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ULTRA-LOW EMISSION HYDROGEN/SYNGAS COMBUSTION WITH A 1.3 MW INJECTOR USING A MICRO-MIXING LEAN-PREMIX SYSTEM

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ABSTRACT

This paper discusses the development and testing of a full-scale micro-mixing lean-premix injector for hydrogen and syngas fuels that demonstrated ultra-low emissions and stable operation without flashback for high-hydrogen fuels at representative full-scale operating conditions. The injector was fabricated using Macrolamination technology, which is a process by which injectors are manufactured from bonded layers. The injector utilizes sixteen micro-mixing cups for effective and rapid mixing of fuel and air in a compact package. The full scale injector is rated at 1.3 MWth when operating on natural gas at 12.4 bar (180 psi) combustor pressure. The injector operated without flash back on fuel mixtures ranging from 100% natural gas to 100% hydrogen and emissions were shown to be insensitive to operating pressure. Ultra-low NOx emissions of 3 ppm were achieved at a flame temperature of 1750 K (2690 °F) using a fuel mixture containing 50% hydrogen and 50% natural gas by volume with 40% nitrogen dilution added to the fuel stream. NOx emissions of 1.5 ppm were demonstrated at a flame temperature over 1680 K (2564 °F) using the same fuel mixture with only 10% nitrogen dilution, and NOx emissions of 3.5 ppm were demonstrated at a flame temperature of 1730 K (2650 °F) with only 10% carbon dioxide dilution. Finally, using 100% hydrogen with 30% carbon dioxide dilution, 3.6 ppm NOx emissions were demonstrated at a flame temperature over 1600 K (2420 °F). Superior operability was achieved with the injector operating at temperatures below 1470 K (2186 °F) on a fuel mixture containing 87% hydrogen and 13% natural gas. The tests validated the micro-mixing fuel injector technology and the injectors show great promise for use in future gas turbine engines operating on hydrogen, syngas or other fuel mixtures of various compositions.

INTRODUCTION

This work is part of a greater DOE-sponsored effort directed at developing technologies to enable the use of abundant domestic coal and biomass resources for energy production, while at the same time, substantially reducing emission of harmful pollutants and greenhouse gases associated with coal utilization. This project was conceived to specifically address the use of hydrogen in mega-watt scale gas turbine engines through development of micro-mixing, multi-point fuel injection technologies for lean premix combustion of hydrogen and syngas. The overall project goal was to develop an injector that delivers 3 ppm NOx emissions at an adiabatic flame temperature of 1750 K (2700 °F) when operating pressures and pressure drops are representative of full-scale gas turbine engines.

The utilization of hydrogen in a gas turbine system presents a number of challenges, especially when constrained by a need to meet aggressive NOx emissions levels. Achieving low NOx emissions in any air based combustion system involves reducing peak combustion temperatures by burning a lean fuel-air mixture. The reason is that NOx formation rates are strongly dependent upon temperature through the so called Zeldovich or thermal mechanism [1]. The temperature dependency of the thermal NOx production is associated with the need to break up the relatively strong triple bond present in molecular nitrogen. Once the triple bond is broken, NO formation proceeds rapidly by combining the resulting atomic nitrogen with the oxygen present in the air. Since the temperature dependency of molecular nitrogen breakup is exponential, even small departures above the mean reaction temperature can lead to significant NOx formation. Consequently, where low single digit NOx is required, great care must be taken in the preparation and combustion of the fuel and air, to minimize unmixedness of the fuel-air stream. Furthermore, the mixture must be sufficiently lean to produce low-enough temperatures to minimize NOx formation.

NOx is formed via a number of mechanisms, in addition to the thermal mechanism, including the “prompt” mechanism (involving CH species), “fuel” (involving elemental N in the fuel), and “N2O” (involving molecular nitrogen, atomic oxygen, and a third body). The dependency of the total NOx emission on these non-thermal pathways can be substantial for low temperature combustion. With no carbon in hydrogen fuel, it would appear that prompt NOx is not a significant concern. Likewise, assuming that the syngas cleanup process is successful, little nitrogen containing species should be present in the fuel stream and, therefore, fuel NOx is not a concern. That leaves only the N2O mechanism as a further contributor to the overall NOx emission from hydrogen combustion. Unfortunately, the N2O mechanism is not as well understood as is the thermal mechanism. The pressure dependency of the mechanism has been found to be negligible in some cases, but present in others [2]. Likewise, the residence time dependency of the N2O mechanism appears to be weak for lean mixtures [3], while other results suggest that longer residence times increase NO formed by the N2O mechanism [4].

Details of the nature of the reaction zone, in particular stretch and strain, may factor into the N2O mechanism. In the case of thermal NOx it is well established that residence time is important. As a result, in addition to reducing temperature, a strategy to minimize the time at high temperature is also preferred. Furthermore, in the absence of strong evidence verifying the lack of dependency on residence time of NO formed via the N2O mechanism, it stands to reason that minimizing the reaction zone volume can also help minimize NO formed via the N2O pathway. As a result, it can be concluded that large scale recirculation zones created by “traditional” swirl stabilized systems may be detrimental to NOx emission. Growing evidence supports this with the demonstration of porous burners [5] and thin flames [6] yielding very low NOx emissions. If the reactions can be stabilized by these means, the small reaction zones appear to result in lower NOx formation. A strategy to provide small scale mixing of fuel and air and minimize the extent of recirculation appears to be a good approach to helping achieve minimum NOx.

Thorough mixing is a critical element to minimizing the occurrence of local peak temperatures. Current commercially sold premixers for both liquid fuel and gaseous fuel applications use multipoint injection strategies. The injection points are placed at a significant distance upstream from the exit of the premixer. The premixing length is typically dictated by the requirement of allowing sufficient residence time for the interaction of the fuel, whether liquid or gaseous, with the air stream. The ultimate goal is to reach fully premixed conditions at the exit of the premixing duct while preventing auto-ignition and flashback. However, the properties of hydrogen may essentially eliminate traditional premixing approaches for achieving the mixing necessary to get rid of high temperature regions. In particular, the turbulent flame speed of hydrogen (4X-10X that of natural gas) creates a major challenge for premixer design. For high hydrogen content fuels, the premixing length would have to be reduced significantly in order to counteract the detrimental effects of high flame speed and its potential influence on flashback. As a result, an injection strategy that gives precise control over the placement of the fuel and air and that can result in small scale rapid mixing is needed to eliminate long mixing times and troublesome aerodynamic features, such as boundary layers and low velocity regions, which can facilitate flashback.

While the discussion above expounded on the difficulties of high hydrogen content combustion; it should be noted that hydrogen offers special advantages. Hydrogen enriched flames offer enhanced stability when compared to natural gas flames and are stable at relatively lower overall equivalence ratio. This means that combustion can occur at relatively lower overall flame temperatures and thus thermal NOx levels can be reduced when compared to natural gas flames. Hydrogen also offers enhanced molecular diffusivity, which promotes mixing at the molecular level and reduces the need for long mixing lengths.

The objective of the current work is to evaluate the emissions and operability performance of a 1.3 MWth multi-point injector based on a single-cup injector design developed through previous work [7-9]. In what follows, the injector hardware used in this study is described along with the experimental setup used in the operability and emissions tests. Results from experiments are presented, focusing on flame structure, emissions and flash-back resistance. The paper ends with a summary and conclusions.

TEST HARDWARE

The above review on low-emission hydrogen combustion points not only to the well established practice of ultra-lean premixed combustion and very low unmixedness, but also to the criticality of short premixer length (for auto-ignition and flash-back avoidance), short residence time in the flame zone, small thin flames (for minimum NOx generation), and exact control over fuel-air mixture and velocity profiles at the exit of premixers (for flash-back control). To achieve all of the above, a multipoint fuel injection zone concept was adopted. This concept is based on the Integrated Dome (IDome) design, shown in Figure 1. The IDome concept is an annular injection scheme in which small injection points are distributed over the entire combustor inlet surface, with all mixing channels for fuel and air integrated into the dome. The figure depicts the 15-degree sector tested to validate the concept. The IDome achieved record-low emissions during liquid fuel combustion tests at NASA [10, 11]. The top and bottom combustor liners are film cooled and the side wall is back side cooled. Assuming that 15% of the combustion air is used for liner cooling, NOx levels less than 30% of the ICAO standard were achieved. The IDome injector is built as a layered construction using Macrolamination, a manufacturing process where etched laminates are bonded to form a structure that combines the fuel and air circuits into a single element. This manufacturing technique allows complex, internal fuel and air manifolding and enables the construction of injectors containing many small-scale mixing cups.

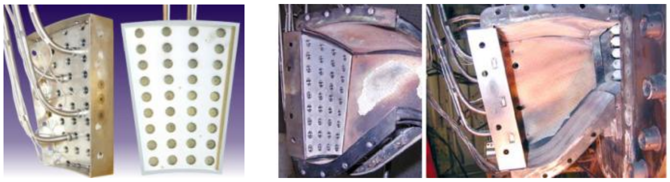

(A) (B)

FIGURE 1: IDOME FUEL INJECTOR (A) FRONT AND REAR VIEW AND (B) PHOTOGRAPH OF MODULE INSTALLED IN THE NASA GRC FACILITY [10]

During this hydrogen/syngas project a 1.3 MWth full-scale injector comprising 16 mixing cup elements was developed using the approach described above. Each pre-mixing cup element contains multiple air-feeds and fuel injection points and represents the basic building block that may be replicated to build multi-cup injectors of any scale. The broad design space of the building block Macrolaminate mixing-cup was explored in previous work [7-9], culminating in the design shown in Figure 2 below. The mixing cup is characterized by a mixed-flow air-circuit design and fuel injection into the core flow at a single axial location. The selection of this configuration was based on extensive CFD studies and testing of single-cup and multi-cup prototype modules like those shown in Figure 3a and 3b, respectively.

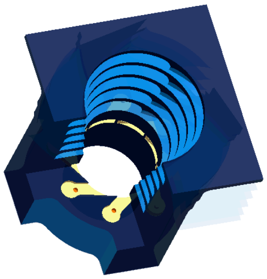


FIGURE 2: MIXING-CUP DESIGN [9]

(A) (B)

FIGURE 3: MICRO-MIXING CUP PROTOTYPE MODULES [9]; (A) SINGLE-CUP MODULE; (B) MULTI-CUP MODULE WITH FOUR INTEGRAL CUPS

The full scale, 1.3 MWth injector shown in Figure 4 comprises sixteen micro-mixing cups based on the design shown in Figure 2. The mixing cups are arranged in two concentric circles, with ten mixing cups on the outer ring, five on the inner ring, and a single pilot cup in the center. The Macrolaminate structure contains four fuel circuits that supply fuel to groups of cups or “zones”. Three of the circuits feed the center cup (pilot circuit), the inner core of six cups (six-cup circuit) and the outer ring of ten cups (ten-cup circuit). The fourth feeds a second fuel circuit within the fifteen cups on the two rings surrounding the pilot (fifteen-cup circuit). This arrangement provides flexibility to operate the injector in multiple schemes. For instance, fuel can be fed to all cups simultaneously in two different ways. First, via the pilot and fifteen-cup circuit, and second, via the six-cup and the ten-cup circuits. Thus, for high Wobbe index fuels, either combination can be used, while for low Wobbe index fuels, all circuits can be combined to effectively provide a single circuit with a higher effective area. Also, by splitting fuel between the different circuits, various staging schemes can be tested. Thus, fuel can be delivered to the five-cup circuit and the pilot, leaving the ten-cup circuit un-fueled, providing a possible low-load operating mode with a low overall air-fuel ratio but stable flame at the six-cup core, possibly anchored by the pilot running slightly richer than the remaining cups.

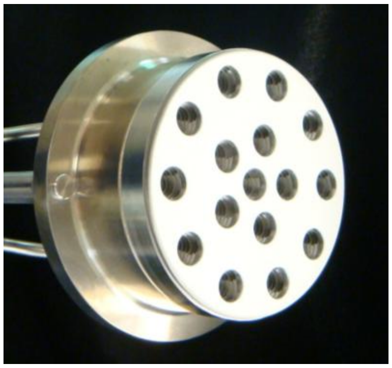


FIGURE 4: FULL-SCALE MICRO-MIXING INJECTOR WITH SIXTEEN MIXING CUPS

EXPERIMENTAL METHODS

For the present work, the emphasis was on studying the operability and emissions performance of the full-scale injector at conditions representative of engine operation using a variety of fuel mixtures in a Solar Turbines test facility in San Diego. Additionally, an atmospheric test stand at the University of California-Irvine Combustion Laboratory (UCICL) used in previous work [8, 9] was implemented to study mixing performance.

The test facility at the UCICL used for atmospheric testing of the full-scale injector is illustrated in Figure 5. The injector is oriented vertically in an up-fired manner and discharged into a quartz liner to facilitate flame imaging and flow-field mapping. The holder mount is designed such that the injector exit plane is raised above the surrounding surfaces to facilitate flame imaging. The holder contains a groove for the quartz liner, centering the injector and preventing air leakage. The holder is attached to the end of an air box that is connected to the facility air supply and mounted on a traverse that positions the injector relative to a fixed extractive probe during fuel concentration testing. Also, a baffle is installed within the air box to help distribute the incoming air flow uniformly to all sixteen mixing cups.

Fuel-air mixing profiles at the exit of two individual mixing cups were measured using an extractive probe approach, shown in Figure 6. The sample probe used is a surgical stainless steel needle 50 mm in length (0.41 mm I.D. x 0.71 mm O.D.). An SRI gas chromatograph (GC) was used to measure hydrogen concentration for multiple locations at the cup exit. The GC was calibrated using a certified sample gas mixture to ensure its accuracy. The GC was calibrated and checked before each test with drift remaining under 1% during all testing. Further details about the operation of the GC are found in previous work [8]. Similarly, a high range flame ionization detector (FID) was used to quantify the natural gas concentrations at the injector exit plane. It was also zeroed and spanned prior to and after the tests.

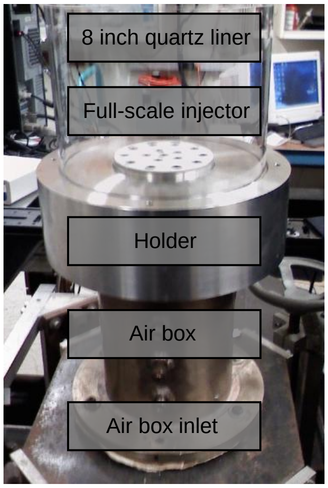


FIGURE 5: FULL-SCALE INJECTOR TESTING SET UP

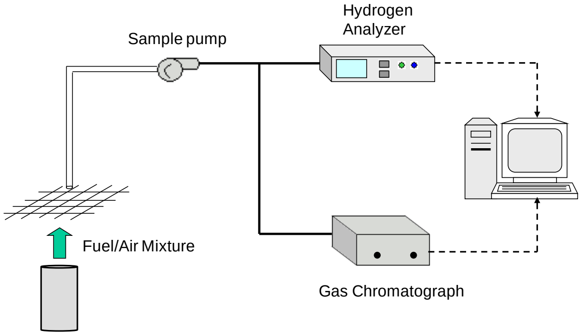


FIGURE 6: SETUP USED FOR FUEL-AIR MIXING MEASUREMENTS

The full-scale OEM combustion tests focused on operability and emissions over a range of operating conditions and fuel mixtures. The operating conditions are representative of part to full load of a megawatt-scale gas turbine engine. A summary of operation conditions and fuel blends studied and the test parameters explored are shown in Table 1 below.

TABLE 1: HIGH PRESSURE TEST PARAMETERS

Combustor pressure (gauge)	**6.9 bar, 8.4 bar, 12.4 bar (100 psig, 120 psig, 180 psig)**
Pressure drop	**3.2%, 3.5%, 4.0%, 4.5%**
Inlet Air Temperature	**617 K, 700 K, 756 K (650 °F, 800 °F, 900 °F)**
Pilot Setting	**Leaned, Neutral, Enriched (various levels)**
Fuel composition (natural gas and hydrogen)	**0% H_2 (100% NG), 50% H_2, 86% H_2, 93% H_2, 100% H2 (0% NG)**
Diluent Content	**N2, CO2, volume fraction up to 40%**

RESULTS AND DISCUSSION

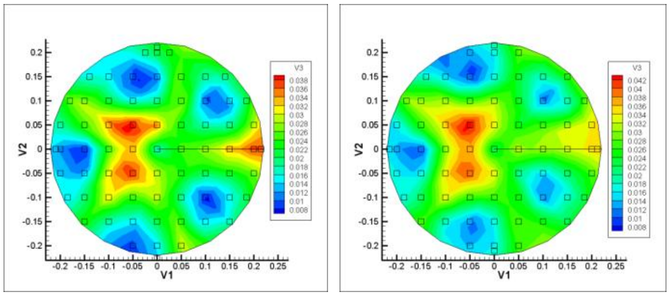
The following sections present sample results from mixing studies conducted in the UCICL atmospheric rig and high pressure emissions and flame imaging tests at Solar Turbines.

Atmospheric testing (UCICL)

Operating at an equivalence ratio of 0.5, the mixing profiles were obtained for 100% hydrogen at pressure drops of 3.5% and 4.5% and for hydrogen with 25% nitrogen dilution at a pressure drop of 3.5%. The pressure drop was varied through control of the mass flow rate of air through the rig. The hydrogen concentration was measured at a total of 69 data points across each cup. The results are shown in Fig. 7 to 9.

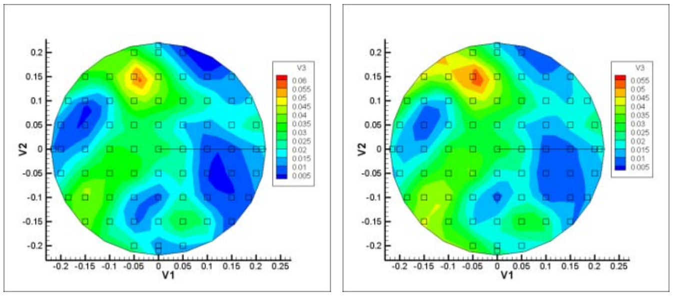
Figure 7 shows the mixing results for the pilot cup at air pressure drops of 3.5% and 4.5%. The mixing profile for the two cases is similar, with only a small difference in actual concentration and only a slightly higher peak concentration (0.042 v. 0.038) for a pressure drop of 4.5%, an effect attributed to reduced mixing time. The profiles exhibit five distinct lean regions, corresponding to the five air slots immediately up-stream of the measurement plane. Figure 8 shows the mixing results for the main cup under the same conditions. Again, the mixing profile is not strongly dependent on the air pressure drop at these conditions.

Figure 9 shows the mixing results for the pilot and main cups with 25% nitrogen dilution in the fuel flow. The measurements were done at 3.5% pressure drop and equivalence ratio of 0.5. Comparison to Fig. 7 and 8 reveals that the addition of nitrogen to the fuel dramatically changes the mixing characteristics within the cups. With nitrogen addition, the highest hydrogen concentration was observed in the middle of the cup and the flow near the cup wall was observed to be relatively lean. These results show that the addition of nitrogen in the fuel flow promotes stronger fuel penetration into the middle of the cup compared to cases without dilution.



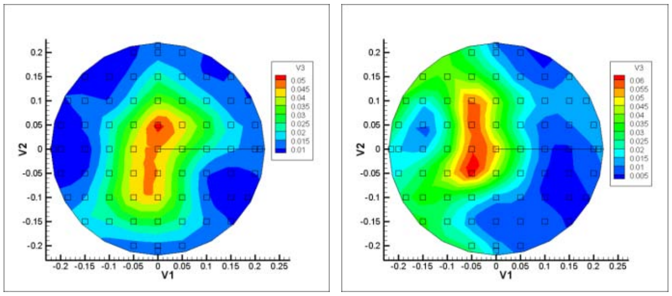
(A) 3.5% ΔP/P, Φ = 0.5 **(B) 4.5% ΔP/P, Φ = 0.5**

FIGURE 7: PILOT CUP MIXING PROFILE-100% H_2; NO DIL.



(A) 3.5% ΔP/P, Φ = 0.5 **(B) 4.0% ΔP/P, Φ = 0.5**

FIGURE 8: MAIN CUP MIXING PROFILE-100% H_2; NO DIL.



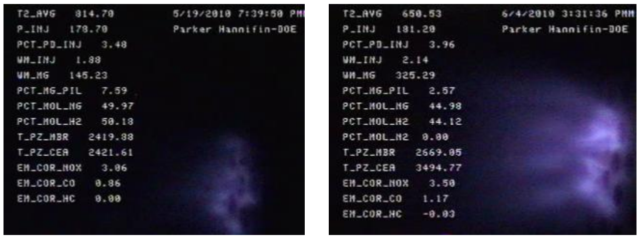
(A) PILOT, 3.5% ΔP/P **(B) MAIN, 3.5% ΔP/P**

FIGURE 9: MIXING PROFILE FOR PILOT AND MAIN CUPS-100% H_2; 25% N_2 DIL.

High-pressure testing (Solar Turbines)

During part-load operability tests for mixtures of hydrogen and natural gas (50% hydrogen and higher), stable combustion was achieved at flame temperatures as low as 1590 K (2402 °F) for a fuel mixture containing 50% hydrogen and as low as 1425 K (2105 °F) on a fuel mixture containing 86% hydrogen. Carbon-monoxide emissions remained well within 1 ppm at all conditions except when blow-out was imminent. Part-load operation of the injector on 100% natural gas was more challenging when operating on all sixteen cups, with lean blow out typically occurring as flame temperature approached 1800 K (2780 °F). These results are not surprising since the injector is primarily optimized for fuels with high hydrogen content and, subsequently, high flame speed. Improvements in lean blow out are expected to be easily achieved through modified cup arrangement, staging and traditional pilot sheltering approaches.

For high-hydrogen fuels, part-load operability was achieved without an enriched pilot and its associated negative impact on emissions performance. For instance, running a fuel mixture containing 87% hydrogen and 13% natural gas combined with 20% carbon-dioxide dilution, the injector could be operated on all sixteen cups at temperatures below 1470 K (below 2200 °F) without the use of an enriched pilot, achieving NOx emissions well below 2 ppm. Flashback resistance was demonstrated over the entire range of conditions and fuel mixtures that were tested, including in tests of 100% hydrogen fuel with 30% carbon dioxide dilution at operating pressure of 8.1 bar (122 psi) and flame temperature above 1600 K (2420 °F).



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T2_AVG    814.70              5/19/2010 7:39:50 PM
P_INJ   178.70                Parker Hannifin-DOE
PCT_PD_INJ   3.48
WM_INJ   1.88
WM_NG   145.23
PCT_NG_PIL   7.59
PCT_MOL_NG   49.97
PCT_MOL_H2   50.10
T_PZ_MBR   2419.88
T_PZ_CEA   2421.61
EM_COR_NOX   3.06
EM_COR_CO   0.86
EM_COR_HC   0.00
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T2_AVG    650.53              6/4/2010 3:31:36 PM
P_INJ   181.20                Parker Hannifin-DOE
PCT_PD_INJ   3.96
WM_INJ   2.14
WM_NG   325.29
PCT_NG_PIL   2.57
PCT_MOL_NG   44.98
PCT_MOL_H2   44.12
PCT_MOL_N2  0.00
T_PZ_MBR   2669.05
T_PZ_CEA   3494.77
EM_COR_NOX   3.50
EM_COR_CO   1.17
EM_COR_HC   -0.03
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(A) 50% H_2-50% NG; 0% DIL. **(B) 50% H_2-50% NG; 10% CO_2 DIL.**

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T2_AVG    807.10              6/3/2010 2:44:55 PM
P_INJ   182.30                Parker Hannifin-DOE
PCT_PD_INJ   4.07
WM_INJ   2.03
WM_NG   587.55
PCT_NG_PIL   2.03
PCT_MOL_NG   30.46
PCT_MOL_H2   30.42
PCT_MOL_N2  39.13
T_PZ_MBR   2695.48
T_PZ_CEA   3491.61
EM_COR_NOX   2.98
EM_COR_CO   0.22
EM_COR_HC   -0.22
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T2_AVG    796.23              6/3/2010 6:48:29 PM
P_INJ   121.96                Parker Hannifin-DOE
PCT_PD_INJ   4.61
WM_INJ   1.32
WM_NG   622.44
PCT_NG_PIL   0.47
PCT_MOL_NG   0.00
PCT_MOL_H2   69.06
PCT_MOL_N2  0.00
T_PZ_MBR   2442.16
T_PZ_CEA   2439.51
EM_COR_NOX   3.27
EM_COR_CO   0.12
EM_COR_HC   0.10
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(C) 50% H_2-50% NG; 40% N_2 DIL. **(D) 100% H_2; 30% CO_2 DIL.**

FIGURE 10: FLAME IMAGES FOR HYDROGEN-NATURAL GAS FLAMES FOR VARIOUS OPERATING CONDITIONS

Figure 10 shows images of the visible flame at several representative operating conditions. Figure 10a shows a 50/50 hydrogen/natural gas flame at a flame temperature of 1599 K (2419 °F) and a pressure near 12 bar (180 psi). The pilot is near neutral, meaning that the local equivalence ratio is the same as for the remaining cups. The flame is short, evenly distributed and well anchored by the six closely-spaced center cups. Figure 10b shows a flame with 10% carbon dioxide dilution operating at 12 bar (180 psi) and at a flame temperature of 1738 K (2669 °F). At these conditions the NOx emissions are 3.5 ppm. Figure 10c shows 1753 K (2695 °F) flames obtained at 12 bar (180 psi) operating pressure with a 50/50 hydrogen/natural gas blend diluted with 40% nitrogen. The figure shows that the flame fills a greater portion of the combustor volume. The flame is well distributed, as evidenced by relatively low luminosity. The NOx emissions at these conditions are 3 ppm. Finally, Figure 10d shows a 1612 K (2442 °F) flame obtained at 8 bar (120 psi) with 100% hydrogen fuel combined with 30% carbon dioxide dilution. In this case the flame resides close to the injector surface. The length of the flames is difficult to discern with certainty due to the low luminosity of the hydrogen flames.

Overall, a study of the flame during testing reveals the expected trend that with high hydrogen content in the fuel (high flame speed), flames are anchored close to the injector face. Likewise, higher equivalence ratios (flame temperature) bring the flame closer to the injector face. The flame anchoring mechanism appears to be in part tied to recirculation of combustion gases in the space between cups. As the hydrogen content in the fuel mixture is reduced or the diluent level increased, the flame stabilizes further downstream of the injector. With decreasing equivalence ratio and lower hydrogen content, the flame occupies a greater portion of the combustor volume. The flames were stable in all cases until lean blow out was imminent.

The emissions results obtained for the various fuel mixtures and diluents are shown in Figure 11 through 14. As a baseline, Figure 11 shows emissions obtained using natural gas without dilution. The figure shows that good emission results were obtained for high flame temperature, with about 7 ppm NOx at a flame temperature of 1822 K (2822 °F) when operating on a neutral pilot. About 1 ppm lower emissions were obtained with a lean pilot. At this high flame temperature, these emissions are close to the "entitlement" NOx that can be obtained with perfect premixing as measured by Leonard and Stegmaier [12].

Figure 12 shows emissions results obtained using a fuel mixture containing 50% hydrogen and 50% natural gas without dilution. Overall, the data shows excellent emissions results over a wide range of operating conditions and fuel mixtures. The emissions results were shown to be insensitive to operating pressure and pressure drop for the ranges tested and, with the exception of the emissions at 12 bar (180 psi) at 3.5% pressure drop, have the exponential dependence on temperature that is expected for well premixed flames. The emissions do depend on the pilot enrichment level, with the lowest emissions obtained when the pilot is operating neutral or slightly leaner than the surrounding mixing cups. NOx emissions of 6 ppm were achieved at a flame temperature of 1750 K (2690 °F) for this undiluted fuel mixture.

Figure 13 shows emissions obtained using fuel mixture containing 50% hydrogen and 50% natural gas various levels of nitrogen dilution. For all cases, the pilot was neutral, i.e., operating at the same equivalence ratio as the remaining cups. At a flame temperature slightly above 1750 K (2690 °F), NOx emissions of 4.5 ppm are obtained with 30% nitrogen dilution. This is substantially lower than the 6 ppm emissions recorded without dilution. The emissions drop further to 3 ppm with 40% nitrogen dilution. At a flame temperature of about 1680 K (about 2565 °F), NOx emissions of 1.5 ppm are obtained with only 10% nitrogen dilution. In comparison, about 4 ppm NOx is recorded at the same flame temperature when no dilution is used (see Figure 12). At a flame temperature of 1783 K (2750 °F) and air inlet temperature of 900 °F, the results show that 10% nitrogen dilution and 30% nitrogen dilution both result in emissions of about 7 ppm. This represents about a 3 ppm drop from the undiluted case. At a flame temperature of 1811 K (2800 °F) and an air inlet temperature of 700 K (800 °F), 10% dilution and 20% dilution both result in NOx emissions of 7 ppm.

Figure 14 shows emissions obtained using carbon dioxide (CO2) as a diluent in place of nitrogen. For a 50/50 hydrogen-natural gas mixture, NOx emissions of 3.5 ppm were recorded at a flame temperature of 1730 K (2650 °F) with 10% CO2 dilution, demonstrating that carbon-dioxide is quite effective as a diluent. For a fuel mixture with 87% hydrogen and 13% natural gas, with 10% CO2 dilution, NOx emissions of about 15 ppm are achieved at a flame temperature of 1750 K (2690 °F). The emissions drop to about 9 ppm when the dilution volume fraction is increased 20%. When comparing the effectiveness of CO2 dilution to the effectiveness of nitrogen dilution shown in Figure 13, one can see that on a volume-percent basis the CO2 is more effective. For instance, at a flame temperature of 2700 °F, 10% CO2 dilution is about as effective as 20% nitrogen dilution and 20% CO2 dilution is equally effective as 35% nitrogen dilution. However, for those diluent levels, the percentage mass flow of CO2 is only slightly lower than the percentage mass flow of nitrogen, and when taking into account the specific heat of CO2 and nitrogen, the total heat capacity of the two diluent streams at the two diluent levels are nearly equal. The conclusion is, therefore, that it is the total heat capacity of the diluent stream that is the primary driver behind the emissions reduction.

Figure 14 also shows emissions obtained when operating on 100% hydrogen fuel. Only two data points were taken for this setting, both using 30% carbon dioxide dilution. For this fuel-diluent mixture, NOx emissions of 3.6 ppm were demonstrated at a flame temperature over 1600 K (2420 °F) for the 100% hydrogen fuel. Note that these NOx emissions are slightly lower than what was measured with 93% hydrogen and 7% natural gas combined with the same amount of dilution and at the same flame temperature and nearly the same pilot setting.

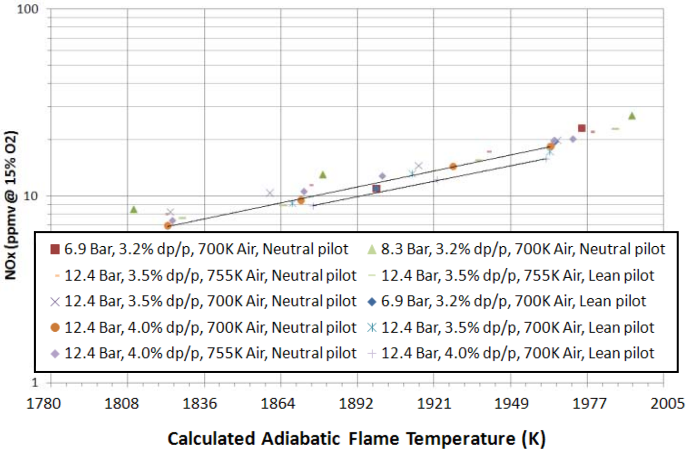

FIGURE 11: EMISSIONS RESULTS-100% NG; 0% DIL.

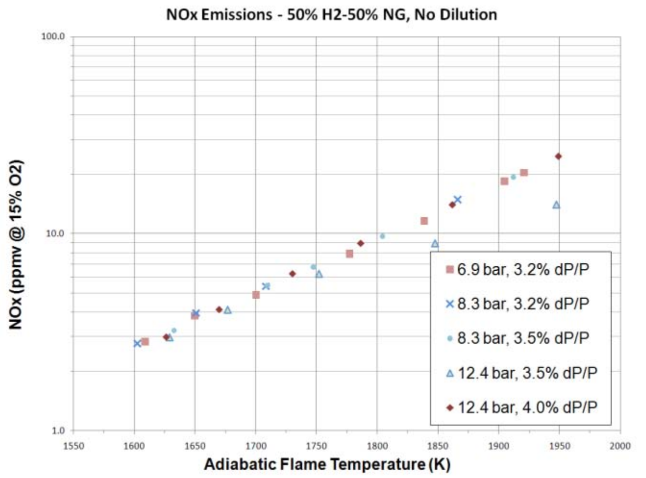

FIGURE 12: EMISSIONS RESULTS-50% H_2-50% NG; 0% DIL.

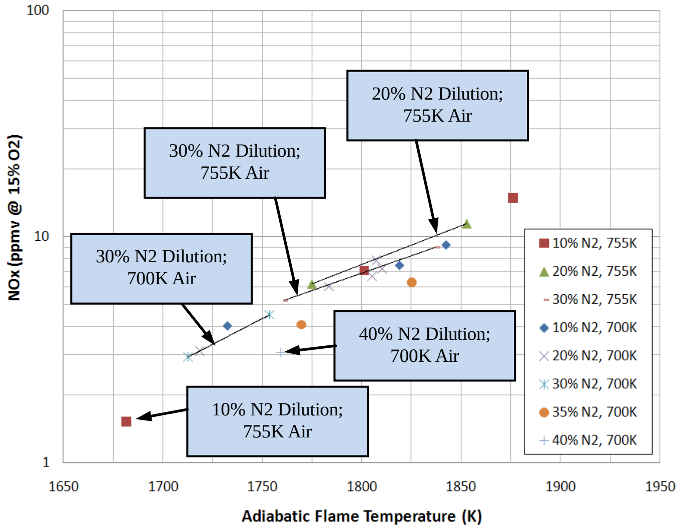

FIGURE 13: EMISSIONS RESULTS-50% H2-50% NG FUEL BLENDS; EFFECT OF NITROGEN DILUTION

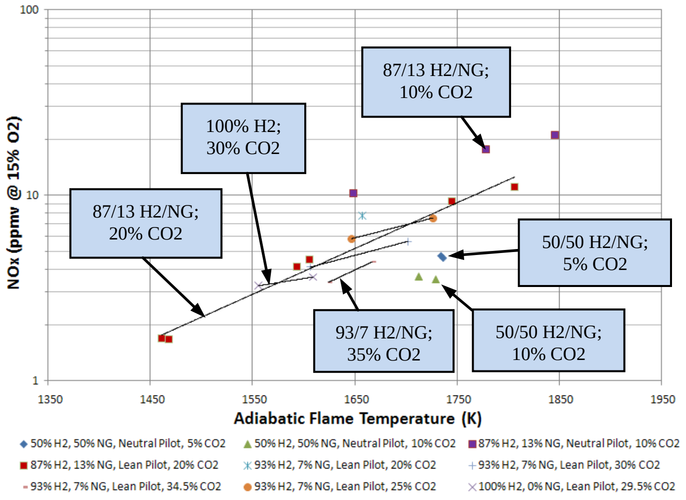

FIGURE 14: EMISSIONS RESULTS-H_2-NG FUEL BLENDS; EFFECT OF CARBON DIOXIDE DILUTION

SUMMARY

Substantial progress has been made on developing scalable injectors for hydrogen and syngas combustion in gas turbines. The full-scale injector demonstrated superior NOx emissions, enhanced flame stability and no flashback at a wide range of operating pressures using high-hydrogen fuels. Excellent part-load operability was also demonstrated for high-hydrogen fuels, and emissions were shown to be insensitive to operating pressure. Program goals of 3 ppm NOx emissions were met at an adiabatic flame temperature of 1750 K (2690 °F) for a fuel mixture containing 50% hydrogen and 1.5 ppm NOx was demonstrated at a flame temperature of 1680 K (2560 °F). After 80 hours of operation with high-hydrogen fuels the injector showed no signs of distress.

The excellent emissions and operability results obtained demonstrate the viability of the micro-mixing fuel injector concept for the challenging high-hydrogen content fuels. The technology is easily adaptable to large scale engines and future work will include developing larger scale injectors in the tens of megawatt range. Now that the basic building block for this technology has been fully validated, new combustor concepts can be designed to take advantage of Macrolamination technology for a wide range of engines and combustion systems from annular to can-annular. Further optimization work can include additional exploration of part-load operability for low-hydrogen content fuels and natural gas. This can be accomplished through innovative cup arrangement and more elaborate fuel staging. Also, further development of the mixing cup is anticipated to yield significant reduction in diluents use for high-hydrogen fuels, thereby reducing cost of operation while improving operability.

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