Effect of Pressure, Environment Temperature, Jet Velocity and Nitrogen Dilution on the Liftoff Characteristics of a N_2-in-H_2 Jet Flame in a Vitiated Co-flow

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Abstract

The CO_2 emission prevention advantage of generating power with high hydrogen content fuels using gas turbines motivates an improved understanding of the ignition behavior of hydrogen in premixed and partially premixed environments. Hydrogen rich fueled flame stability is sensitive to operating conditions, including environment pressure, temperature, and jet velocity. Furthermore, when premixed or partially premixed operation is needed for nitric oxide emissions reduction, a diluent, such as nitrogen, is often added in allowing fuel/air mixing prior to combustion. Thus, the concentration of the diluent added is an additional independent variable on which flame stability dependence is needed. The focus of this research is on characterizing the dependence of hydrogen jet flame stability on environment temperature, pressure, jet velocity and diluent concentration by determining the dependence of the liftoff height of lifted flames on these 4 independent parameters. Nitrogen is used as the diluent due to its availability and effectiveness in promoting liftoff. A correlation modeling the liftoff height dependence on operating conditions is developed which emphasizes the factors that bear the greatest impact on ignition behavior.
Keywords: Hydrogen; jet flames; turbulent combustion; flame propagation; autoignition

Introduction

Hydrogen (H_2) is an attractive stationary gas turbine fuel because its products of combustion do not contain carbon monoxide or Carbon Dioxide (CO_2) [1]. H_2 can be produced by reforming natural gas or by gasifying coal and when burned, the generation of power from fossil fuels in this manner is known as pre-combustion Carbon Capture and Sequestration (CCS). For gas turbine performance optimization, increased understanding of H_2 combustion stability in gas turbine environments is desired. Since the majority of stationary gas turbines are fueled by natural gas, most stationary gas turbine combustor designs operate most effectively when burning natural gas. Therefore, the knowledge base which led to the state of the art in gas turbine combustors is restricted to a single fuel. H_2, however, differs markedly in its combustion properties from natural gas (greater energy density by mass, reduced autoignition delay times, wide flammability limits, high flame speeds [1]). A key research flame beneficial for developing knowledge which is critical for optimizing stationary gas turbine combustor performance with H_2 is the lifted flame. Additional data sets characterizing lifted H_2 jet flames in gas turbine environments are beneficial for numerical model development and in developing an improved understanding of the factors that influence partially premixed flame ignition and stability. The liftoff height (L) for lifted flames is a readily measurable quantity which serves as a challenging benchmarking parameter for numerical models.

Many explanations of the flame stabilization mechanism of turbulent lifted jet flames are available [1, 2, 3] which are utilized in this research in understanding lifted H_2 jet flame stability. Peters [4] explains that quenching near the nozzle due to excessive

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local strain rates precedes liftoff. The broad flammability limits and high diffusivity of H_2, however, makes lifted H_2 flame generation difficult. For example, at atmospheric conditions and with a jet nozzle diameter of d_{jet} = 2.4 mm, the flame remains attached even at the sonic velocity of H_2 (1300 m/s). Consequently, the diluent nitrogen (N_2) is added to H_2 which encourages liftoff for subsonic jet velocities.

The primary independent variables thought to control lifted flame stability include jet velocity (V_{jet}), nitrogen dilution mole fraction (y_{N2}), environment temperature, and environment pressure in addition to d_{jet}. With the exception of d_{jet}, the impacts of each of these independent variables on L are experimentally explored in this research.

Experimental liftoff height results from prior work at atmospheric pressure motivated the development of a liftoff height correlation [1]. The correlation based on the Damköhler number, $D\alpha$, and the same correlation is applied in this research in assessing its applicability with pressure as an additional parameter. The chemical time scale, (τ_{chem}) in the denominator of $D\alpha$ motivates the utilization of a computational model in lieu of experimental measurements for complexity reduction.

Experimental Methods

Berkeley's Vitiated Co-flow Burner (VCB) [1] has been redesigned and built in the interior of a pressure chamber in adding functionality for investigating the pressure effect on lifted N_2-in-H_2 flames. An illustration of Berkeley's VCB is depicted in Fig. 1.

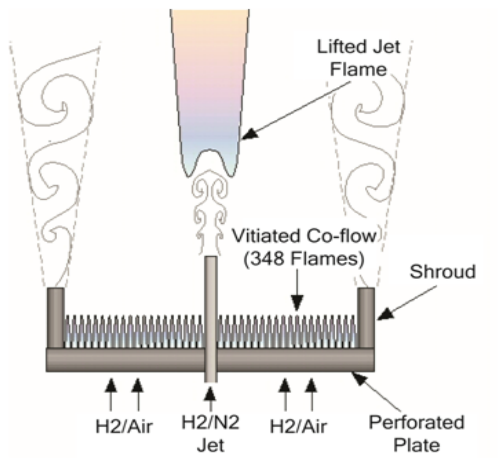

Fig. 1. Conceptual illustration of Berkeley's Vitiated Co-flow Burner (VCB).

Premixed H_2 and N_2 issue through a circular nozzle without taper and an inner diameter of d_{jet} = 2.4 mm. The nozzle is placed around a co-flow composed of combustion products of premixed H_2 and air. The premixed H_2 and air flames are stabilized on a perforated plate with 348 1.6 mm diameter perforations arranged hexagonally with 4.8 mm separation between perforations. The total blockage ratio is 89%. The jet nozzle extends 25 mm above the base of the co-flow burner plate, and a 19 mm tall shroud is placed around the co-flow which reduces outside air (or vitiated air) entrainment while maintaining visibility of the jet nozzle. A blunt-edge nozzle (also known as a squared-off nozzle) is used because early scoping work indicated that changing from a blunt edge nozzle to a tapered nozzle bears no discernible impact on L. It is assumed that the insensitivity of liftoff height on nozzle geometry occurs because the liftoff heights generated with this burner configuration are sufficiently far away from the nozzle ($L/d \geq 10$ in all cases) for negligible liftoff height contributions from local recirculation effects around the nozzle exit. Since a blunt-edge nozzle facilitates modeling (primarily because meshing a square nozzle is significantly less complicated), a square nozzle is used here. Thin walled tubes are avoided in reducing heat transfer from the co-flow products to the jet reactants. Simple 1D heat transfer calculations where performed [1] which show that even with the most conservative assumptions the fuel temperature would rise by only 28 K. These calculations indicated that fuel temperature increases in the jet nozzle are negligible.

The redesigned burner includes minor modifications in the design of the co-flow which were necessary for interfacing the hardware with a pressure chamber. Additionally, a spark-plug igniter is added to the co-flow as well as an additional igniter downstream for ignition of the jet. The pressurized VCB is shown in Fig. 2.

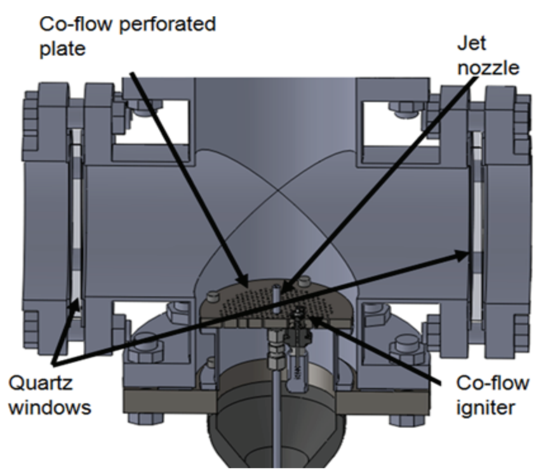

Fig. 2. Pressurized VCB showing the igniter and windows for viewing access.

The jet nozzle height is adjustable between 0 mm and 40 mm, though in this research it is held constant at 25 mm. 15 cm diameter windows allow viewing access used for schlieren imaging and direct imaging. Direct imaging was opted for L measurements due to difficulties with jet product accumulation in the stagnant regions between the co-flow and the windows which commonly obscures the schlieren images.

Typically, heat loads to the walls of the combustion chamber exceed levels at which reasonable methods for achieving steady state conditions via traditional wall cooling techniques can be employed. Instead, the burner operates in a quasi-transient mode, where the walls do not reach steady state conditions, while liftoff characteristics remain steady over the time span during which data is gathered. The co-flow burns for 6.5 seconds before jet reactant flow begins. The jet flows for 2 seconds and data is gathered for the last 500 ms of this time period. The timing sequence is determined through an iterative process achieving a workable balance between obtaining manageable combustor wall heating per experiment, eliminating flow transients at startup, and capturing a statistically significant mean value for L. The adequacy of the time span over which the mean liftoff height is determined is assessed by ensuring that a minimum number of repeating turbulence events occurs within the measurement span and that the pressure and flow rate variation over the selected time span is acceptably low. The minimum number of repeating turbulence events is estimated by counting the number of times L oscillates during the chosen time span. Typical oscillation counts vary between 10 and 20 occurrences over the chosen time span.

Figure 3 shows the pressure trace for a representative experiment. Pressure variability in the final 500 ms of the test is acceptably low. Concurrently, Fig. 4 demonstrates acceptably low variability in N_2 and H_2 flow rates during the time period of data gathering.

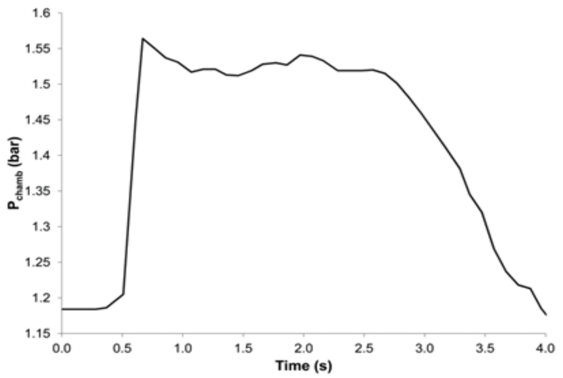

Fig. 3. Pressure trace for a representative experiment with a quasi steady-state pressure of ~ 1.5 bar.

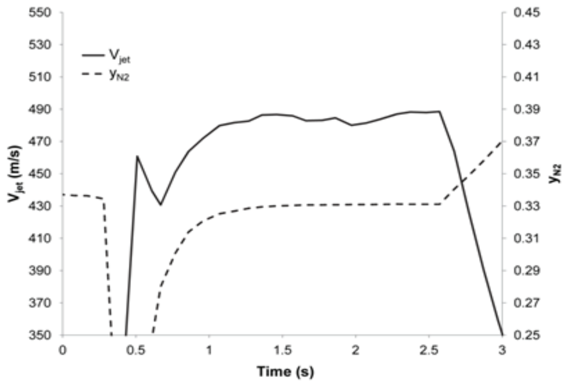

Fig. 4. y_{N2} and V_{jet} traces corresponding to the pressure trace given in Fig. 3. The quasi steady-state y_{N2} value is 0.33 and the quasi steady-state V_{jet} target is ~500 m/s for this example case.

All reactant flow rates are controlled via sonic flow control orifices. H_2 and N_2 timing control is accomplished with solenoid valves. The ignition system timing and valve actuation is controlled via LABVIEW. A high speed camera is triggered by illuminating a light emitting diode in the field of view and the camera's control software is set to begin capturing video data when the light is illuminated with LABVIEW. Video data is taken at 1000 Hz.

The mean value of L is determined through analysis of high speed video data using MATLAB. An example video snapshot is given in Fig. 5.

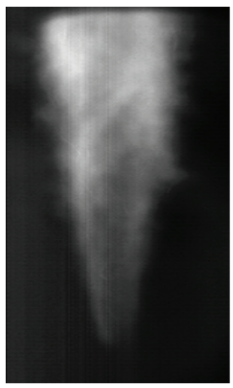

Fig. 5. Example snapshot of a lifted N_2-in-H_2 jet flame captured from high speed direct imaging.

The post-processing program scans the selected video still-frames starting at the bottom of the image and moving upward until the mean value of the monochromatic signal for the central 42 pixels exceeds a threshold of 60 (a value of 256 represents pixel saturation and a value of 1 represents an absence of light). The 500 ms of video is broken into 50 equally separated frames (in time), and the mean value of L determined from this set of frames is taken as L.

As described in section 1, the independent variables explored in this research include environment temperature, environment pressure (P_{chamb}), y_{N2}, and V_{jet}. The environment temperature with the VCB is dependent on the equivalence ratio of the co-flow ($\varphi_{co\text{-}flow}$ determines $T_{co\text{-}flow}$). The impact of environment temperature is assessed in a sensitivity analysis of L to $\varphi_{co\text{-}flow}$, while the effect of pressure is investigated more heavily. $\varphi_{co\text{-}flow}$ is held constant at $\varphi_{co\text{-}flow} = 0.15$ for pressure investigations in keeping the data set size manageable, which corresponds to a co-flow temperature of ~664 K [1].

Numerical Simulations

The correlation utilized to model the liftoff height dependence of diluted hydrogen flames on the operating conditions is based on the Damköhler number of the flow and thus requires an adequate assessment of the characteristic chemical time scale, τ_{chem}. In the suggested correlation the characteristic chemical time scale is represented by the quotient of flame thickness and flame speed, referred to as flame time, τ_{flame} [1]. Flame stabilization occurs if the flame time is minimized.

In this study detailed numerical simulations using a one-dimensional combustion model are applied in computing τ_{flame}. The model accounts for detailed chemical kinetics and detailed physical transport including differential diffusion [5]. The GRI 3.0 reaction mechanism for methane oxidation including a subset for the nitrogen chemistry [6] is used to model chemical kinetics. In order to identify the conditions at which flame time exhibits its minimum the flame speed and flame thickness of laminar flat flames [7] are determined for different jet compositions, equivalence ratios in the co-flow and pressures.

Results and Discussion

Liftoff height dependence on P_{chamb}, $\varphi_{co\text{-}flow}$, y_{N2}, and V_{jet}, has been characterized with particular focus on pressure dependence. The sensitivity of L with respect to these parameters was characterized first for determination of the most influential variables. The sensitivity analysis was conducted for a base case with $\varphi_{co\text{-}flow} = 0.15$, $y_{N2} = 0.33$, $V_{jet} = 400$ m/s, and $P_{chamb} = 1.5$ bar using the following expression.

$$S_{y,dy} = \frac{(L_{y+dy} - L_y) - (L_{y-dy} - L_y)}{dy/y} \qquad (1)$$

The sensitivity analysis results are summarized in Fig. 6:

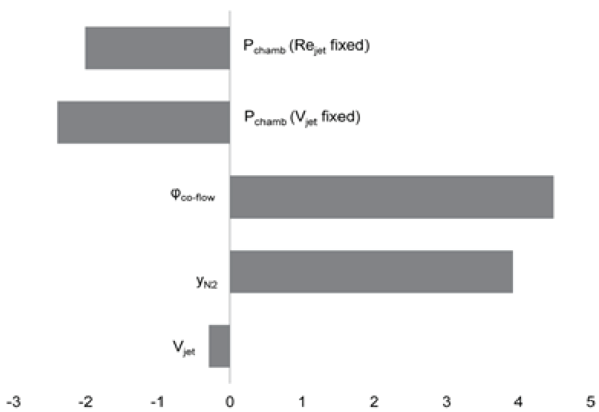

Fig. 6. Sensitivity analysis showing the sensitivity of L with respect to V_{jet}, y_{N2}, $\varphi_{co\text{-}flow}$, and P_{chamb} with both V_{jet} and Re_{jet} fixed.

0.1 bar was chosen as the increment value (dy) for P_{chamb} (both with Re_{jet} and V_{jet} fixed) sensitivity, 0.005 for $\varphi_{co\text{-}flow}$ sensitivity, 0.04 for y_{N2} sensitivity, and 100 m/s for V_{jet} sensitivity. As expected, L exhibits negative sensitivity to P_{chamb}, particularly when V_{jet} is held constant because pressure increases lead to V_{jet} decreases when Re_{jet} is fixed causing reduced liftoff height reductions. Also as expected, a strong positive sensitivity of the liftoff height with respect to y_{N2} is observed. Nitrogen addition increases jet momentum which increases fluid velocity downstream of the nozzle exit and reduces the flame propagation speed. Both of these factors bear positive contributions toward V_{jet} - L sensitivity. Surprisingly, a strongly positive sensitivity with respect to co-flow equivalence ratio is observed. The increase in co-flow equivalence ratio leads to an increase in flame speed which serves to reduce the liftoff height [1]. However, since the co-flow air flow rate is held constant as equivalence ratio is varied with these experiments, the increased co-flow velocity accompanying stoichiometry increases likely effects L sensitivity more than temperature under these conditions. In short, as $\varphi_{co\text{-}flow}$ increases, the accompanied temperature increase causes an additional co-flow velocity increase (accompanied by the co-flow velocity increase contribution from the co-flow H_2 flow rate increase) because of the vitiated air density reduction. Previous research by Montgomery et al. [8] and others explores and explains liftoff height dependence on co-flow velocity.

The dependence of L on P_{chamb} is characterized for various values of V_{jet} and y_{N2} as well as cases where Re_{jet} is held constant since it is unclear whether fixing V_{jet} or Re_{jet} is most appropriate. Figure 7 shows a comparison between results where L pressure dependence is characterized for $V_{jet} = 400$ m/s and 500 m/s for $y_{N2} = 0.33$ and $\varphi_{co\text{-}flow} = 0.15$.

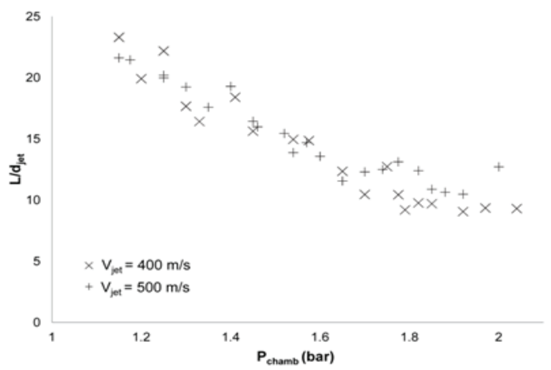

Fig. 7. Experimental measurements for L normalized by d_{jet} versus P_{chamb} with constant jet velocities of V_{jet} = 400 m/s and 500 m/s, and with y_{N2} = 0.33 and $\varphi_{co\text{-}flow}$ = 0.15 ($T_{co\text{-}flow}$ = 664 K).

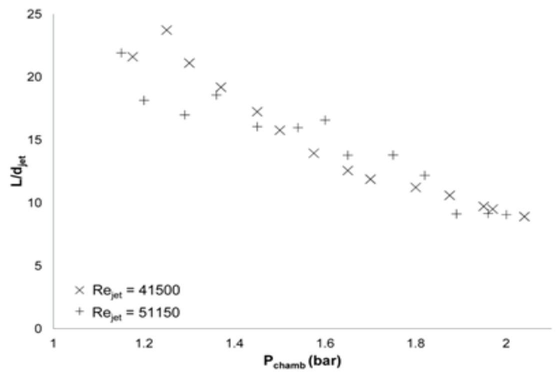

Fig. 8. Experimental measurements for L normalized by d_{jet} versus pressure at constant jet Reynolds numbers of Re_{jet} = 41500 and 51150, and with y_{N2} = 0.33 and $\varphi_{co\text{-}flow}$ = 0.15 ($T_{co\text{-}flow}$ = 664 K).

Consistent with the sensitivity analysis, L pressure trending is nearly identical for the two V_{jet} values. L insensitivity to V_{jet} for fully turbulent jet flames can be explained in a similar manner that flame length insensitivity to V_{jet} is explained for attached turbulent jet flames. As jet velocity increases, turbulent diffusivity (D_t) increases, leading to faster mixing which can balance the reduction in flow time [9].

A pressure sweep where Re_{jet} is fixed instead of V_{jet} as pressure increases further demonstrates L insensitivity to V_{jet}.

The value of V_{jet} at 1.15 bar (the minimum pressure explored due to apparatus limitations) is 400 m/s and 500 m/s for Re_{jet} = 41500 and 51150, respectively. As P_{chamb} is increased, the reduction in V_{jet} for Re_{jet} = 41500 and 51150 scales by an equivalent factor, so Fig. 8 demonstrates L insensitivity to Re_{jet} which does not diminish with velocity reductions resulting from increases in pressure up to 2 bar.

In assessing conditions for which D_t does not scale linearly with V_{jet}, an addition pressure sweep where y_{N2} = 0.20 demonstrates that L insensitivity to V_{jet} occurs only when turbulence intensity is great enough to be considered "fully turbulent", or for conditions where Re_{jet} exceeds a threshold value.

As with Fig. 8, the value of V_{jet} at P_{chamb} = 1.15 bar is equivalent for the two cases considered. The reduction in Re_{jet} resulting from the reduction in y_{N2}, however, introduces a significant L sensitivity on V_{jet}. As P_{chamb} is increased, the reduction in V_{jet} for the constant Re_{jet} cases causes a flame stabilization location departure between the constant Re_{jet} cases and constant V_{jet} cases. This result suggests that for Re_{jet} = 31000, turbulence intensity is not great enough for linear D_t - V_{jet} scaling. Scaling laws used for understanding flame length insensitivity (shown in Fig. 10) on V_{jet} apply in a similar manner in explaining liftoff height insensitivity on V_{jet} shown here.

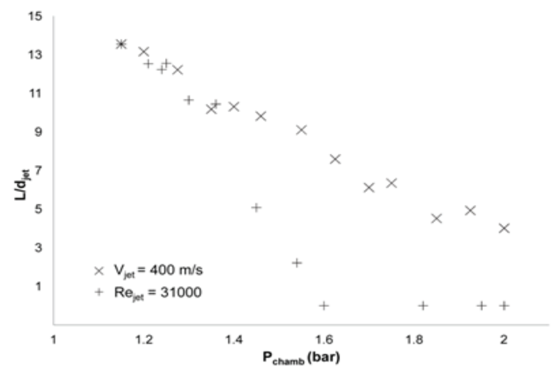

Fig. 9. Experimental measurements for L normalized by d_{jet} versus pressure for a constant jet velocity of V_{jet} = 400 m/s and a constant jet Reynolds number of Re_{jet} = 31000, and with y_{N2} = 0.20 and $\varphi_{co\text{-}flow}$ = 0.15 ($T_{co\text{-}flow}$ = 664 K).

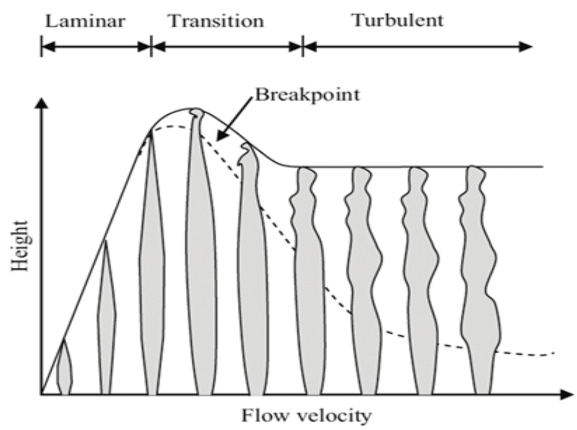

Fig. 10. Qualitative depiction of flame length versus jet flow velocity showing flame height insensitivity on jet flow velocity for fully turbulent jet flames [9].

The elevated pressure liftoff height data is next correlated with the Damköhler number ($D\alpha$) using a similar methodology employed by North et al. [1].

The data is first plotted together versus P_{chamb} in understanding the level of scatter encountered as the chosen independent parameters are varied.

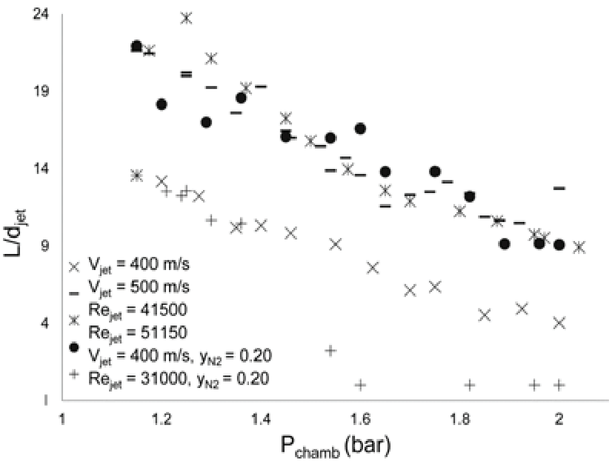

Fig. 11. Liftoff height data summarized in a single plot used for correlation formulation.

Cases with y_{N2} = 0.33 exhibit minimal dependence on jet velocity and the dependence on the choice of holding V_{jet} or Re_{jet} constant is also weak for y_{N2} = 0.33. A departure occurs when y_{N2} decreases as shown with the y_{N2} = 0.20 data.

The Damköhler number is formulated such that τ_{flow} represents an estimated time which the fluid travels before reaching a 'minimum' flame time [1]. V_{jet} is weighted by the square root of the jet density to surrounding fluid density in incorporating the momentum increase effect imparted by N_2 dilution onto τ_{flow}. τ_{chem} is computed as the ratio of the flame thickness (δ) to the laminar flame speed (S_L). This formulation presupposes that flame propagation effects bear a dominant role in influencing the stabilization location, which has been shown a reasonable assumption for $\varphi_{co\text{-}flow} < 0.20$ [1]. τ_{chem} is therefore hereafter denoted as τ_{flame}.

$$D\alpha = \frac{\tau_{flov}}{\tau_{chem}} = \frac{z_{\bar{\varphi}mr} / (V_{jet}(\rho_{jet}/\rho_{\infty})^{1/2})}{\delta / S_L} \qquad (2)$$

Prior work analyzing atmospheric (and unconfined) jet flames [1] with similar independent parameter choices indicated that the local equivalence ratio which minimizes τ_{flame} is a consistent value of $\bar{\varphi}_{mr}$ = 1.5. For the elevated pressure conditions, however, the minimum is slightly leaner as outlined in Figs. 12 and 13.

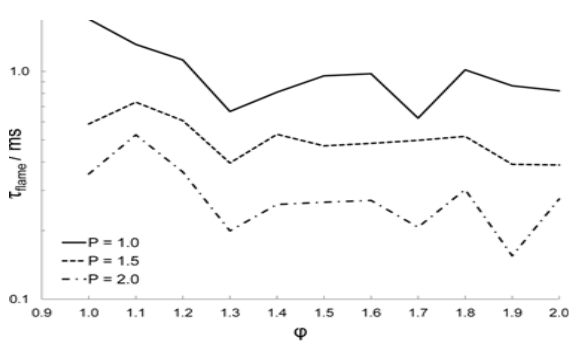

Fig. 12. Flame time versus local equivalence ratio for y_{N2} = 0.33 and $\varphi_{co\text{-}flow}$ = 0.15 for selected pressures.

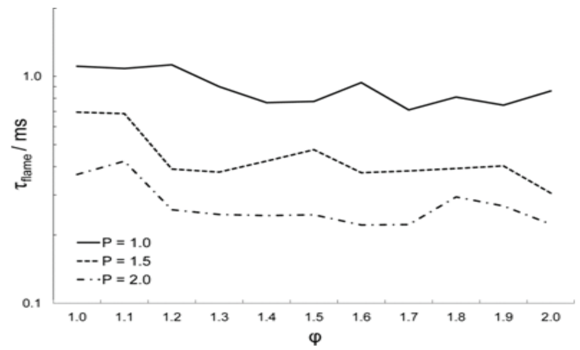

Fig. 13. Flame time versus local equivalence ratio for y_{N2} = 0.20 and $\varphi_{co\text{-}flow}$ = 0.15 for selected pressures.

The base cases with y_{N2} = 0.33 exhibits a local minimum when $\bar{\varphi}_{mr}$ = 1.3. Other local minimums exist, though it is reasonable to postulate that the flame most often anchors where the local minimum in τ_{flame} is closest to the stoichiometric value because the flame propagates toward the nozzle until the steep rise observed for $\bar{\varphi}_{mr} < 1.3$. With y_{N2} reduced to 0.20, however, the flame time sensitivity on $\bar{\varphi}_{mr}$ reduces. Furthermore, the local minimum in τ_{flame} is a function of pressure for y_{N2} = 0.20. The reduced sensitivity likely increases the impact of factors other than τ_{flame} on the liftoff height. Nonetheless, the local minimum observed for P = 1.4 is selected for implementation into the Da correlation for the y_{N2} = 0.20 data because this is the minimum for the atmospheric pressure cases. Consequently, this is the only flame time minimum for which the jet velocity is equivalent between the cases where V_{jet} and Re_{jet} are held constant with the intent of understanding the observation that fixing this independent parameter becomes important when y_{N2} is reduced.

The axial location (at the jet centerline) where the minimum in flame time occurs is computed from [11]:

$$z_{\bar{\varphi}mr} = \left[4 \frac{y_{yet}}{y_{mr}} \left(\frac{\rho_{jet}}{\rho_{\infty}} \right)^{1/2} - 5.8 \right] d_{jet} \qquad (3)$$

It is assumed here that the distance between the real stabilization location (which is not in general located on the jet centerline) and the axial location where $\overline{\varphi}_{mr}$ resides can be neglected [1]. The resulting dependence of the normalized liftoff heights measured and the Damköhler number is presented in Fig. 14:

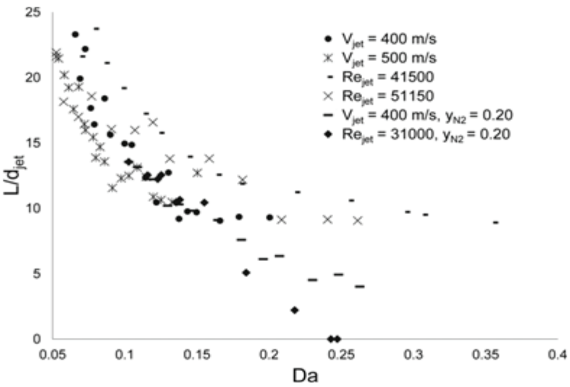

Fig. 14. Normalized measured liftoff heights versus $D\alpha$ for all data presented.

Generally, the L/d_{jet} data trends surprisingly well with Da. Trending is poor for y_{N2} = 0.20 which is attributable to the additional effect of turbulent diffusivity scaling nonlinearly with V_{jet} for lower Reynolds number jets – an effect which is not included with this correlation.

Conclusions

Improvements in the understanding of stability and ignition for diluted premixed and partially premixed H_2 flames are beneficial for H_2 optimized gas turbine combustor development. Lifted flames are an attractive target flame for numerical model benchmarking and flame stabilization theory improvements because the measurable liftoff height is dependent on chemical, transport, and fluid dynamic effects. Numerical models capable of accurately replicating experimentally measured liftoff heights under all relevant conditions can be used in gas turbine combustor development with increased confidence because the complexities which inherently influence the stabilization location in laboratory flames are equally applicable in gas turbine environments. This paper presents a data set characterizing the stabilization height of turbulent N_2-in-H_2 jet flames in a vitiated co-flow versus pressure for selected values of V_{jet} and y_{N2} and with $\varphi_{co\text{-}flow}$ held constant at 0.15 in keeping the independent parameter space manageable. L dependence on pressure is negative indicating that the reduction in flame time resulting from pressure increases is the dominant factor imparted by pressure effects. For high jet Reynolds numbers ($Re_{jet} \geq 41500$), L is insensitive to V_{jet} which indicates that the rate at which turbulent diffusivity increases balances the reduction in flow time as V_{jet} is increased for the conditions investigated. When Re_{jet} is reduced to $Re_{jet} = 31000$ by reducing the concentration of the N_2 diluent, however, L sensitivity to V_{jet} becomes positive. A sensitivity analysis confirms L insensitivity to V_{jet} for high turbulence intensity. The sensitivity analysis also indicates highly positive L sensitivity to $\varphi_{co\text{-}flow}$ and y_{N2}, whereas L sensitivity to pressure is highly negative both when V_{jet} is held constant and Re_{jet} is held constant as pressure is varied. A previously developed method for correlating liftoff height data in vitiated co-flows for $0.15 < \varphi_{co\text{-}flow} < 0.20$ with a specially formulated Damköhler number was utilized which exhibits good trending with experimental data. Consequently, the Damköhler number can be used as a means of estimating the liftoff height when experimental data is nonexistent for guiding future experimental and numerical work when pressure is parameterized.

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