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Abstract

Structures of methane and propane jet diffusion flames under liftoff to blowout conditions were studied. The focus of this investigation was on the dynamic, time-varying features of flame propagation and stabilization near the flame base. The turbulent velocity and length scales of the flame motion were directly measured using a thin-filament pyrometry (TFP) technique at high sampling rates. The results indicate a significant change in turbulent velocity and length scales as the jet velocity increases approaching blowout. The deduced turbulent diffusivity displayed over an order of magnitude increases from liftoff to blowout. However, the strain rate never exceeded the limit of ∿ 600 1/sec. Near blowout, the flame zone assumed the characteristics of distributed combustion.

1.0 Introduction

Topics related to propagation and stabilization of turbulent, lifted jet diffusion flames have been widely investigated.[1] However, the progress of the flame motion near the flame base remains one of the many unanswered questions. Understanding of dynamic flame stabilization processes requires information on the time-varying properties of the lifted flame.

To obtain time-varying information on flame propagation, Chen and Goss[2] have utilized thin-filament pyrometry (TFP) to profile the temperature at high sampling rates. The velocity and length scales associated with flame motion were measured for methane and propane flames under critical liftoff conditions. The thermal-zone thickness and velocity and length scales were found to increase significantly after flame liftoff. However, the time scale associated with large-scale flame movement remains within a narrow range. As a result the turbulent diffusivity increases with increasing jet velocity and downstream location, while the strain rate remains essentially constant. For methane and propane flames at a critical liftoff velocity, the strain rate sustained by the flame surface is measured to be ≤ 450 1/sec. This result is consistent with that of other researchers.[3,4]

In this paper lifted flames with exit velocity greater than the critical liftoff velocity are examined. Questions of particular interest include 1) How does the thermal zone vary along the flame under various liftoff conditions; 2) Will the strain rate remain limited, and what is the range of strain rate which the flame sustains when approaching blowout; and 3) Will the time scale of the dominant flame motion remain constant and, if so, why. In addition, efforts have been made to quantify intermittent flame-base motion.

2.0 Experimental

A short, tapered contour nozzle with 5-mm inner diameter was used as the fuel jet in these studies. The contraction ratio of the nozzle was 20 to 1. To isolate the flame from room-air disturbance, a 25-cm duct was utilized to confine the co-annular air jet having a constant exit velocity of 0.15 m/sec. The experimental setup for utilizing the thin-filament pyrometry technique for the study of flame lifting and flame/flow interactions of turbulent jet diffusion flames is described in Ref. 2 in detail. Therefore, only a brief description will be given below.

Time-dependent temperature profiles for the propane and methane jet flames were made from the blackbody emission of a SiC thin filament, ∿ 10 μm in diameter, at a rate of > 3,000/sec. Each temperature profile was curve fitted to permit the position of the flame surface and thermal-zone thickness to be determined accurately. Since the data were taken at a high sampling rate, the time-varying information could be properly captured and recorded. From the time-series trace of the flame surface, the radial velocity and length scales of the flame propagation could be deduced. The radial velocity is the time derivative of the flame trace; this trace is obtained by the filament aligned in the radial direction. The root mean square (rms) value of the radial velocity, v', is defined as the velocity scale, whereas the rms value of the radial flame location, y', is defined as the length scale, L.

The experimental conditions are summarized in Table 1. For the propane flame, the heat released was very intense. The exhaust facility would not allow a high-velocity propane flame to be run for long periods of time. Thus, the propane flame was not tested for conditions over 40 m/sec. For the methane flame the heating problem was less severe. However, for a methane flame having an exit velocity > 60 m/sec, the liftoff height was greater than 140 mm and the height fluctuated at an amplitude > 35 mm. In addition, the flame was no longer flamelet-like. The fitting process for locating the flame peaks could not be justified in this case.

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Table 1 Experimental Conditions

Fuel	Exit Velocity (m/sec)	Flame Status	Origin of Data	(Case No.)
Propane	19.5	Attached	Ref. 2	
Propane	19.5	Lifted	Ref. 2	
Propane	29	Lifted	Present Study	(1)
Propane	38.5	Lifted	Present Study	(2)
Methane	31.	Attached	Ref. 2	
Methane	31.	Lifted	Ref. 2	
Methane	40.	Lifted	Present Study	(3)
Methane	50.	Lifted	Present Study	(4)
Methane	60.	Lifted	Present Study	(5)
Methane	70.	Lifted	Present Study	(6)

Therefore, temperature profiles for the methane flames having a velocity of 70 m/sec were made but not analyzed with the fitting process. The flame conditions shown in Table 1 (labeled Case Nos. 1-5) were examined, and the results are presented in this paper.

3.0 Results and Discussion

In Ref. 2 it was shown that under critical liftoff conditions, the methane diffusion flame experiences stronger flame/flow interaction than the propane flame. When the flame condition approaches blowout, the flame/flow interaction becomes stronger for both flames. For examining flame behavior, data will be presented in the following order: General flame liftoff characteristics will be described in Sect. 3.1, the thermal-zone thickness and velocity and length scales in Sect. 3.2, the deduced diffusivity and strain rate in Sect. 3.3, and the crossing frequency which behaves in a similar manner to the strain rate in Sect. 3.4.

3.1 Liftoff Height and Fluctuations

The classical approach to studying the stabilization of lifted flames is to first examine the liftoff height.[5,6] Measurement of liftoff height has often been accomplished by direct observation but can easily be achieved by using a thin filament to indicate the presence of the flame. The observed instantaneous flame height fluctuates which indicates the dynamic interaction of the shear zone and the flame zone. After the flame lifts, this interaction becomes even stronger. The interaction may be affected by 1) chemical kinetics of the mixture in the fuel jet, 2) fluid properties of the fuel jet and co-flowing jet, 3) flow conditions such as exit velocity (profiled) and turbulence intensity, and 4) geometry effects which may be inherent in the flow conditions. This unsteady interaction can cause intermittent flame behavior. To characterize the range of intermittent flame-base motion, both the lower and the upper bounds of the liftoff heights were recoded along with the average height.

The average liftoff height is shown in Fig. 1 as a function of exit velocity. The difference in liftoff height between the lower and upper bound, ΔH, is shown in Fig. 2. The exit velocity was calculated from the volume flow rate and the nozzle diameter, D = 5 mm. The liftoff condition for the methane and propane flames is marked in Fig. 1.

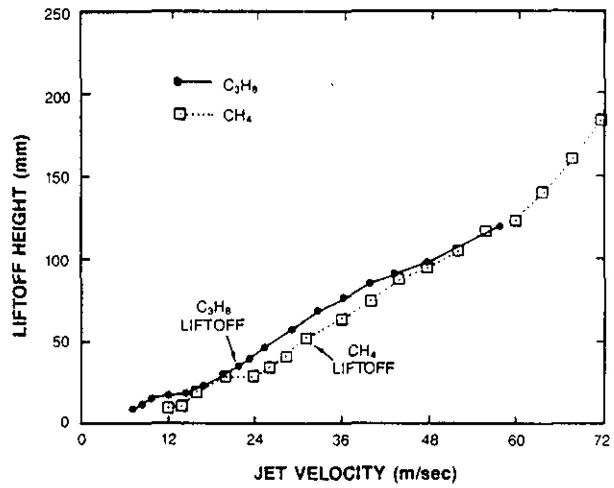

Fig. 1 Average liftoff height as function of jet exit velocity.

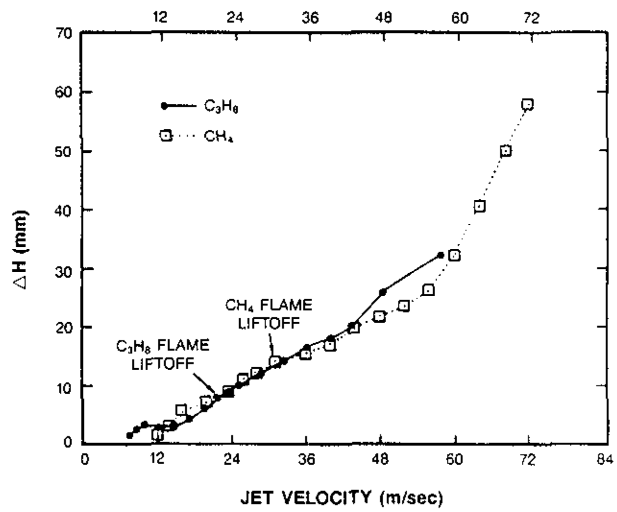

Fig. 2 Amplitude of liftoff-height fluctuation as function of jet exit velocity.

After the flame lifts, it jumps to an initial liftoff height. A reduction of the jet velocity will reduce the liftoff height and eventually cause the flame to re-attach. This re-attaching regime is also presented in the figure as the region where the velocity is lower than the initial liftoff velocity. The blowout velocity for the methane flame is ∿ 80 m/sec and for the propane flame is > 90 m/sec.

For the methane and propane flames, a linear relationship between liftoff height and jet velocity is observed which confirms the results of a previous study by Kalghatgi.[5] In this linear region the relation for the liftoff height and exit velocity for propane is given by

$$h = -21.74 + 2.50\, U_e \qquad (1)$$

and for methane by

$$h = -28.45 + 2.61\, U_e \qquad (2)$$

In Eqs. (1) and (2) the height, h, is in millimeters and the exit velocity, U_e, is in meters per second. From Fig. 1 the initial liftoff height for the propane flame is ∿ 30 mm which is much less than that of the methane flame, ∿ 52 mm.

A linear relationship also exists between the velocity and the height fluctuation for both the methane and the propane flame. For the jet-velocity range 16-45 m/sec, the fluctuation of the liftoff height for the two flames is nearly equal. The relation is

$$\Delta h = -5.66 + 0.626\, U_e \qquad (3)$$

Considering the differences in the reaction kinetics and fluid properties of methane and propane flames, the equal liftoff-height fluctuation shown in Fig. 2 requires further investigation. Comparing Δh to h for the flames studied, Δh is ∿ 20% of h. In addition, Δh is ∿ 50% of the flame diameter or 100% of the flame radius. The flame may be characterized as "not so turbulent" in nature, yet the fluctuations cannot be characterized as small. Approaching the blowout condition, the liftoff height was ∿ 200 mm and the fluctuation of the height ∿ 60 mm, as shown in Figs. 1 and 2.

Since co-flowing air was employed, the results cannot be directly compared with those obtained by other investigators. However, for modeling comparison purposes, one can examine the concept of the non-dimensional study by Kalghatgi.[5] For the hydrocarbon gases the relationship between liftoff height and jet exit velocity was given[5] by Kalghatgi as

$$h = C_1 (U_e \nu / S_u^2)(\bar{\rho})^{1.5} \qquad (4)$$

where ν is the kinematic viscosity, S_u the maximum value of the laminar burning velocity, and $\bar{\rho}$ the density ratio of the fuel and the ambient air. C_1 in this equation is an empirical constant which is independent of the gas used. If the fluid properties of the gases employed are known, the constant C_1 can be obtained by comparing Eqs. (1), (2), and (4). For the case of methane and propane flames, C_1 was determined to be 59 and 61, respectively. These two numbers are essentially equal within the experimental uncertainty of this measurement. Thus, these measurements support the universal law described in Eq. (4), having an empirical constant C_1 of ∿ 60. The value cited by Kalghatgi is 50; the difference could be due primarily to the flow conditions related to the co-flowing air and the nozzle geometry. In this study, co-flowing air was employed (at 0.15 m/sec); in Kalghatgi's study co-flowing air was not employed.

3.2 Velocity Scale, Length Scale, and Thermal-Zone Thickness

Since the turbulent flame has been viewed as an ensemble of flamelets, the following properties were measured in order to characterize the progress of the propagation and stabilization of the lifted jet flames. The radial velocity scale, length scale, and thermal-zone thickness associated with the turbulent flame motion are shown in Figs. 3-5.

In Fig. 3 the radial velocity fluctuation, v', for the motion of the flame surface is plotted as a function of axial locations for the five flame conditions selected for this study. With increasing jet velocity and downstream location, the velocity fluctuation of the flame surface for both propane and methane increased consistently. The methane

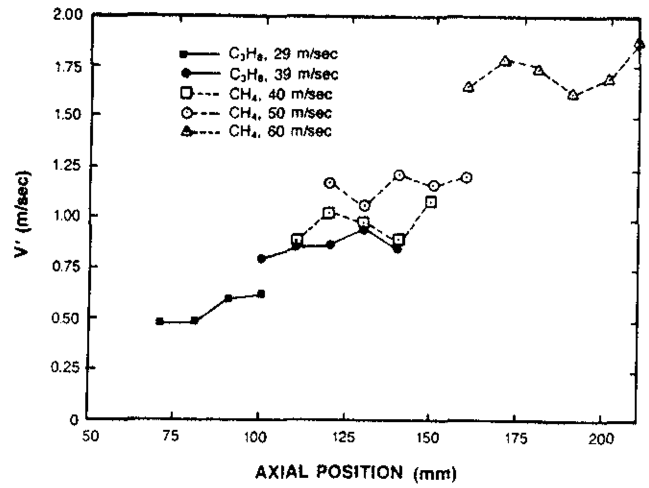

Fig. 3 Measured rms value of radial velocity fluctuation.

flame displays a higher fluctuation than the propane flame, as seen in Ref. 2. The maximum radial velocity observed was ∿ 1.8 m/sec for the lifted methane flame having a jet exit velocity of 60 m/sec. The local maximum axial velocity at the measurement location was estimated to be ∿ 12 m/sec. Under this circumstance the normalized velocity fluctuation is ∿ 15%, which is comparable to the jet turbulent intensity. For this flame condition the flame surface motion may be passive and is dominated by the flow field. This maximum turbulent velocity is approximately four to five times the maximum laminar flame velocity.

The rms value of the flame fluctuation, L, is shown in Fig. 4. Since L is an rms value, the actual range of the inner and outer bound of the flame position should be ∿ 2.83 L. This range is called the flame-brush width and is the right-hand vertical axis in Fig. 4. The dependence of the value L upon the flame conditions and axial location is similar to that of the velocity scale. When the flame-brush width is normalized by the radius of the flame cone, the normalized value is found to be ∿ 20% for most of the flame conditions tested. For Test Condition No. 5--the methane flame having an exit velocity of 60 m/sec--the above normalized value approached 58%.

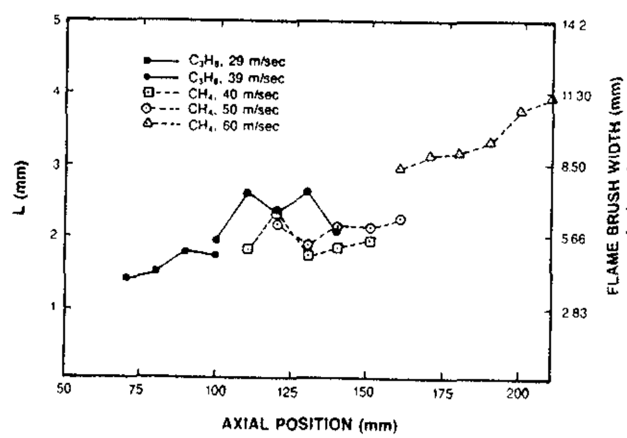

Fig. 4 Measured rms value of flame fluctuation.

Figure 5 shows the thermal-zone thickness which is defined as the area displaying a flame temperature ≥ 1300 K. *Measurements of the reaction-zone* thickness require a spectroscopic technique[7] and were not attempted in this study. The thermal zone should be thicker than the reaction zone since the thickness of the former is equal to the thickness of the latter plus the thermal-boundary-layer thickness. However, measurement of the thermal-zone thickness yields the size of the area confining the hot combustion products which have a temperature higher than the ignition temperature. The results in Fig. 5 clearly indicate that the methane flame has a thicker thermal zone than the propane flame, presumably due to the higher thermal diffusivity of methane.[2]

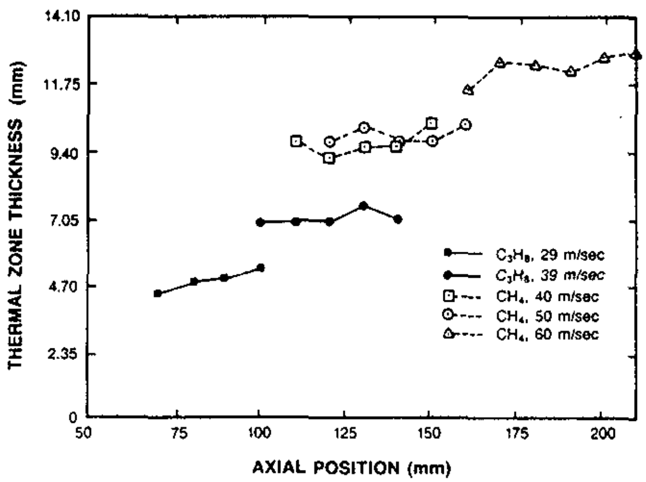

Fig. 5 Thermal-zone thickness as function of downstream location.

For Flame Condition No. 5, the thickness observed was ∿ 13 mm. For the methane flame having a slightly higher exit velocity of 70 m/sec, which is very near blowout, the thermal zone becomes so thick that the entire flame cone assumes the characteristics of distributed combustion. This is *demonstrated in Fig. 6 by the evolution of the temperature profile near the flame base.* Figure 6 clearly shows that the entire flame cone is filled with hot combusting gases. Note that in this figure the intermittent flame motion is observed. When the flame is stabilized at a location higher than the filament, no signal appears. When the flame moves down toward the filament, the high temperature zone begins to appear. This transition clearly shows that the thermal zone is thick, even *at the stabilized flame base.*

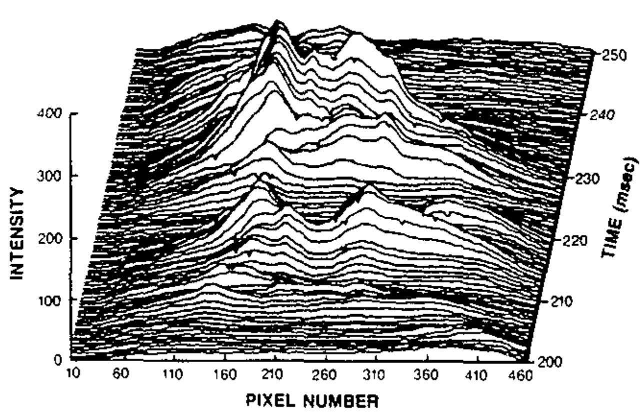

Fig. 6 Three-dimensional plot of TFP results for methane flame base at 70 m/sec.

3.3 Turbulent Diffusivity and Strain Rate

The measured velocity scale, v', and the length scale, L, can be used to determine the turbulent diffusivity and strain rate as follows:[2]

$$D_t = v'L \quad (5)$$

$$S_r = v'/L \quad (6)$$

Figure 7 shows the turbulent-diffusivity results and Fig. 8 contains strain-rate results. Since at a high jet velocity the flame base for the methane flame could not qualify as an ideal flamelet, the quality of the data for the methane flame is lower than that for the propane flame. In addition, the total number of profiles sampled at each location is only 720, which could constitute under-sampling. This is especially true for the diffusivity and strain-rate calculations which are composed of two measured data quantities. Therefore, the data presented in this section should not be considered benchmark results. Instead, attention should be focused on the trend and ranges of the results.

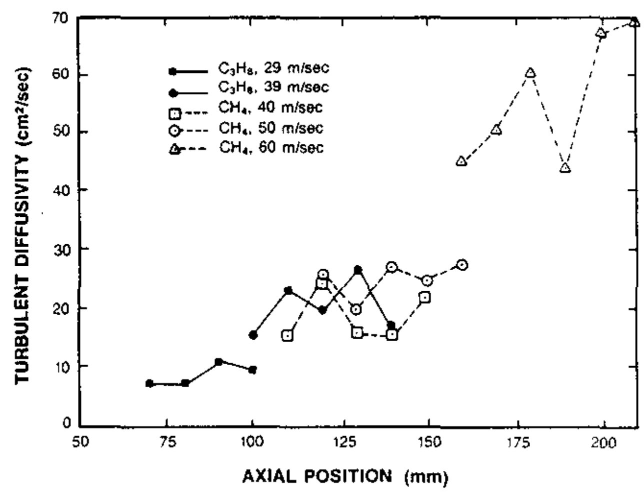

Fig. 7 Turbulent diffusivity associated with turbulent-flame-surface motion.

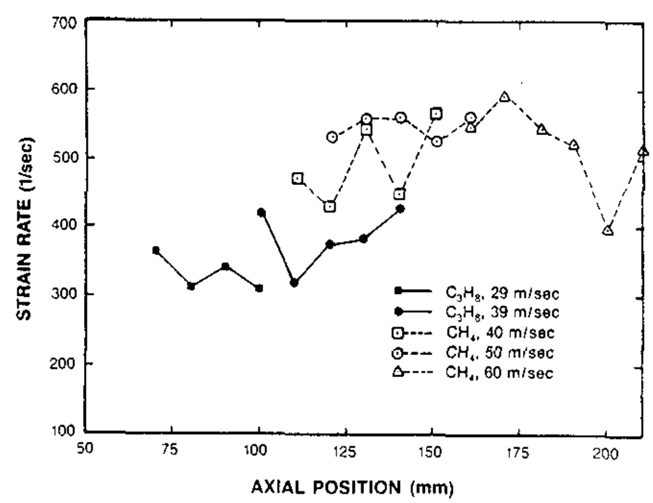

Fig. 8 Measured strain rate sustained by flame surface.

With the critical liftoff velocity, the turbulent diffusivity at the liftoff height for the propane flame is ∿ 2 cm^2/sec and for the methane flame ∿ 10 cm^2/sec. Figure 7 shows that turbulent diffusivity consistently increases with an increase in the jet velocity and downstream location. However, the strain rate sustained by the flame surface remains relatively constant, as seen in Fig. 8. For the propane flame, the strain rate for the lifted flame remains at ∿ 350 1/sec which is lower than that for the attached flame at the critical liftoff velocity. For the methane flame the strain rate for the lifted flame remains at ∿ 540 1/sec which is higher than that for the attached flame at the critical liftoff velocity. It appears that the flame sustains a certain strain rate over a wide range of flame conditions.

3.4 Crossing Frequency of the Flame Surface

As discussed in Ref. 2, the flame can affect the flow just as the flow can affect the flame behavior. This is evident in the results of the crossing frequency which is defined as the frequency at which the flame front crosses its mean position. Before reaching the end of the potential core, the jet-shear-layer structure becomes larger after the flame lifts. Consequently, the flame crossing frequency decreases after the flame has lifted. For the methane flame the interaction is strong and the structure less coherent, causing the frequency to decrease irregularly.[2] However, the frequency of the lifted flame falls between 100 and 150 Hz. For the propane flame in which the interaction of the shear zone and the flame zone is weaker, the frequency clearly decreases[2] from 200 by one-half to 100 Hz. For the flame conditions selected for this study which range from liftoff to blowout, this trend remained. The majority of the measured frequency remains within 100 to 150 Hz, as shown in Fig. 9.

The exact reason for the crossing frequency of the methane and propane flames falling into the range ∿ 100 - 150 for a wide exit-velocity range is not clear. Nevertheless, this is a measure of the dominant time scale over which the lifted flame responds to the flow modulation. Since the region between the lifted flame base and the nozzle mouth

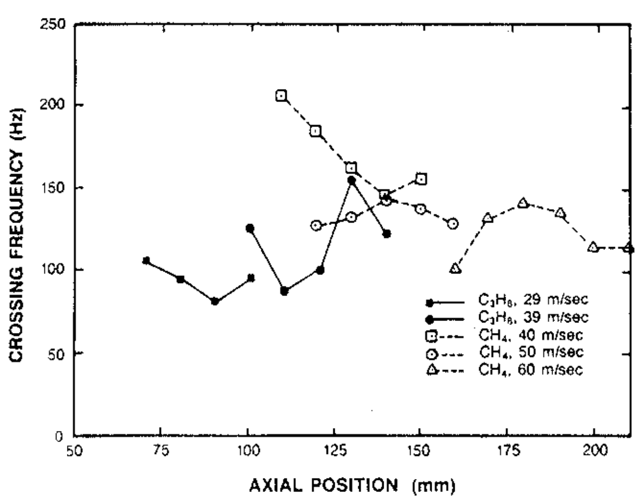

Fig. 9 Measured crossing frequency of flame surface at different downstream locations.

is a preferred location for entraining air,[2] it is physically sound to take the liftoff height as an important length scale which affects flame behavior. Variation of liftoff height will affect air entrainment, local fuel-air mixing and, thus, flame stabilization. To quantify the consequence of this unsteady flame/flow coupling, a non-dimensional ratio equivalent to the Strouhal number, S_t, can be defined as

$$S_t = fh/U_e \tag{7}$$

where f is the dominant frequency. In the above definition, global parameters such as h and U_e are used. From the data shown in Fig. 1, the Strouhal number is found to range from ∿ 0.10 to 0.15. Note that over a wide range of flame conditions, the ratio h/U_e remains constant, as was shown in Fig. 1.

4.0 Conclusions

A novel approach was taken to characterization of the stabilization-zone structure in jet flames. Methane and propane flames having an exit velocity ranging from liftoff to near blowout were examined and the results compared. Emphasis in this study was placed on the measurement of time-varying properties in order to characterize the dynamic behavior related to flame propagation and stabilization. The results are summarized below.

1. Within the region from the flame base to the end of the blue flame zone, the thermal-zone thickness and the velocity and length scales associated with the flame motion increase with respect to an increase in the jet velocity and downstream distance. Under the same jet-velocity conditions, the methane flame fluctuates at higher velocity and amplitude than the propane flame.

2. For the wide range of flame conditions tested, the strain rate sustained by the flame seems to remain relatively constant. Local flame-stretching models may be a valid approach to the study of flame extinction.

3. Characterization of the intermittent behavior of the flame-stabilization zone was carried out. The fluctuation of the liftoff height was measured to be ∿ 20% of the average value.

4. Unsteady flame/flow coupling results in a Strouhal number ranging from ∿ 0.10 to 0.15. The liftoff height is considered to be an important physical length scale.

5. Approaching the near-blowout condition, the flame base fluctuates violently and the flame takes on distributed-combustion characteristics.

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