

Ignition and Unburned Hydrogen Escaping From Hydrogen Diffusion Jet Flame Diluted with Nitrogen

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1 Abstract

Ignition and unburned hydrogen escaping from hydrogen jet diffusion flames diluted with nitrogen were experimentally studied. The successful ignition locations were about 2/3 of the flame length above the nozzle for undiluted flames and moved much closer to the nozzle for diluted flames. For higher concentrations of the diluent or higher flow rates, there existed a region within which a diluted hydrogen diffusion flame can be ignited and burns with a stable liftoff distance. If ignition is initiated below this region, after ignition, the flame propagates quickly and attaches to the nozzle rim. The amount of unburned hydrogen in the combustion product stream increased as the nitrogen concentrations increased.

2 Introduction

Hydrogen has been considered as clean fuel for transportation, power generation, and high-speed aeropropulsion of the future. Concerns, however, have been given to its high flame temperature that can significantly lead to high thermal NO_x emissions. Thus, in this regard, controlling thermal NO_x emissions from hydrogen combustion can be of critical importance. For this purpose, diluting hydrogen with an inert gas or steam has been considered as the most effective approach to reduce the flame temperature slowing down the thermal NO_x formation mechanism [1, 2].

Since diluting the fuel jet stream with an inert gas has a strong effect on the reactant Schmidt number, Lewis number, the mixture strength and the differential diffusion of heat and mass transport among mixture components [3-5], diluted hydrogen diffusion flames might encounter with problems such as ignition difficulty and unburned hydrogen escaping through the flame tip [6]. The present work, therefore, will investigate into these issues when a hydrogen jet diffusion flame is diluted with nitrogen.

3 Experimental Apparatus

The present experimental apparatus is described in [6]. It mainly consisted of a fuel injection nozzle, a LIBS system and a laser ignition system. Using laser ignition is important because it is a non-intrusive ignition source so it does not interfere with the flow. The LIBS system consisted a laser induced breakdown chamber, a pulsed Nd-Yag laser, a Multichannel Instaspec IV CCD detection system, and a water-cool gas sampling probe. Cooling the probe to room temperature is important for two reasons: (i) to condense all the water vapor in the combustion products gases and (ii) to prevent possible reactions of the leaking hydrogen with air inside the

probe. The probe was placed about 10 mm above the flame tip for all tests. The combustion gases were sampled and delivered to the laser breakdown chamber using a vacuum pump.

4 Results and Discussions

4.1 Ignition Instability

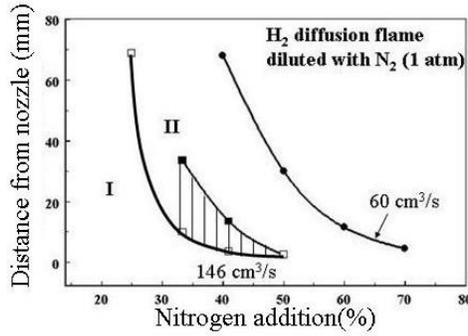


Figure 1: Ignition location as a function of nitrogen addition

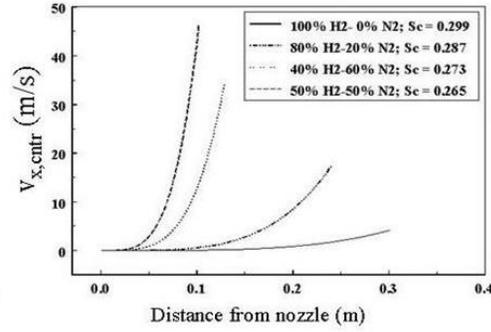


Figure 2. Effect of nitrogen content on $v_{x,ctr}$ ($121 \text{ cm}^3/\text{s}$)

Figure 1 summarizes the present results. The curves show the maximum distance from the nozzle tip within which the ignition source can be located such that after it is ignited the flame front can propagate up either to a stationary liftoff position or all the way to the nozzle and anchors to the nozzle rim. For the flow rate of $60 \text{ cm}^3/\text{s}$, the flame was ignitable at any location along the jet if nitrogen addition is less than 40%. With nitrogen dilution of 40% or higher, if the ignition source was at a location farther than 68 mm, the flame was ignited but it was blown off immediately. When the ignition source was below this location the flame was ignited and its front propagated up all the way to the nozzle rim leaving behind a nozzle-anchoring stable diffusion flame. Similar observations were also made for higher nitrogen concentrations and it was found that the ignitable distance became as short as 4.5 mm when nitrogen addition increased up to 70%.

The results obtained for $146 \text{ cm}^3/\text{s}$ flow rate, however, showed that at a given dilution concentration there exist two locations at which a diluted hydrogen flame can be ignited. Curve I represents the so-called stable-ignition location as a function of dilution concentrations. That is, if ignition is initiated at these locations, the ignited front can propagate to the nozzle. Curve II represents the highest locations at which, after ignition, the flame was stabilized with a stationary liftoff distance just few millimeters below the ignition point. Thus, the region covered by curve I and II (the shaded region) is designated as the unstable ignition region.

Based on the structure of the triple flame, the fuel concentration is assumed to be stoichiometric at the stabilization point. Thus, the propagation of the stabilization point is along the stoichiometric contour, $Y_F = 1/(1 + \nu_s)$, where ν_s is the stoichiometric ratio, and it is driven by the competition between the flame speed and the flow velocity along this contour. Using the simple jet theory, the x-component velocity along the stoichiometric contour, $v_{x,ctr}$ is obtained as

$$v_{x,ctr} = \left\{ \frac{3\rho_e (8\pi\mu)_{Sc_F}^{\frac{1}{Sc_F}-1}}{[(2Sc_F + 1)(1 + \nu_s)Y_{F,e}\rho_e]_{Sc_F}^{\frac{1}{Sc_F}}} \right\} v_e \left(\frac{2 - \frac{1}{Sc_F}}{Sc_F} \right) x^{\left(\frac{1}{Sc_F} - 1 \right)} \quad (1)$$

Where x is the axial distance, v_e is the jet velocity, $Y_{F,e}$ is the fuel mass fraction at the jet exit, Sc_F is the fuel Schmidt number, ρ is the flow density. Thus the behavior of the velocity along the stoichiometric contour depends strongly on the fuel Schmidt number. When the fuel Schmidt number is equal to 1 the velocity is constant, it decreases toward the flame tip when Sc_F is greater than 1 and it decreases toward the nozzle tip when

the fuel Schmidt number is less than 1. For hydrogen jet diffusion flame, the fuel Schmidt number is less than about 0.3 as tabulated in Table 1. Thus, the flow velocity along the stoichiometric contour always decreases toward the nozzle as shown in Fig. 2. Thus if the flame is initiated at a location that the flow velocity is within the order of the laminar flame speed it front can propagate toward the nozzle. If the flame is initiated at a location where the flow velocity is faster than the laminar flame speed the flame is blown out.

Table 1 Fuel Schmidt number as a function of nitrogen addition

N2 (%)	0	20	40	50	60	70
Sc _{H2-mix}	0.299	0.276	0.247	0.230	0.212	0.192
Sc _{H2-air}	0.299	0.287	0.273	0.265	0.255	0.245

4.2 Hydrogen escaping from the flame tip

Shown in Fig. 3 is a typical 160 nm-wide spectrum of the LIBS signals from the sampling gas withdrawn from the combustion products of a gaseous jet of 40% N₂-60% H₂ issuing into a quiescent air with and without burning. The NI-lines at 746.8, 744.2 and 742.3 nm are emitted by electronically excited nitrogen dissociated from the nitrogen molecules in the fuel stream and air. The H_α-line at 656.3 nm is emitted by electronically excited hydrogen dissociated from the hydrogen in the fuel stream. Figure 3A is for the cold flow case (no flame) and figure 3B is for the burning case. By comparing the intensities of the H_α-line in Fig. 3A and 3B it can be seen that the intensities of the H_α-line after combustion was still significant and it was about 30% of that without combustion. Thus, there must be some amount hydrogen that can escape through the flame without being burned.

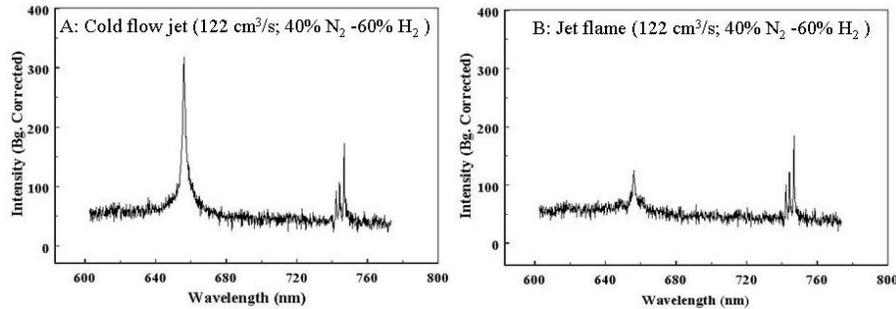


Figure 3. LIB Emission lines of NI at 746.8, 744.2 and 742.3 nm, and H_α line at 656.3 from (A) cold flow jet of 40% N₂-60% H₂; (B) combustion products gases from a 40% N₂-60% H₂ diffusion jet flame.

We define the hydrogen escape index H_{INDX} as

$$H_{INDX} = \frac{\left(I_{o,H\alpha} / I_{o,NI} \right)_{burning}}{\left(I_{o,H\alpha} / I_{o,NI} \right)_{cold\ flow}} \quad (2)$$

Where $\left(I_{o,H\alpha} / I_{o,NI} \right)_{burning}$ is the ratio of the intensities of the H_α-line to NI-lines measured for the burning case and $\left(I_{o,H\alpha} / I_{o,NI} \right)_{cold\ flow}$ is that of the measured intensities of the H_α-line to NI-lines for the unburned case (cold flow) for the same jet conditions of velocity and nitrogen addition. The defined hydrogen index is, therefore, an indicative of the presence of the hydrogen remaining in the flow after burn. As shown in Fig. 4, as nitrogen concentration increased, $\left(I_{o,H\alpha} / I_{o,NI} \right)_{cold\ flow}$ decreased, $\left(I_{o,H\alpha} / I_{o,NI} \right)_{burning}$ remained constant and

the hydrogen escape index, H_{INDEX} increased. Thus, there must be a significant increase in the unburned hydrogen in the product gases. Thus, it is clear that diluting the fuel stream with nitrogen can cause unburned hydrogen to escape through the flame tip significantly.

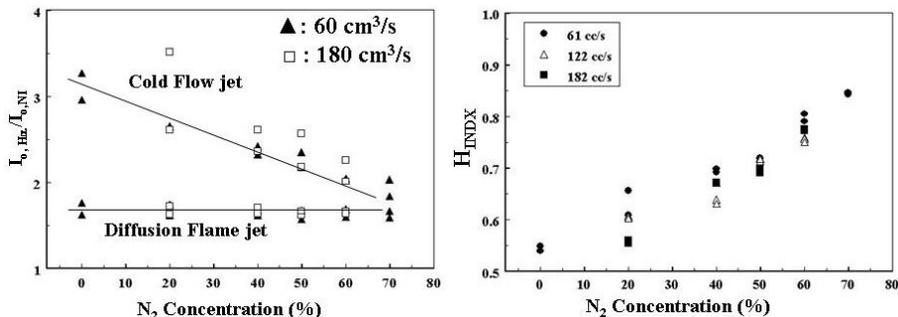


Figure 4. Emission intensity and the hydrogen escaping index as a function of nitrogen concentration.

5 Conclusions

We have conducted an experimental study on the ignition and unburned hydrogen escaping from hydrogen diffusion flames diluted with nitrogen and observed that adding nitrogen can cause difficulty in flame ignition and hydrogen leakage as unburned fuel into the combustion product stream. It has been reported in literature that diluted and undiluted hydrogen flame does not have a stable liftoff distance. However, our results show that this is true only for the undiluted case or for the case of low dilution concentrations or low jet flow rates. When the dilution concentrations or the jet flow rates are high the flame can be blown off, stabilizes at a stationary location or anchors to the nozzle rim depending totally on where the ignition spark is located. We also observed that, although the flame with a stable liftoff distance is stable, it is not desirable because it is noisy and a significant amount of unburned hydrogen can leak through the flame tip. Thus, the favorable ignition region is the one that is confined into a small region not too far from the nozzle tip. A flexible, movable ignition system, therefore, is more desirable for this application. Write here the text of another paragraph.

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