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Stability of Hydrogen/Hydrocarbon Blended Fuel Flames

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An experimental and numerical investigation is presented to delineate the effects on the stability of natural gas jet flames when hydrogen is added. It is observed that the flame liftoff height decreases nonlinearly with the addition of hydrogen in a natural gas flame. Blowout velocity sharply increases with the increase of hydrogen content in the mixture. It is evident that hydrogen fuel dominates the stability behavior of the mixed fuel. The turbulent mixing rate of nonreacting hydrogen/hydrocarbon hybrid fuel was computed numerically. The Favre averaged Navier–Stokes equations were solved numerically, and the local concentrations of hydrogen and hydrocarbon fuels were calculated for different inlet mixture conditions. The significance of the local concentration on the flame stability mechanism is presented.

Nomenclature

B_H = function of mass diffusivity of atom H
B_O = function of mass diffusivity of atom O
B_{OH} = function of mass diffusivity of radical OH
C_r = concentration of the reactant mixture
D_H = binary diffusion coefficient of H atom
D_O = binary diffusion coefficient of O atom
D_{OH} = binary diffusion coefficient of OH radical
d_j = burner diameter
H = characteristic flame length, Eq. (4)
h = flame length
k' = general rate of reaction for hydrocarbon fuel
L_H = normalized liftoff height
R_H = Reynolds number based on characteristics flame length H
Re_j = jet exit Reynolds number
r = multiplication factor
$(S_L)_{\max}$ = maximum laminar flame speed for pure fuel
U_b = blowout velocity
U_n = normalized blowout velocity
X_i = species mole fraction
Y = fuel mass fraction
Y_s = stoichiometric fuel mass fraction
μ = molecular (laminar) dynamic viscosity
μ_F = dynamic viscosity of fuel
ρ = density
ρ_A = air density
ρ_F = fuel density

Subscript

s = stoichiometric
EFI = equivalent equivalence ratio
CFI = equivalent ratio based on CH_4
HFI = equivalent ratio based on H_2

Introduction

RECENTLY hydrogen/hydrocarbon blends have received increased attention as alternative fuels for numerous power-generation applications. Lean burning of hydrocarbons yields exceptionally low pollutant emissions and superior combustion characteristics. However, the lean flammability limit of most hydrocarbon fuels makes achieving a stable combustion condition in the lean burning regime extremely difficult. In contrast, because of the extremely low lean flammability limit, burning of hydrogen is quite attractive. However, severe flashback and difficult storage problems due to its low volumetric density make the use of hydrogen in most of the practical combustion applications difficult. In this context, a hydrogen/hydrocarbon hybrid fuel is an attractive solution. The relatively slow reaction rate of a typical hydrocarbon fuel can be accelerated by mixing it with hydrogen, which results in an improved ignitability and flame holding.

The stabilization mechanism of jet diffusion flames is a long-time interest in combustion research due to numerous practical applications. Previously, several investigators have suggested that the isothermal mixing process of a nonburning fuel jet and an oxidizer determines the stability behavior of their turbulent jet diffusion flames.[1–3] These studies have also shown that it is possible to develop empirical expressions from known mixing behavior of the flow to determine the liftoff and blowout characteristics of the flame. Although these investigations have included a wide range of fuels and flow conditions, very little information is available regarding the stability mechanism of composite or mixed fuels. Kalghatgi[4] studied the blowout velocity of gas mixtures such as methane/air, methane/carbon dioxide, propane/air, and propane/carbon dioxide. Broadwell et al.[1] extended that study to derive an expression for the blowout velocity of gas mixtures. However, none of these studies included the stability mechanism of hydrogen/hydrocarbon mixtures. Furthermore, some investigators have identified that, although the prediction of blowout velocity through these models is good for hydrocarbon fuels, its agreement with measurements is poor for pure hydrogen fuel. In this context, we felt that further investigation was required to understand the stability mechanism of jet diffusion flames of hydrogen/hydrocarbon fuel blends.

In this paper, a study is presented to quantify the effects of hydrogen addition on the stability of hydrocarbon jet diffusion flames. Flame stability was studied for different contents of hydrogen in natural gas/hydrogen fuel mixture. The result was explained in the context of existing analytical and empirical formulation. The

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turbulent mixing rate of a nonreacting blended fuel was solved numerically, and the local concentrations of fuel/air were calculated for different inlet mixture conditions. The effects of the local concentration field on the flame stability mechanism were also analyzed.

Analysis

Liftoff and Blowout of Turbulent Jet Diffusion Flames

Generally, the reaction zone of a turbulent jet flame is considered to be located at a certain distance from the burner exit where the average concentration of the fuel in its isothermal mixture with surrounding air renders its flame speed maximum.[3] Hence, an estimation of the local concentration of an isothermal fuel jet issued into air yields a good prediction of the liftoff height. Kalghatgi[4] proposed the semi-empirical correlation to calculate the liftoff height based on the maximum laminar flame speed,

$$\frac{\rho_F (S_b)_{\max} L_H}{\mu_F} = 50\left(\frac{U_b}{(S_b)_{\max}}\right)\left(\frac{\rho_F}{\rho_A}\right)^{1.5} \tag{1}$$

This expression predicts liftoff height for hydrocarbon fuels with considerable accuracy; however, the previous studies showed that it did not work well for hydrogen.[3]

Some theories on the blowout of turbulent diffusion flames emphasize that the imbalance between the local flow velocity and turbulent flame speed is the primary cause of flame blowout. When the local flow velocity increases to a critical value, combustion cannot be sustained, and flame extinction occurs. In accord with these concepts, flame blowout is due simply to a flow equilibrium processes. Other investigators have explained flame blowout behavior based on the mixing of large-scale turbulent structures. These models are based primarily on the competition between the turbulent mixing time and combustion/ignition time in large-scale turbulent structures. Kalghatgi[4] proposed the following correlation to estimate blowout velocity of jet flames:

$$[U_b/(S_b)_{\max}](\rho_F/\rho_A)^{1.5} = 0.017 Re_H \left(1 - 3.5 \times 10^{-6} Re_H\right) \tag{2}$$

The Reynolds number R_H is given by

$$R_H = \rho_F (S_b)_{\max} H / \mu_F \tag{3}$$

The characteristic length H is the distance along the burner axis where the mean fuel concentration falls to its stochiometric value and is estimated by

$$H = 8\left[(Y/Y_s)(\rho_F/\rho_A)^{0.5} - 5.8\right] r_j \tag{4}$$

The predictions showed a qualitative agreement with measurements for most hydrocarbon fuel mixtures,[5] however, yielded a poor agreement for hydrogen/air mixtures.

Prediction of Liftoff Height and Blowout Velocity of Composite Fuel Turbulent Flames

The current analytical and semi-empirical models for liftoff height and blowout velocity of turbulent diffusion flames can predict the stability behavior of most hydrocarbon fuels with considerable accuracy. Several studies showed that experimental results agreed well with the predicted value.[1–3] On the other hand, because of crucial assumptions, in the case of a hydrogen flame, the model predictions do not match well with the experimental findings. Furthermore, the validity of these models has not yet been investigated for hydrogen/hydrocarbon mixtures. To use these models for hydrogen/hydrocarbon mixture flames several parameters such as maximum laminar flame speed $S_{L\,\max}$, stochiometric mass fraction of fuel f_S, and equivalence ratio of composite fuels are to be properly defined and estimated. In the following section, the approach used in the present investigation to define and estimate these parameters is discussed.

Laminar Flame Speed of Blended Fuels

Experimental or theoretical studies in literature to predict the maximum laminar flame speed of a mixture of fuels are limited. Although several studies have delineated the effects of inert diluents on flame speed, those results are inapplicable to the present study because both components of the mixture are reactive. A study with moist carbon monoxide has shown that the flame speed is raised considerably by an addition of a very small amount of hydrogen or hydrogen-containing fuels.[3] One way of estimating the maximum laminar speed of hydrogen/hydrocarbon composite fuels is to assume a linear dependence of the flame speed with the relative concentration of each constituent of the mixture. Yu et al.[6] have shown that the laminar flame speed varies quasi linearly with a specially defined parameter to indicate the contribution of hydrogen in the composite fuel. However, the parameter varies nonlinearly with fuel mole fraction, and thus, the laminar flame speed has a nonlinear relation with hydrogen content in the mixture. Furthermore, two crucial assumptions, that is, complete oxidation of hydrogen and nonexistence of competitive reactions made in deriving the parameter, make this concept less attractive for use in diffusionally controlled flames. In this context, a diffusion theory of flame speed could be a good approximation for a mixture. The theory by Tanford and Pease (see Ref. 7, pp. 298–302), assumed that the rate of diffusion of active radicals into the unburned gas determines the magnitude of the flame velocity. Their results also indicated that the equilibrium concentration of hydrogen atoms is an important factor in determining the flame velocity. Later, the theory was modified, and the concentrations of hydroxyl radicals and oxygen atoms were also taken into account:

$$S_b = \sqrt{\frac{rC_r}{X_i} k' \left(\frac{D_{\mathrm{H}} p_{\mathrm{H}}}{B'_{\mathrm{H}}} + \frac{D_{\mathrm{OH}} p_{\mathrm{OH}}}{B'_{\mathrm{OH}}} + \frac{D_{\mathrm{O}} p_{\mathrm{O}}}{B'_{\mathrm{O}}}\right)} \tag{5}$$

For most of the hydrocarbon fuels, the value of k' is 1.4×10^{11} cm^3/mole · s and r is a multiplication factor calculated based on the total number of moles of water vapor and carbon dioxide required to form per mole of hydrocarbon. Later Dugger et al. (see Ref. 7, p. 313) combined Tanford–Pease theory and Zel'dovich–Frank–Kamenetsky–Semenov theory together and formed a unique correlation of maximum laminar flame speed $S_{L\,\max}$ and a combination of partial pressures $6.5 p_{\mathrm{H}} + p_{\mathrm{OH}} + p_{\mathrm{O}}$. The maximum laminar flame speed of fuel blends (methane and hydrogen) calculated from the Dugger et al.[7] correlation and compared with the experimental data of Yu et al.[6] is shown in Fig. 1. The chemical kinetics computational code CHEMKIN was used to compute the equilibrium compositions of H, O, and OH for different hydrogen/natural gas mixtures.

Equivalent Fuel Formula and Stochiometric Fuel Mass Fraction

An equivalent representation of hydrogen/hydrocarbon composite fuels in terms of fuel formula C_xH_y is required to calculate the stochiometric fuel mass fraction Y_s (Choudhuri and Gollahalli[8]).

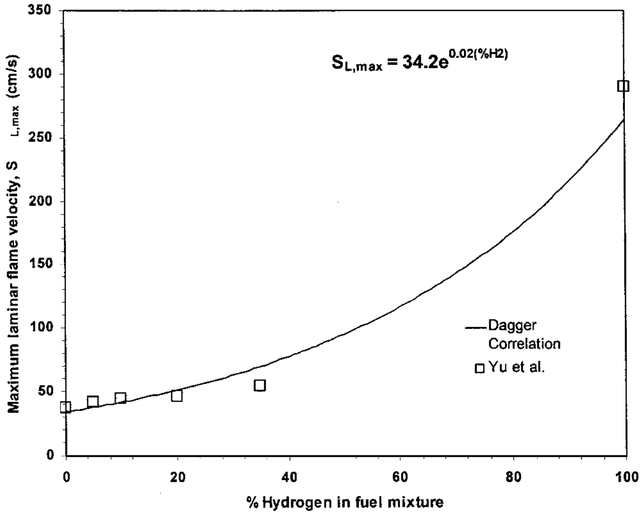


Fig. 1 Variation of maximum laminar flame speed $S_{L,\max}$ with percent hydrogen in the fuel mixture.

Table 1 Equivalent fuel formulas (C_xH_y) (Choudhuri[9])

%CH4–H2%	x	y	Y_s
100–0	1	4	0.0548
95–5	0.99	3.98	0.0547
90–10	0.986	3.972	0.0547
80–20	0.969	3.938	0.0546
65–35	0.937	3.938	0.0544

For different hydrogen contents in hydrogen/natural gas mixture, the calculated values of x and y and corresponding Y_s are given in Table 1 (see Ref. 9).

Equivalence Ratio for Composite Fuel

An effective equivalence ratio for composite fuels needs to be developed. If the mole fractions of the hydrogen, hydrocarbon fuel (methane in the present study), and air are C_{H_2}, C_{CH_4}, and C_A, respectively then to oxidize C_{H_2} amount of hydrogen totally, $C_{H_2}/(C_{H_2}/C_A)_s$ of air will be needed. If the remaining air is used to oxidize the hydrocarbon fuel, an effective equivalence ratio (EFI) can be defined as

$$\mathrm{EFI} = \frac{C_{CH_4}/\{C_A - [C_{H_2}/(C_{H_2}/C_A)_s]\}}{(C_{CH_4}/C_A)_s} \tag{6}$$

Two other equivalence ratios based on pure methane (CFI) and pure hydrogen (HFI) are also defined by considering only methane or hydrogen in the mixtures:

$$\mathrm{CFI} = \frac{C_{CH_4}/C_A}{(C_{CH_4}/C_A)_s} \tag{7}$$

$$\mathrm{HFI} = \frac{C_{H_2}/C_A}{(C_{H_2}/C_A)_s} \tag{8}$$

The details of the development of these equations and calculation methodology may be found elsewhere.[9]

Experimental Procedure

The circular fuel burners used in this experiment consisted of sharp-edged stainless steel tubes of 1, 2, 3.8, and 4.5 mm i.d., which injected fuel into a slow moving stream of air (<0.5 m/s). All of the burners had a same wall thickness of 0.8 mm. The burners were mounted on a computer-operated, stepper-motor-driven, two-dimensional traversing mechanism. The burners were located in a vertical steel combustion chamber of 76 × 76 cm cross section and 143 cm height. The chamber was fitted with rectangular windows of dimensions 20 × 20 × 145 cm on all of its four side walls (Fig. 2). Air was induced by natural convection into the test chamber through a 20-cm-diam circular opening in the base plate. Three layers of fine-wire-mesh screens (1 × 1 mm square opening) were used to provide a uniform flow. The velocity distribution of the incoming air inside the chamber at a height of 14.5 cm (at the burner exit plane) was measured with a hot-wire anemometer while a natural gas flame issued from a 3.8-mm burner ($Re_j = 8.7 \times 10^3$) was burning inside the chamber. The velocity profile indicated a uniform velocity (<4% freestream turbulence) in the central zone of the laboratory combustion chamber. The top of the combustion chamber was open to atmosphere through an exhaust duct. A relay-operated butterfly valve was used to open the exhaust duct during experiments. The ambient pressure of the laboratory was maintained slightly above the atmospheric pressure to ensure a positive draft inside the test chamber. The two fuels were mixed inside an annular ejector-type mixing device in which a secondary fuel was injected into the stream of primary fuel through a concentrically located injector. The length of the mixing device was sufficiently large (>150 hydraulic diameters) to ensure a homogenous mixture of fuels. For a fixed jet exit Reynolds number, the volume flow rate of the mixed fuel was calculated for different mixture conditions.[9] The volume flow rates of the primary and secondary fuels were then regulated with computer controlled precision digital flow meters with a thermal conduction detector. The estimated measurement uncertainties are given in Table 2.

Table 2 Estimated uncertainties[a]

Measurements	% of Mean value
Visible flame length	1.8
Volumetric fuel flow rate	2.1
Flame blowout velocity	2.6
Liftoff height	1.8

[a] At 95% confidence level.

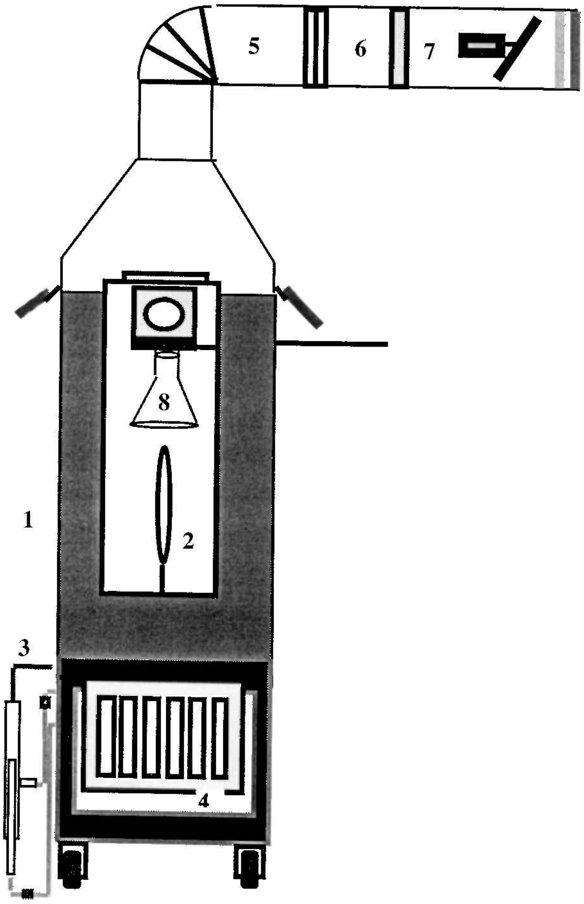


Fig. 2 Laboratory combustion chamber: 1) combustion chamber, 2) flame with burner, 3) mixing device, 4) rotameters, 5) damper, 6) filter, 7) relay valve, and 8) exhaust collection cone.

Computational Methods

The Favre averaged Navier–Stokes equations were solved over a two-dimensional axisymmetric computational domain to calculate the turbulent mixing of fuel jet with air. The local concentration of fuels and air were then postprocessed to calculate the local equivalence ratios. The details of the computational technique may be found elsewhere.[10] The flowfield was modeled using a multidomain approach with a body-fitted coordinate system and structured gird system. The axisymmetric computational domain (half of the flame) extended 85.6 cm in the axial direction and 14 cm in the radial direction and had a burner (3.8 mm i.d.) protruding 2 cm inside the domain. The whole computational domain was divided into three blocks for smoother grid generation. A total number of 13,845 (195 × 71) cells were generated using nonuniform grid spacing to provide an adequate resolution near the jet axis and close to the burner where gradients were large. The grid spacing was increased in the radial and axial directions to save the CPU time because gradients were small in the far field. During grid generation and

Table 3 Computational domain[a] boundary conditions

Parameter	Inflow	Outflow
Velocity	Fixed velocity $U_{\mathrm{air}} = 2$ m/s $V_{\mathrm{air}} = 0$ $U_{\mathrm{fuel}} = 55$ m/s $V_{\mathrm{fuel}} = 0$	Extrapolated
Pressure	P (relative) $= 0$	Extrapolated
Temperature	$T = 300$ K	Extrapolated
Kinetics Energy (k/U_c^2)	0.002 (air) 1 (fuel)	3
Dissipation	0.1 (air) 0.1 (fuel)	400

[a] Axial dimension 85.6 cm, radial dimension 14 cm, 13,854 (195 × 71) grids, and hyperbolic tangent grid clustering.

Table 4 Flow turbulence computational domain initial conditions[a]

Parameter	Value
Velocity	$U = 5$ m/s $V = 0$
Pressure	P (relative) $= 0$
Kinetic energy	$2\ (k/U_c^2)$
Dissipation	300

[a] Turbulent Prandtl number = 0.73 and turbulent Schmidt number = 0.73.

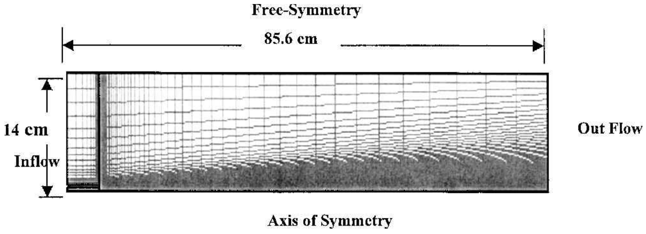


Fig. 3 Computational domain.

geometric modeling, important factors such as right-handed grid, smooth transition from small to large cells (grid tolerance), and grid orthogonality were also taken into account. Furthermore, the computational results were checked for grid independence, and it was found that increasing the total number of cells to 19,565 (215 × 91) produced only a change of 0.8% in mixture fraction for the baseline conditions. The computational domain (Fig. 3) was bounded by the axis of symmetry and free boundary in the radial direction and by the inflow and outflow in the axial direction. The outer boundaries were located far from the burner exit (220 burner diameters) and the symmetry axis (37 burner diameters). The effect of turbulence was accounted for via turbulent viscosity and the k–ε model. The SIMPLEC algorithm was used for solution. Details of the computational domain are summarized in Tables 3 and 4.

Results and Discussion

Liftoff Height at Blowout Conditions

Figure 4 shows flame liftoff height as a function of hydrogen content in the hydrogen/natural gas mixture for different burner sizes. The measured liftoff height for 100% natural gas (NG) agrees well with the data in the literature for all burner sizes. For the 2.3-mm-i.d. burner, the liftoff height is 6.0 cm, which is within ±4% of those measured by Pitts.[3] Also, it agrees well with the theoretical prediction (6.1 cm) using Eq. (1). In agreement with the photographic observations of Choudhuri,[10] flame liftoff height at blowout condition decreases with the increase of hydrogen content in the mixture. The mixture flame speed increases with the increase of hydrogen content in the mixture, which eventually reduces the flame liftoff height by moving the flame base toward the burner. Also, as discussed earlier, due to wide flammability limits, even the presence of a small amount of hydrogen keeps the flame close to the burner exit by directly and indirectly altering the flame characteristics. The addition of 5% H_2 to 100% NG causes on an average 3–5% decrease in liftoff height for all burner conditions. However, at higher concentrations of hydrogen in the fuel mixture, the rate of decrease is around 9–13%. The variation of the normalized liftoff height, $L_H = \rho_F S_{L,\max} L_b/\mu_F$, as a function of normalized blowout velocity, $U_n = (U_b/S_{L,\max})(\rho_F/\rho_A)^{1.5}$, is shown in Fig. 5. Note that it is possible to correlate the blowout velocity and liftoff height at blowout condition with a unique relation.

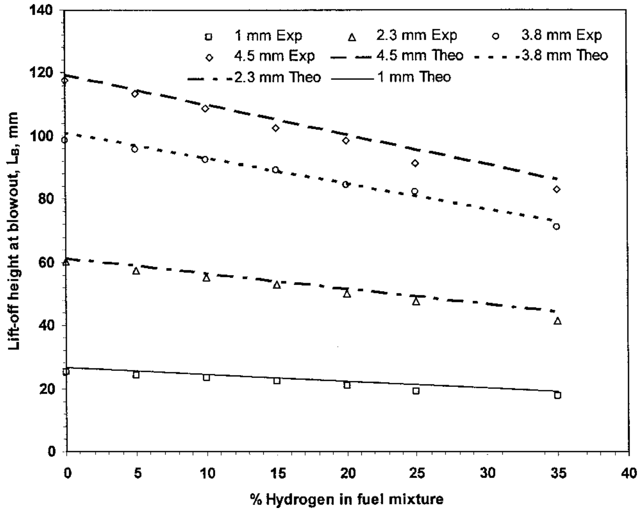


Fig. 4 Variation liftoff velocity with percent hydrogen in the fuel mixture.

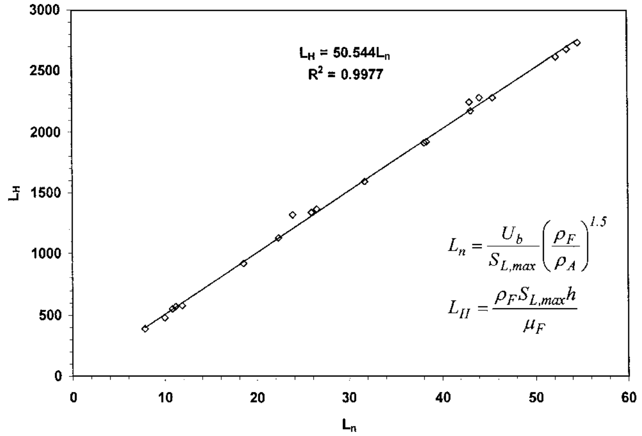


Fig. 5 Variation normalized liftoff height with normalized blowout velocity.

Blowout Velocity

The variation of blowout velocity as a function of hydrogen content in the mixture for different burner diameters is shown in Fig. 6. As mentioned earlier, blowout velocity increases with the increase of hydrogen content in the mixture. For the 1-mm-i.d. burner, the blowout velocity of the 100% natural gas is 9.6 m/s, which increases to 12.8 m/s with the addition of 5% hydrogen to the mixture. The increase in blowout velocity is slow initially for the 1-mm burner; however, the rate increases as the hydrogen concentration goes above 20% of the fuel mixture. The effect of hydrogen addition on flame stability is also pronounced for burners with larger diameters. In general, an addition of 5% H_2 to the fuel mixture causes a 25–30% rise in flame blowout velocity. However, the rate of increase is higher for higher concentrations of hydrogen in the mixture. The rate of increase of flame blowout velocity is 35–40% with the increase of additional 5% H_2 in the 70–30% NG/H_2 composite fuel. Clearly, these trends indicate the strong effect of hydrogen in the stability mechanism of hydrogen/hydrocarbon composite fuel.

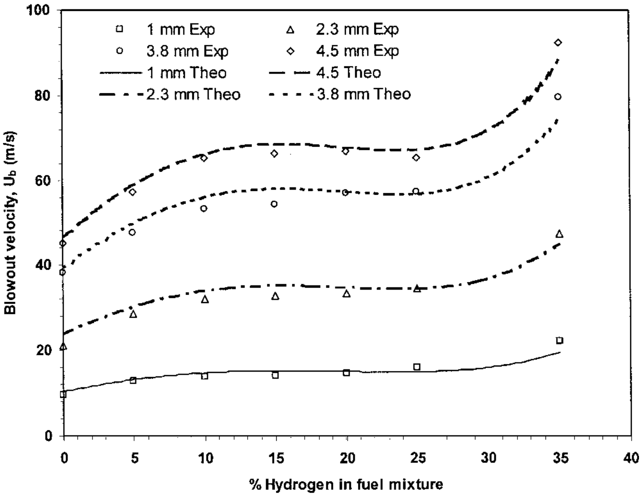
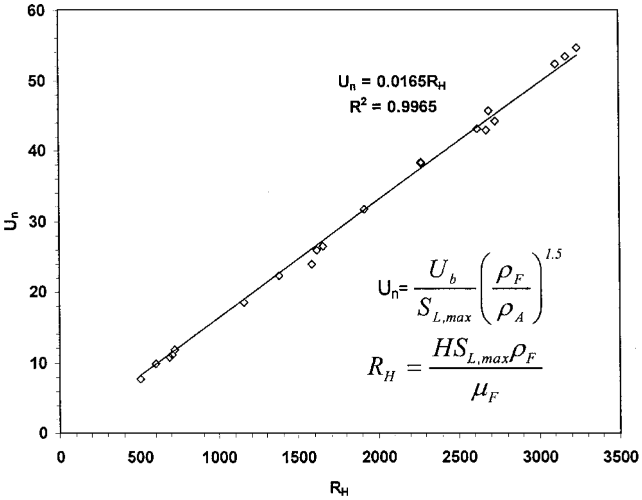


Fig. 6 Variation blowout velocity with percent hydrogen in the fuel mixture.



$$U_n = \frac{U_b}{S_{L,max}}\left(\frac{\rho_F}{\rho_A}\right)^{1.5}$$

$$R_H = \frac{HS_{L,max}\rho_F}{\mu_F}$$

Fig. 7 Variation normalized blowout velocity with Reynolds Number R_H.

Predictions of blowout velocities based on Eqs. (2–4) are also shown in Fig. 6. The maximum laminar flame velocities are calculated using Eq. (5) and the Dugger et al. correlation (see Ref. 7). The equilibrium compositions are calculated using the chemical kinetics code CHEMKIN. The experimental measurements agree fairly well with the theoretical predictions. Within experimental uncertainties, the predicted values are slightly higher for fuel mixtures with 35% H_2 concentration. The accuracy of theoretical predictions largely depends on the proper estimation of the maximum laminar flame speed. In the absence of adequate experimental data, the diffusion theory proposed by Tanford and Pease (see Ref. 7) seems to be a reasonable choice for computing maximum laminar flame speed because it actually considers the effects of H, O, and OH radical concentrations for estimating flame speed, which are important in hydrogen/hydrocarbon composite fuel combustion. The variation of normalized blowout velocity, $(U_b/S_{L,\max})(\rho_F/\rho_A)^{1.5}$, with a specially defined Reynolds number, $R_H = HS_{L,\max}\rho_F/\mu_F$, is shown in Fig. 7. The normalized blowout velocity data from 1-, 2.3-, 3.8-, and 4.5-mm burners collapse on to a single line and are uniquely correlated with the parameter R_H. However, note that this correlation is only possible when the maximum laminar flame speed, stochiometric mass fraction, and equivalence ratio of the composite fuels are properly estimated.

Local Equivalence Ratio

The local equivalence ratio is calculated using the computed local air and fuel concentrations. As mentioned earlier, three

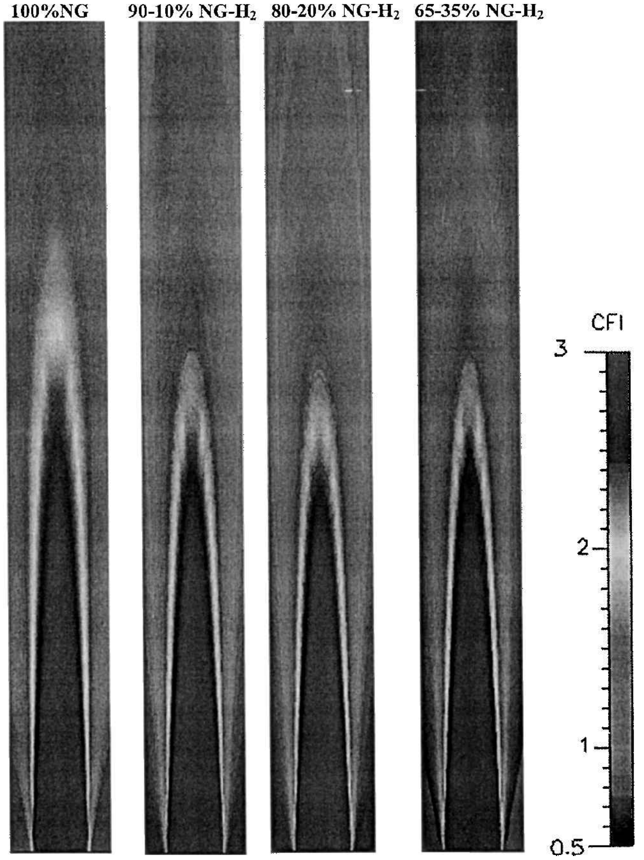


Fig. 8 Computed CFI contour of cold fuel jets at various mixture conditions.

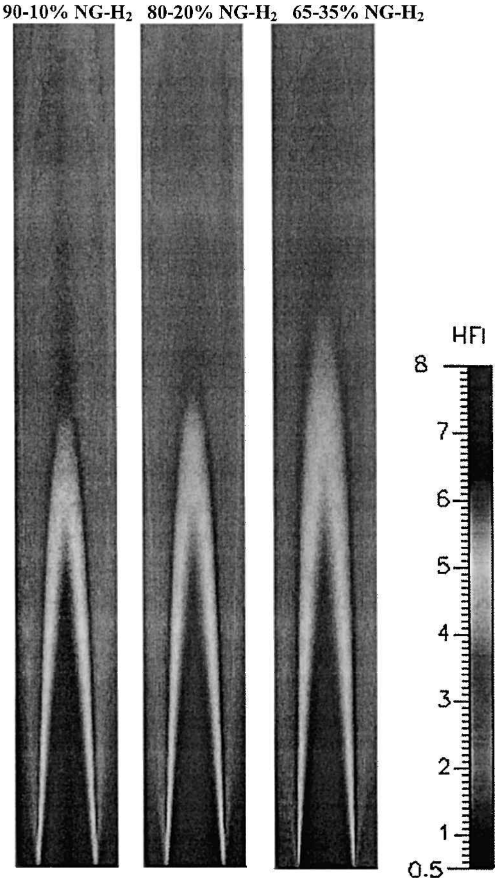


Fig. 9 Computed HFI contour of cold fuel jets at various mixture conditions.

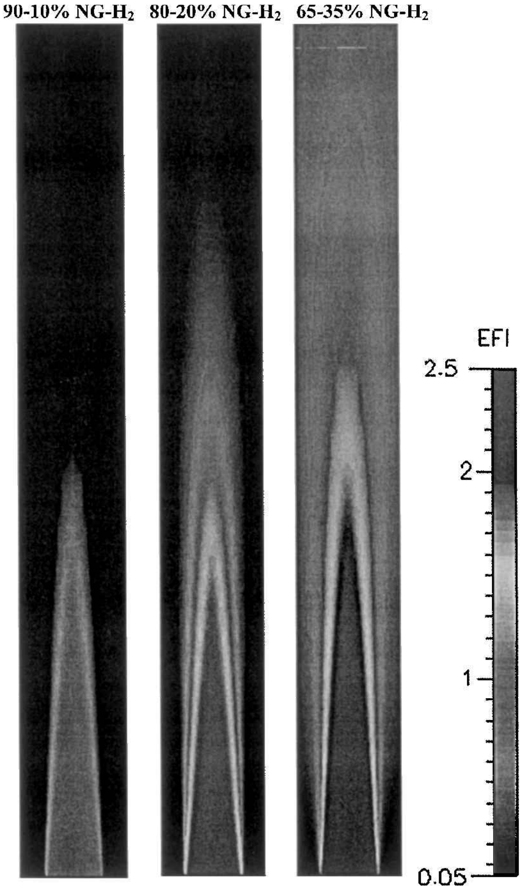


Fig. 10 Computed EFI contour of cold fuel jets at various mixture conditions.

equivalence ratios are defined to demonstrate the effect of equivalence ratio on the flame stability mechanism. The gray-scale representation of two-dimensional color contours of the three equivalence ratios calculated using the local concentrations predicted with the computational fluid dynamics analysis for different mixtures of hydrogen and natural gas is shown in Figs. 8–10. The contour plots of Figs. 8–10 represent two-dimensional areas, which extend to $20d_j$ in the axial direction and $4d_j$ in the radial direction. For all fuel mixtures, CFI has its maximum value on the centerline, which decays in the outward radial direction. With the increase of hydrogen concentration in the mixture, the CFI decreases in the near-field region. At an axial location of $15d_j$ the CFI values are between 1.2 and 1.4 (Fig. 8). As mentioned earlier, the 100% NG flame does not exist in this location for a jet exit velocity of 55 m/s. The CFI value decreases in this location as hydrogen concentration increases in the mixture. For the 90–10% NG/H_2 flame, the CFI values in this location range between 0.5 and 1.0. However, the HFI value increases because of the addition of hydrogen to the mixture. The HFI values (Fig. 9) lie between 1.8 and 2 for the 90–10% NG/H_2 flame. The corresponding EFI values (Fig. 10) are 0.2–0.5; and as mentioned earlier, flame also does not exist in this location for the 90–10% NG/H_2 mixture. However, unlike the 100% NG flame, the condition is just after the blowout of the 90–10% NG/H_2 flame. As more hydrogen is added to the mixture, the CFI value decreases, and both HFI and EFI increase. For the 80–20% NG/H_2 mixture, a stable lifted flame can be obtained. The corresponding CFI, HFI, and EFI values for this condition are 1.2, 3.5, and 0.75, respectively. As seen HFI $= 3.5$ keeps the flame anchored at this location despite a low CFI. The corresponding EFI $= 0.75$ indicates the condition of natural gas/hydrogen mixture at which the mixed fuel flame exists. A further increase in hydrogen concentration (65–35% NG/H_2) results in stable a attached flame. The CFI, HFI, and EFI values at the same axial location are 1.1, 3.9, and 1.0, respectively. Hence, EFI is the appropriate parameter for predicting the stability of a mixed fuel.

Summary

Stability (liftoff height and blowout velocity) of the H_2/NG composite fuel diffusion flames is presented. Measured values are compared with predictions from analytical and semi-empirical theories. The primary issue for the failure of the theories in predicting the stability parameters of the hydrogen/hydrocarbon mixtures is resolved by employing a diffusion theory for laminar flame speed calculation and by defining an equivalent stoichiometry. The analysis has demonstrated that the flame stability of blended fuel strongly depends on the concentrations of OH, H, and O radicals, and their binary diffusion coefficients. Also, a local EFI can be computed to demonstrate the effect of local stochiometry on flame blowout mechanism. The following correlations have been developed.

1) The maximum laminar flame speed increases and exhibits an exponential relation, $S_{L,\max} = 34.2\ e^{0.02(\%H_2)}$; $(R^2 = 0.95, 0 \le \%H_2 \le 100)$, with the volumetric concentration of hydrogen in the composite fuel.

2) The blowout velocity is represented with a correlation, $(U_b/S_{L,\max})(\rho_F/\rho_A)^{1.5} = 0.017(HS_{L,\max}\rho_F/\mu_F)$, $(R^2 = 0.99, 0 \le \%H_2 \le 35)$, where the characteristic flame height is defined as $H = 8[(Y/Y_s)(\rho_F/\rho_A)^{0.5} - 5.8]r_j$, $1 \le 2r_j \le 4$ mm.

3) The maximum liftoff height at blowout condition is represented with a general correlation, $(U_b/S_{L,\max})(\rho_F/\rho_A)^{1.5} = 50.54(L_b S_{L,\max}\rho_F/\mu_F)$, $(R^2 = 0.99, 0 \le \%H_2 \le 35)$.

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