: NOx and CO emissions f or hydrogen doped into both the pilot and the main at a flame temperature of approximately 2400°F.

Recommendations

For the most part, this study has proved to be consistent with the literature for extending the lean blow out limits of a lean premixed natural gas flame via hydrogen injection. In order to reinforce this study, atmospheric tests should be conducted on the other injectors of interest to explore the effects of geometry on blow out and optimal injection location. A larger hydrogen mass flow controller should be purchased and high-pressure tests should be conducted in order to study the effect that pressure has on both the ability for hydrogen to extend the lean blow out limit and lower emissions. Optical techniques, such as chemilumenescence, PLIF, and laser absorption methods should be employed to measure OH radical concentration in the reaction zone and actual flame temperature.

Acknowledgements

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