

Liftoff and Blowout Characteristics of Laminar Syngas Nonpremixed Flames

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Abstract

Liftoff and blowout behavior of nonpremixed syngas flames is investigated using a time-accurate CFD code with a detailed description of transport and chemistry. Lifted flames are established in coflowing laminar jets using N₂ dilution in the fuel jet. Results focus on the effects of syngas composition and temperature on the liftoff, stabilization, and the edge (triple) flame structure. For a given syngas mixture, as the N₂ dilution exceeds certain value, the flame lifts off from the burner rim and propagates along the stoichiometric mixture fraction line, and its structure changes from diffusion to double flame. With further dilution, the flame liftoff height increases rapidly, the base structure transitions from double to triple flame, and its stabilization involves a balance between the triple flame speed and local flow velocity. The temporal evolution of propagating jet flame also exhibits a similar behavior. The transition from diffusion to double and then to triple flame is examined using state relationships in mixture fraction coordinate. As H₂ fraction in syngas and/or temperature is increased, the N₂ dilution required for flame liftoff and blowout increases. The ratio of the triple flame speed to the unstretched premixed flame speed also increases with the increase in H₂ fraction. For H₂ fraction above 30%, the flame liftoff and blowout become less sensitive to syngas composition and temperature.

Keywords

Flame Liftoff; Syngas flames; Triple flame structure; State relationships; Numerical simulations

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1. Introduction

Lifted flames occur in a wide range of combustion devices, including gas turbines, diesel engines and stationary power systems. The liftoff of nonpremixed and partially premixed flames has been a subject of numerous investigations, and different mechanisms have been proposed for their stabilization. Chung and Lee [1] employed a cold jet theory and showed that the Schmidt number (Sc) plays an important role in flame liftoff, and stable lifted flames are possible only for fuels for which $Sc < 1$. This implied that lifted propane and n-butane flames can be stabilized, whereas methane and ethane flames blowout directly from the burner-stabilized mode. Ghosal and Vervisch [2] extended Chung and Lee's analysis and showed that a lifted laminar flame is possible for a fuel for which Sc is greater than a critical value, which is less than unity. However, Kioni et al. [3] and Plessing et al. [4] established lifted methane flames using nitrogen dilution.

Takahashi and Katta [5] proposed that the nonpremixed flame stabilization involves the presence of an ignition or reaction kernel that synergistically provides radical species upstream, enhancing reaction rates for some key elementary reactions in a small stabilization region. In case of preheated reactants, a related mechanism suggested for anchoring lifted flames is autoignition, which is controlled by mixing and chemical kinetics effects [6]. Wichman and Ramadan [7] stated, on the contrary, that upstream radical transport is not a necessary condition, and that flame stabilization can result just due to the existence of a premixing zone of sufficient reactivity. A more common viewpoint for both laminar and turbulent flames is the edge-flame stabilization involving the propagation of a triple flame [3], and a balance between the local flow velocity and the triple flame speed. Qin et al. [8] distinguished between near and far field region stabilization. In the near region, the liftoff height was observed to vary linearly with increasing inflow velocity, whereas in the far region, it exhibited nonlinear behavior with respect to velocity.

Briones et al. [9] and Aggarwal [10] reported numerical and experimental results for dilution-induced liftoff and blowout of methane flames. They provided a more unified viewpoint, involving near field stabilization through the presence of an ignition kernel and far field stabilization through the presence of a triple flame. At certain level of dilution, depending on other conditions, a nonpremixed methane flame is lifted, and its base exhibits a double flame structure (i.e., containing rich premixed and nonpremixed reaction zones) in the near-field region, where the flame stabilization depends on a balance between the reaction rate and the scalar dissipation rate. With further increase in dilution level, the flame becomes weaker and stabilizes at a location that has a lower scalar dissipation rate. As the liftoff height increases, the flame base exhibits a triple flame structure, containing a rich premixed reaction zone (RPZ) on the fuel side, a lean premixed zone (LPZ) on the oxidizer side, and a nonpremixed zone (NPZ) sandwiched between the RPZ and LPZ. The flame stabilization mechanism then involves a balance between the triple flame speed and local flow velocity.

While previous studies have provided a significant database and fundamental understanding of flame liftoff and stabilization, most of this research has considered pure fuels, whereas most practical fuels contain a mixture of compounds with noticeable differences in their reactivity and transport properties. The objective of the present study is to examine the liftoff and blowout characteristics of laminar, nonpremixed syngas flames. It is important to note that the liftoff and blowout of turbulent diffusion and partially premixed flames are often described by the propagation of triple flamelets [6, 9, 11, 12]. The choice of syngas is based on several considerations. First, syngas being a mixture of CO and H₂) represents a fuel blend for which relatively little research has been reported dealing with liftoff and blowout behavior. Second, it represents a cleaner and renewable fuel, and there is significant interest in using it for both stationary and mobile power generation. It is also considered a sustainable energy source as it can be produced from a variety of biomass and other renewable sources [13]. Third, its oxidation chemistry is fairly well established [14], and its combustion characteristics have been extensively

investigated [15, 16]. However, the liftoff and blowout characteristics of syngas flames have not been examined, **although Chung and coworkers have reported simulations of auto-ignited lifted syngas [17] and methane [18] jet flames in heated coflowing air.** It is also important to note that the main constituents of syngas, namely H₂ and CO, have widely disparate reactivity and diffusivity, and thus it is of interest how this disparity influences the liftoff behavior. A computational study is performed using a time-accurate implicit algorithm with a detailed description of chemistry and transport processes. Syngas lifted flames are established in axisymmetric coflowing jets using nitrogen dilution in the fuel stream. Results focus on the flame liftoff, stabilization, and blowout characteristics, including liftoff height and base structure at different heights for various syngas compositions. The effect of inflow temperature on flame liftoff and blowout is also examined.

2. Computational Model

Simulations of jet diffusion flames are performed using a 2-D CFD code, UNICORN (UNsteady Ignition and COmbustion using ReactionNs), which is capable of performing direct numerical simulations (DNSs) of reacting flows. Details are provided elsewhere [9, 10]. The numerical algorithm solves u- and v-momentum equations, continuity, and enthalpy- and species-conservation equations on a staggered-grid system. Using cylindrical coordinates (r, z), these equations in a generalized form can be written as

$$\frac{\partial(\rho\Phi)}{\partial t} + \frac{\partial(\rho v\Phi)}{\partial r} + \frac{\partial(\rho u\Phi)}{\partial z} = \frac{\partial}{\partial r}\left(\Gamma^\Phi \frac{\partial\Phi}{\partial r}\right) + \frac{\partial}{\partial z}\left(\Gamma^\Phi \frac{\partial\Phi}{\partial z}\right) - \frac{\rho v\Phi}{r} + \frac{\Gamma^\Phi}{r} \frac{\partial\Phi}{\partial r} + S^\Phi \quad (1)$$

Here ρ is the mixture, density t the time, and u and v the axial (z) and radial (r) velocity components, respectively. The general form of the equation represents conservation of mass, momentum, species, or energy conservation, depending on the variable used for Φ . The transport coefficient Γ^Φ and the source terms S^Φ appearing in the governing equations are described in Ref. [19]. Introducing the overall species conservation equation and the state equation completes the equation set. The syngas oxidation chemistry is modeled using the San Diego (SD)

mechanism [20], which contains 52 species and 544 elementary reactions. Validation of the mechanism is discussed in the next section.

The thermodynamic and transport properties appearing in the governing equations are considered temperature and species dependent. The transport properties such as viscosity, thermal conductivity and binary molecular diffusion coefficients for each species are evaluated using Chapman–Enskog treatment for colliding molecules and Lennard–Jones potentials and reduced temperatures as described in Ref. [21]. Mixture viscosity and thermal conductivity are then estimated using the Wilke and Kee expressions, respectively. Molecular diffusion is assumed to be of the binary-diffusion type, and the diffusion velocity of a species is calculated using Fick’s law and the effective-diffusion coefficient of that species in the mixture. To account for thermal radiation from the flame [9, 22], a sink term based on an optically thin gas assumption is included in the energy equation in the form $q_{rad} = -4\sigma K_p(T^4 - T_o^4)$, where T denotes the local flame temperature, σ is the Stefan–Boltzmann constant and K_p accounts for the absorption and emission from the participating gaseous species (CO_2 , H_2O , CO and H_2).

The finite-difference forms of the governing equations are obtained using an implicit QUICKEST scheme for the momentum equations, and hybrid scheme for the species and energy equations. Details of the finite-differencing schemes and the methodologies used for handling stiff species-conservation equations are given in Ref. [23]. Figure 1 illustrates the computational domain used in the simulations. It extends 200 x 100 mm in the axial (z) and radial (r) directions, respectively, and is represented by a nonuniform grid system of 151x71, with a minimum spacing of 0.15 mm. A staggered grid system is employed with grid lines clustered in the jet shear layer and near the flame surface to resolve the steep gradients of the dependent variables. Due to axisymmetric geometry, only one-half of the domain is considered. The boundary conditions include inflow at the bottom boundary, outflow conditions at the upper and right

boundaries, and symmetry condition at the left boundary. Velocities, temperatures and species mass fractions are specified at the inflow boundary.

Syngas nonpremixed flames are established by issuing N₂-diluted syngas mixture through a 12mm diameter fuel nozzle. In order to minimize the effect of outside disturbances, the fuel nozzle is surrounded by a large concentric tube of 100 mm diameter. For a given syngas composition, the N₂ concentration in the fuel jet is varied in order to investigate the flame liftoff, stabilization, and blowout phenomena. It is important to note that the simulated lifted flames are confined within 12 mm and 110 mm in the radial and axial directions, respectively. Moreover, once the flame liftoff height exceeds 110 mm, it leads to blowout.

No ignition is needed for obtaining these flames. However, the flame simulation using the UNICORN code involves two steps. In the first step, a global one-reaction mechanism is employed that provides the initial conditions in terms of velocity, species and temperature distribution in the computational domain. The solution obtained in the first step is then employed in the second step that uses the detailed mechanism. It is also important to note that no fluid-dynamic instabilities are observed for the considered velocity conditions. Time-dependent simulations are continued till the steady state solutions are obtained. In the absence of fluid-dynamic instabilities such as Kelvin-Helmholz instabilities, flame base doesn't oscillate around the stabilization height. In fact, when the flow velocity is increased or decreased the flame base moves downstream or upstream accordingly. There is no hysteresis for these lifted flames. Note that burner stabilized flames could exhibit hysteresis effects when the velocity is changed.

The scalar dissipation rate (χ) represents a useful analytical tool to characterize the flame liftoff and stabilization behavior [8, 13]. It is defined as:

$$\chi = 2D \left(\frac{\partial \xi}{\partial x_\alpha} \right)^2 = 2D_{F-mix} \left[\left(\frac{\partial \xi}{\partial x} \right)^2 + \left(\frac{\partial \xi}{\partial y} \right)^2 + \left(\frac{\partial \xi}{\partial z} \right)^2 \right] \quad (2)$$

Here D_{F-mix} is the diffusivity of syngas with respect to the mixture, and ξ is the mixture fraction, defined as the mass fraction of material originating in the fuel stream. The diffusivity of syngas is computed based on the mass-averaged diffusivities of CO and H₂. The mixture fraction may be defined as:

$$\xi = \frac{Z_F - Z_{F,l}}{Z_{F,r} - Z_{F,l}} \quad (3)$$

The subscript F stands for one or a combination of elements, such as C and H, in the fuel stream, and subscripts l and r refer to the fuel-lean and fuel-rich streams, respectively. Z is defined as:

$$Z = \sum_{i=1}^{N_C} n_{C,i} Y_{C,i} \frac{M_C}{M_{C,i}} + \sum_{i=1}^{N_H} n_{H,i} Y_{H,i} \frac{M_H}{M_{H,i}} \quad (4)$$

Here N_C and N_H represent the total number of species containing carbon and hydrogen, respectively, $n_{C,i}$ and $n_{H,i}$ are the number of carbon and hydrogen atoms in the i th species, $Y_{C,i}$ and $Y_{H,i}$ are the mass fraction of the i th species containing carbon or hydrogen, M_C and M_H are the molecular weights of carbon and hydrogen, respectively, and $M_{C,i}$ and $M_{H,i}$ are the molecular weights of the i th species containing carbon or hydrogen. The fuel diffusivity (D_{F-mix}) is calculated using the same methodology as described earlier.

3. Results and Discussion

3.1 Validation and Grid Independence

The computational algorithm has been extensively validated in previous studies using experimental data for ignition, extinction, stability limits, and the dynamic characteristics of flames burning different fuels [23, 24]. In addition, validation for the prediction of liftoff heights of nonpremixed and partially premixed methane flames has been reported in Refs. [9, 10]. Additional validation for the San Diego (SD) mechanism was provided by comparing its predictions of premixed syngas flame speeds with measurements and the predictions using the Davis [25], and USCII [26], and Curran [27] mechanisms. As discussed in Ref. [28], good agreement was observed between the measurements and predictions of the four mechanisms over

a wide range of equivalence ratios. For another validation, the dilution-induced extinction of syngas nonpremixed flames in an opposed-jet configuration was simulated [28] using the SD, Davis, and AramcoMech [29] mechanisms. The flame was established by using a 40%CO/40%H₂/20%N₂ mixture in the fuel stream and 100%O₂ in the oxidizer stream. The flame extinction was then simulated by gradually decreasing the O₂ mole fraction (X_{O_2}) in the oxidizer stream. Some representative results from Ref. [28] are presented in Figure 2, which compares the flame temperatures versus X_{O_2} . For the AramcoMech and Davis mechanisms, 1-D results obtained using the Chemkin software [30] are shown, whereas for the SD mechanism, both 1-D and 2-D results are presented. As indicated, for a wide range of X_{O_2} , from 1 until extinction, there is good agreement between the predictions of the three mechanisms, as well as between the 1-D and 2-D simulations, except for somewhat lower temperatures at extinction for the 2-D case.

In order to assess the grid independence of results, numerical simulations were performed for a lifted syngas flame using three different grids, i.e., 151x71, 151x142 and 121x201, in the z and r directions, respectively. Note that the additional grid points were provided in the regions of large gradients. Results are shown in Fig. 3, which presents the radial profiles of H radical in a lifted flame stabilized at 4mm from the burner rim. The syngas composition is 70%CO-30%H₂, and N₂ dilution is 65%. For all three grids, the calculations were started using the same initial conditions. The differences between the computed profiles for the three grids are very small, suggesting that the results are fairly grid independent. **For the 151x71 grid, the profile is slightly shifted, which may be due to the fact that diffusion of smaller radical species is sufficiently resolved for this grid. Moreover, the predicted temperature and major species profiles for the three grids exhibited even smaller differences, and the predicted liftoff heights were the same for the three grids.** Therefore, the minimum grid spacing used for our simulations is 0.15 mm in the axial and radial directions corresponding to the 151x71 grid.

3.2 Flame Liftoff and Stabilization

Processes associated with the stabilization and blowout of lifted flames are discussed by considering three representative cases corresponding to a burner-stabilized flame, a lifted flame in the near region, and a lifted flame in the far region. Figure 4 depicts these three flames established with 70%CO-30%H₂ syngas fuel and using N₂ dilutions of 65%, 68%, and 71% by volume in the fuel jet. The fuel and air jet velocities are 1.2 m/s and 0.2 m/s, respectively, and the temperature is 473K. The effect of temperature is discussed in a later section. The Reynolds number is 417 and the Schmidt number (Sc) varies between 0.6-0.7 depending upon the syngas composition, its value increasing with the increasing CO fraction. The Schmidt number has been considered an important parameter for flame stabilization [1, 2], and the Sc values in the present study are within the previously reported range for which the lifted flames can be stabilized in coflowing jets. The structure of each flame is shown in terms of temperature contours and velocity vectors. The stoichiometric mixture fraction (ξ_s) line is also shown for further analysis. For these conditions, the minimum N₂ dilution required to cause the flame to liftoff from the burner is 65%². Once the flame is lifted, its liftoff height (L_f) first increases slowly and then rather rapidly with N₂ dilution. L_f values for the two lifted flames in Fig. 4 are 1.5mm and 29mm, respectively. **The liftoff height is computed using an axial location corresponding to a minimum in scalar dissipation rate profile (discussed later in the paper) along the stoichiometric mixture fraction line.** Consistent with previous studies [1, 9], L_f = 1.5mm and 29mm are defined as the near and far regions, respectively. As discussed in the following, there are noticeable differences between the structure and stabilization characteristics of the flames stabilized in the near and far regions. It is also interesting to note the similarity between our results and those reported by Won et al. [31], who described the above two regions of flame stabilization as the developing and developed regions.

Figure 5 presents the detailed structures of the above three flames in terms of the state relationships [32], which include the volumetric heat release rate (HRR) and mass fractions of

²The flame is attached with 65% N₂ dilution, but gets lifted as N₂ dilution exceeds this value.

reactant (CO , H_2 , O_2) and major product (CO_2 , H_2O) species plotted with respect to mixture fraction (ξ). Here $\xi=1$ and 0 correspond to the fuel and oxidizer sides, respectively. The burner-stabilized flame exhibits a typical diffusion flame structure with peaks in HRR, CO_2 , and H_2O locating the nonpremixed reaction zone (NPZ) near the stoichiometric mixture fraction $\xi_s=0.516$. It is interesting to note that the intersection of CO and O_2 profiles is located on the oxidizer side, while that of H_2 and O_2 is located on the fuel side. This is due to the higher reactivity of H_2 , which provides OH radicals for the conversion of CO to CO_2 through the reaction $\text{CO} + \text{OH} = \text{CO}_2 + \text{H}$.

The two lifted flames (cf. Fig. 4) exhibit a partially premixed structure in the base region. With 68% N_2 dilution, as the flame is lifted, its base (or edge) moves along the ξ_s line and gets stabilized in the near region on the air side. The flame edge location corresponds to a local minimum in scalar dissipation rate, which is evident in Fig. 6a. For this flame, the base exhibits a double flame structure, and its stabilization mechanism involves a balance between the reaction rate and scalar dissipation rate. The double flame structure contains a weak rich premixed zone (RPZ) on the fuel side, as indicated by a local peak in the HRR profile (cf. Fig. 5b) near $\xi=0.9$, and a strong nonpremixed zone (NPZ) located near $\xi_s=0.537$. **Since this flame is lifted, there is also some leakage (diffusion) of fuel species (H_2 and CO) to the oxidizer side, as indicated by local peaks in H_2 and CO profiles in the region near $\xi \approx 0$. However, the mixture is too lean to support combustion in this region. In contrast, flame (c) is lifted much higher ($L_f=29\text{mm}$), facilitating sufficient leakage (transport) of fuel species to the oxidizer side and sustaining lean premixed combustion in the region $\xi=0.1-0.3$. Consequently, flame (c) contains a triple flame structure at the base, as depicted by HRR profile in Fig. 5c.**

Additional details of the base region are provided in Fig. 6, which shows the scalar dissipation rate (χ), axial velocity (u) and radial velocity (v) plotted versus distance along the ξ_s line for the two lifted flames. The scalar dissipation rate has its peak value at the burner rim due to large

mixture fraction gradients ($\nabla\xi$) there, and then decreases sharply in the mixing layer, attaining a minimum value at the flame edge. Subsequently, it increases in the base region and then decreases again. For the flame stabilized in the near region, as indicated in Fig. 6a, the axial velocity decreases, attaining a minimum value at the flame edge, and then increases due to the dilation effect. This minimum axial velocity may be related to the edge flame speed. However, the edge-flame speed for syngas flames stabilized in the near region is not as well defined as that for flames stabilized in the far region. The radial velocity in the base region also increases due to the dilation effect. Note that the distinction is made here between the near-field and far-field stabilization corresponding to whether the lifted flame exhibits a double structure or a triple flame structure.

With further increase in dilution, the flame reactivity decreases. Consequently, the flame moves downstream along the ξ_s line to an axial location where it can withstand a lower scalar dissipation rate. Moreover, as the liftoff height increases, the flame moves in the far field region, where the flame base exhibits a triple flame structure. The liftoff height now increases rapidly with increasing N_2 dilution, and the flame stabilization now depends on a balance between the triple flame speed and the local flow velocity near the base. The transition from double flame to triple flame structure is illustrated in Fig. 7, which shows the HRR contours for the two lifted flames with 68% and 71% N_2 dilution. The liftoff heights for these two flames are 1.5mm and 29mm, respectively. The double and triple flame structures can be seen through the two and three local peaks in HRR contours in Figs. 7a and 7b, respectively, as well as through the HRR and species profiles in Figs. 5b and 5c. For the flame stabilized in the far region, the HRR profile (Fig. 5c) indicates the presence of a strong RPZ near $\xi=0.85$, a relatively weak NPZ near $\xi_s=0.564$, and a LPZ near $\xi=0.35$. The presence of RPZ is further confirmed by the local peak in O_2 profile near $\xi=0.85$, indicating partial premixing due to the leakage of O_2 to the fuel side. Similarly, the presence of LPZ can be seen through the local peaks in CO and H_2 profiles near

$\xi=0.25$, indicating the leakage of fuel species to the oxidizer side. In addition, as indicated by the HRR profiles in Fig. 7, another difference between the flames stabilized in the near and far regions pertains to the flame edge size, which extends 3 mm in radial direction for flames in the near region and over 6 mm for flames in the far region.

Several researchers have described the propagation characteristics of a lifted flame in terms of flow velocities upstream of the flame edge and the adiabatic laminar flame speed of an appropriate fuel–air mixture. While different hypotheses have been proposed, and some experimental data has also been reported [33], there has not been any consensus regarding a relationship between the edge (triple) flame speed and the premixed flame speed. Dold [34] postulated that the triple flame speed is bounded by the maximum adiabatic laminar flame speed of the system, while Kioni et al. [3] measured the velocity of a lifted triple flame and found it to be well above the laminar flame speed of the corresponding stoichiometric premixed fuel–air mixture. Ruetsch et al. [35] also reported triple flame speeds that are higher than the corresponding planar premixed flame speed. In addition, they predicted that the minimum velocity near the flame stabilization location is close to the laminar flame speed, but the overall flame speed of the triple flame, considered further upstream, is higher. Briones et al. [9] also found the triple flame speed to be higher than the premixed flame speed for propagating triple flames in coflowing CH_4/H_2 and air jets.

While there is considerable variation in the reported ratio of triple flame speed to the corresponding premixed flame speed, most previous studies suggest that the minimum axial velocity near the triple point is related to the laminar flame speed, and the maximum flow velocity further upstream of the triple point may describe the global triple flame speed. Based on this hypothesis, we report herein the relevant computed velocities near the triple points of lifted flames from our simulations. Figure 6b presents the scalar dissipation rate (χ) and axial velocity (u) profiles in the z direction along the ξ_s line for a lifted flame with triple flame structure at the

base. As indicated, the local minimum in the χ profile locates the flame edge or the triple point. The u profile also exhibits a minimum at the triple point, followed by a sharp increase in the base region due to flow dilatation caused by heat release. In addition, the u profile indicates a local maximum upstream of the triple point. Table 1 lists these local minimum (U_h) and maximum (U_{max}) axial velocities along with the liftoff heights (L_h) for some representative lifted flames that are stabilized approximately at the same height. In order to examine the effect of fuel composition, these four flames were simulated using different syngas mixtures with 95%, 90%, 70% and 50% CO. The N_2 dilution was varied so as to keep the liftoff heights (L_h) within a narrow range, although L_h is higher for the 50%CO-50% H_2 flame compared to the other three flames. The unstretched premixed flame speed (S_L), which was computed using the Chemkin software [30] for N_2 -diluted syngas mixtures, is also nearly the same for the four cases, since the increase in S_L due to higher H_2 content in syngas is compensated by the decrease due to higher N_2 dilution. Results indicate however that U_{max} , which is a measure of the triple flame speed, increases as the H_2 fraction in syngas is increased. Thus an important observation here is that the ratio of triple flame speed to laminar flame speed (U_{max}/U_h) varies with the fuel composition, and increases as the H_2 fraction in syngas is increased.

3.3 Temporal Characteristics of Lifted Propagating Flames

The preceding results examined the flame liftoff and stabilization processes by considering steady lifted flames that are stabilized at different heights corresponding to different N_2 dilution. Another useful way of analyzing the liftoff process is through the temporal evolution of a lifted flame as it propagates along the ξ_s line. Figure 8 presents the images of such a flame at three different times during its propagation. Each image contains the temperature and HRR contours. The syngas composition is 95%CO-5% H_2 and N_2 dilution is 51.8%. As the flame lifts off from the burner rim, it propagates along the ξ_s line, and its structure changes from a diffusion flame to a double flame and then to a triple flame structure at the base. It eventually stabilizes at a height

of $\approx 25\text{mm}$. For the flames at 0.7s and 0.9s, the HRR contours indicate a double flame structure with a RPZ on the fuel side and a NPZ near the ξ_s region, while the flame at 1.8 exhibits a triple flame structure. The double and triple flame structures for the flames at 0.9s and 1.8s can be seen more clearly through the HRR contours presented in Fig. 9. Additional details about the base structures of these two flames are provided in Fig. 10, which plots the χ , u , and v axial profiles along the $\xi_s=0.449$ line. Similar to the results discussed in the context of Fig. 8, the flame edge location is indicated by the local minima in χ and u profiles.

3.4 Effect of Fuel Composition and Temperature on Flame Liftoff and Blowout

Figure 11 presents the flame liftoff and blowout characteristics in terms of the liftoff height as a function of N_2 dilution for different syngas compositions. The fuel and air jet velocities are 1.2 m/s and 0.2 m/s, respectively, and the temperature is 298K. The transition height at which the base structure changes from double flame to triple flame is indicated by a dotted line. This line also marks a separation between the near-field and far-field liftoff. The zoomed view of the results at lower liftoff heights is shown in Fig. 11b. As noted earlier, for a given fuel composition, there is a minimum N_2 dilution needed to cause the flame to lift off from the burner rim. As the dilution is increased above this value, the flame liftoff height first increases gradually, and then quite rapidly until the flame blows out, when it cannot find a stabilization point within the computational domain. Moreover, the flame structure in the base region changes from double flame to triple flame. Regarding the effect of syngas composition, the minimum N_2 dilution required for liftoff increases as the CO mole fraction in the fuel is reduced, or the H_2 mole fraction increased. Accordingly, the N_2 dilution for flame blowout also increases with the reduction in CO . In addition, the transition height decreases with the increase in H_2 mole fraction, which may be attributed to the higher diffusivity of H_2 , causing the LPZ to develop earlier. Furthermore, results indicate that with higher H_2 content, the liftoff height becomes

relatively more sensitive to N₂ dilution. This may be due to the higher triple flame speed with increased H₂ content in syngas.

The effect of fuel temperature on the flame liftoff and blowout is illustrated in Figure 12, which plots the liftoff height versus N₂ dilution for temperatures of 298K and 473K, and three different syngas compositions. As the temperature is increased, the minimum N₂ dilution required for liftoff increases noticeably. However, once the flame is lifted, its liftoff and blowout behavior appears to be insensitive to temperature, except that the liftoff height exhibits somewhat greater sensitivity to N₂ dilution at higher temperature. This may be due to the effect of higher temperature on flame propagation speed and/or on diffusivity leading to increased leakage of fuel and O₂ after the flame is lifted. The effect of syngas composition and temperature on flame liftoff and blowout is further summarized in Table 2, which lists the amount of N₂ dilution (mole fraction) required for flame liftoff and blowout for several cases. Results indicate that the N₂ dilution required for liftoff and blowout is strongly influenced by syngas composition and temperature for H₂ mole fraction below 0.3, but becomes relatively insensitive to syngas composition for H₂ mole fraction above 0.3. This implies that for H₂ mole fraction above 0.3, the flame liftoff and blowout characteristics are largely determined by H₂ rather than by CO.

4. Conclusions

Liftoff and blowout characteristics of nonpremixed syngas flames have been investigated numerically. While the numerical algorithm has been previously validated using measurements in a variety of flames, additional validation for the mechanism is provided for premixed flame speeds and dilution-induced extinction of nonpremixed flames. Lifted flames were established in coflowing laminar jets using N₂ dilution in the fuel jet. Results focused on effect of fuel composition on the liftoff, stabilization, and blowout behavior, including the flame base (edge) structure and propagation. The effect of fuel temperature was also investigated. For the conditions investigated, the Reynolds number is 417, and the Schmidt number is in the range 0.6-

0.7, which is within the previously reported range for the stabilization of lifted flames burning pure fuels. Important observations are:

1. For a given syngas mixture, there is a minimum N_2 dilution at which the flame lifts off from the burner rim. As the dilution exceeds this value, the flame lifts off and propagates along the stoichiometric mixture fraction (ξ_s) line to a location where there is balance between the reaction rate and the scalar dissipation rate (χ), and its structure changes from diffusion to double flame. With further increase in dilution, the flame reactivity decreases, and it moves downstream along the ξ_s line to a location where it can withstand a lower χ . As the liftoff height increases, the base structure transitions from double to triple flame containing a RPZ on the fuel side, a LPZ on the air side, and a NPZ near the ξ_s line. The liftoff height then increases rapidly and the flame stabilization involves a balance between the triple flame speed and the local flow velocity. Further increase in dilution leads to blowout as the flame cannot find a stabilization point within the computational domain. The transition from diffusion to double and then to triple flame is examined using state relationships in mixture fraction coordinate.
2. A lifted propagating flame temporally exhibits a similar behavior as outlined above, i.e., the flame propagates along the ξ_s line, and its base structure changes from diffusion to double and then to triple flame until it stabilizes at a certain height or blows out depending upon mixture conditions at the inflow boundary.
3. The flame edge is characterized by a local minimum in both the scalar dissipation rate and axial velocity. Consistent with previous studies, the minimum axial velocity at the flame edge or triple point, and the maximum velocity further upstream are used to define the triple flame speed and the unstretched premixed flame speed, respectively. The ratio of these two speeds increases with the increase of H_2 fraction in syngas.

4. **An important result from the present study is that the basic stabilization mechanism of lifted flames for fuel blends is essentially the same as that for pure fuels. It is based on edge flame (double or triple flame) stabilization, as determined by a balance between the edge flame speed and the local flow velocity, or a balance between the reaction rate and scalar dissipation rate. However, the lifted flame characteristics, such as liftoff height, edge flame speed and structure, depend on the fuel composition.**
5. As the H₂ fraction in syngas is increased, the minimum N₂ dilution required for flame liftoff and blowout increases. In addition, the liftoff height exhibits greater sensitivity to N₂ dilution, which may be due to the increased triple flame speed as a result of higher H₂ content in syngas. However, the transition height, where the base structure changes from double to triple flame, decreases with the increase in H₂ fraction, which may be attributed to the higher diffusivity and reactivity of H₂, causing the LPZ to develop earlier.
6. The effect of higher temperature is to increase the minimum N₂ required for flame liftoff. However, once the flame is lifted, its liftoff and blowout behavior is relatively insensitive to temperature, except that the liftoff height exhibits somewhat greater sensitivity to N₂ dilution, which may be due to the increase in flame propagation speed and/or in diffusivity, which increases the leakage of fuel and O₂. Thus increasing fuel temperature or increasing H₂ content affects flame liftoff in a similar manner.
7. For H₂ mole fractions above 30%, the flame liftoff and blowout behavior becomes less sensitive to syngas composition and temperature, implying that the behavior is now largely determined by H₂. This is an important result suggesting that future research on flame liftoff should consider other fuel blends containing more and less reactive components.

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