Acknowledgment

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Liftoff Characteristics of Methane Jet Diffusion Flames

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Nomenclature

d	=	inner diameter of burner exit
R	=	inside radius of burner exit
r	=	radial position from center of burner exit
Uc	=	average centerline velocity
Um	=	average axial velocity
$Urms$	=	root mean square velocity
X_i	=	mole fraction of fuel with inert gas i
x	=	position normal to burner exit

Introduction

THE mechanisms responsible for the liftoff from the burner rim and stabilization of jet flames are not clearly understood.[1] Early works[2,3] studied the stability of jet flames in open air and identified four different regimes concerning flame stability. Of the four stability regimes 1) liftoff, 2) blowoff, 3) lifted, and 4) blowout, only the liftoff process will be studied in this Note. The liftoff condition is referred to the instant when the flame detaches from the burner rim in a discontinuous manner. After the flame detaches from the burner rim, it may stabilize at a downstream location (i.e., lifted flame) or it may result in flameoff conditions (or the blowoff condition).

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More recent works[4–7] have determined important parameters such as jet exit lip thickness, annular velocity, diluents, etc., which significantly effect the liftoff process. Current data are inconclusive to determine the mechanism(s) responsible for the liftoff process. The present study adds new information to the data base and reveals interesting comparisons to previous liftoff data.

Experimental Consideration

The experiments were conducted with a small vertical combustion tunnel.[8] The fuel and inert gas flows are regulated by rotameters. The burner is positioned vertically upward, at the center of the coflowing annular air that has a diameter of 250 mm. The burner tip extends 25-mm above the annulus exit plane. A stainless steel honeycomb mesh is placed in the annulus perpendicular to the axial direction, upstream of the burner exit. The burner assembly is situated under a forced-draft exhaust hood (1.22 × 1.22 m) with window screens surrounding the combustor. The exhaust system is equipped with a blower rated at 0.944 m^3/s. The dry annulus air (dew point at −40°C) is metered by a mass flow meter. The inert gas is added only to the fuel flow. A pressure gauge downstream of the rotameters is used to monitor the pressure drop between the rotameters and the burner exit. The pressure drop for the conditions reported here is less than 0.69 kPa, which has a negligible back-pressure effect relative to the rotameter reading. The flow meters are specified with an accuracy of ±5% of the full-scale reading. Liftoff conditions were recorded with and without the exhaust hood operating; no difference in the liftoff velocities was observed.

The burner configuration is a tapered nozzle. The burner exit i.d. is 5 mm. The burner is made of a long stainless steel tube, having an o.d. of 25.4 mm, and a reducing section near the burner tip. The tapered nozzle has a gradually tapered section, at a rate of 1–20 radius-to-length ratio, over a length of 100 mm, forming a 2.9-deg angle to the vertical plane. The tapered burner has a sharp lip, about 0.3 mm in thickness, and yields a flat velocity profile at the burner exit as shown in Fig. 1.

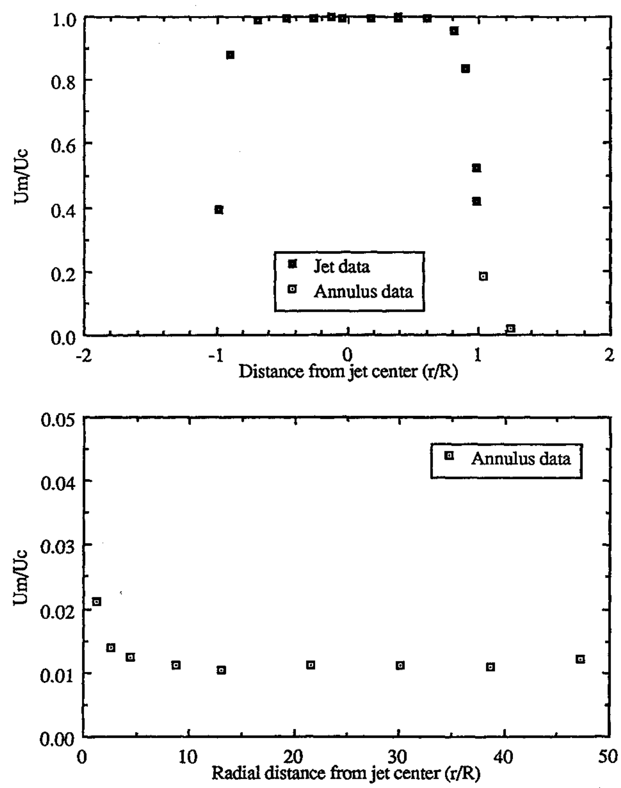

Fig. 1 Average velocity profile using argon jet at condition B, x/d = 0.4.

Liftoff conditions of methane (CH_4) diluted with three inert gases 1) nitrogen (N_2), 2) helium (He), and 3) argon (Ar), were experimentally determined. The purity of the gases is better than 97% for methane (technical grade), and 99.9% for the diluents. The fuel mole fraction at the jet exit varies from 0.3 to 1. Three different annular airflow rates were used, conditions are identified as conditions A, B, and C in the discussion herein (average velocities of 0.07, 0.15, and 0.30 m/s, respectively). These velocities were based on the mass flow readings with an accuracy of ± 0.005 m/s. The liftoff velocities were determined by setting a fixed annulus airflow rate, then increasing the jet velocity until the flame lifted from the nozzle exit and stabilized at a downstream location. The fuel-diluent liftoff velocities were obtained by setting the fuel flow rate (less than the liftoff velocity) and increasing the diluent flow rate until liftoff. This procedure was repeated several times at each condition. The reproducibility of the liftoff velocity is within $\pm 2\%$ of the results reported in this Note. The fuel jet velocity reported here is also based on the rotameter readings.

A single-channel laser Doppler velocimetry (LDV) system was used to quantify the exit condition of the combustor. The LDV system was operated at 514.5 nm in the forward scattering mode. A burst counter was used to process the signal. A microcomputer was used for data acquisition and to analyze the data. Details of the LDV system are given in Ref. 1. The LDV system collected a minimum of 3000 velocity measurements at each location as shown in Figs. 1 and 2. A conditional seeding technique was used, where either the jet or annular flow was seeded with 1-μ-diam Al_2O_3 particles. All locations displayed a Gaussian profile. A time-weighted averaging technique was used to determine the average and root-mean-squared velocities.[1] The average velocity measurements have a maximum uncertainty of $\pm 3\%$.[1]

Results and Discussion

The fuel jet and annular air have relatively uniform axial velocities at the combustor exit. As an example, the axial velocity of an argon jet at $x/d = 0.4$ (i.e., at near injector exit) is shown in Fig. 1. The Reynolds number of the argon jet is 4700 and has the same momentum flux at the burner exit as the methane jet at the near liftoff condition with annular air set at condition B (0.15 m/s). The argon jet has a flat velocity profile extending from $r/R = 0$ to $r/R = 0.8$, and a sharp decrease beyond $r/R = 0.8$. The velocity decreases to 0.1 of its centerline value at $r/R = 1.2$. The annular air also has a relatively uniform velocity profile which is shown in Fig. 1. The turbulence level ($Urms/Uc$) is approximately 1% at the jet center ($0 < r/R < 0.8$), 0.2% in the outer annulus ($r/R > 1.2$), and obtains a maximum value of 14% in the jet shear layer ($0.8 < r/R < 1.2$). The turbulence level profile is shown in Fig. 2.

Stability curves of methane jet diffusion flames diluted by Ar, N_2, or He are shown in Fig. 3. The stability curve is defined as the fuel jet liftoff velocity vs initial fuel mole fraction. The annular air velocity is a parameter in the construction of the stability curve. Three annular air velocities are considered, i.e., conditions A, B, and C.

The stability curves show that the jet liftoff velocity decreases as fuel is diluted by the inert gases, i.e., N_2, Ar, or He. The stability curves also show that the liftoff velocity decreases when the annular air velocity is increased. The annular-air effect is in agreement with Takahashi[7] in that the fuel jet liftoff velocity decreased when the coflowing air velocity is increased. It is also clear from the stability curves presented in Fig. 3 that the fuel jet liftoff velocity decreases when the dilution concentration is increased. At condition A, the fuel jet liftoff velocity decreases from 31.4 m/s for pure methane (i.e., $X_F = 1$) to 0.94 m/s for argon dilution at $X_{Ar} = 0.29$; it decreases to 0.74 m/s for nitrogen dilution at $X_{N_2} = 0.4$; and it decreases to 0.66 m/s for helium dilution at X_{He}

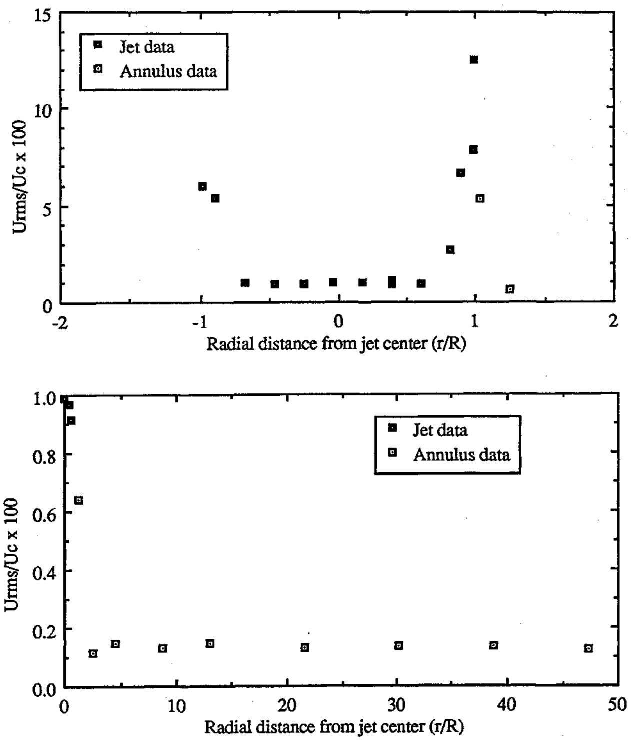

Fig. 2 Velocity fluctuation profile using argon jet at condition B, $x/d = 0.4$.

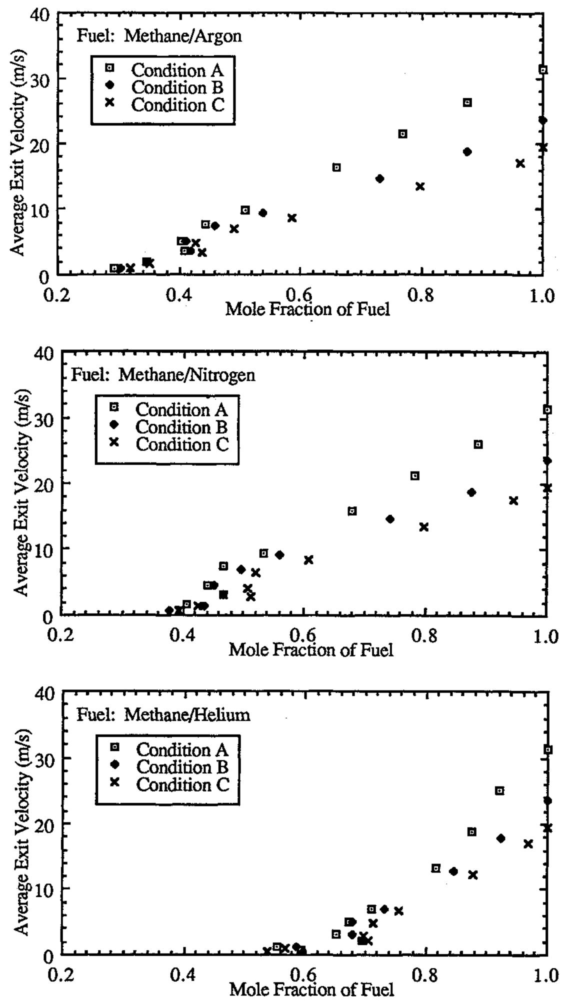

Fig. 3 Annular air velocity effects on methane jet diffusion flame liftoff.

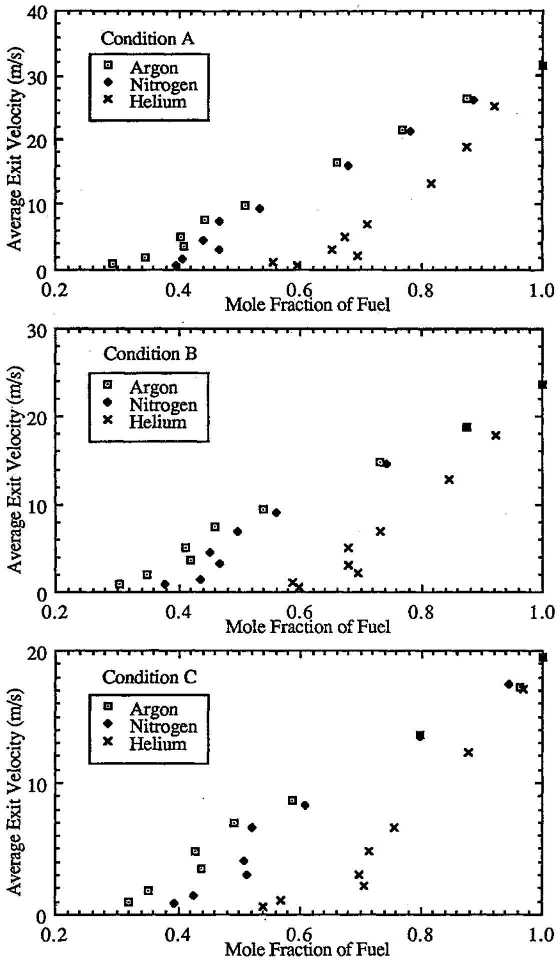

Fig. 4 Diluent effects on methane jet diffusion flame liftoff.

= 0.6. Similar observations are made for conditions B and C. The respective values at condition B are 23.7 m/s at X_F = 1, 0.99 m/s at X_{Ar} = 0.3, 0.82 m/s at X_{N_2} = 0.38, and 0.59 m/s at X_{He} = 0.6. Those values at condition C are, respectively, 19.5 m/s at X_F = 1, 0.97 m/s at X_{Ar} = 0.32, 0.79 m/s at X_{N_2} = 0.39, and 0.57 m/s at X_{He} = 0.54.

The data of Fig. 3 are replotted to show the diluent effects by Fig. 4. It appears that helium has the most destabilizing effects, i.e., the helium diluted jet has the lowest liftoff velocity when the same mole fraction of dilution is considered. Argon dilution shows the least destabilizing effect among the three inert gases examined. This observation is in contrast to previous work investigating the same diluents in a hydrogen jet diffusion flame at liftoff.[4,5] The hydrogen jet diffusion flame liftoff was investigated using normal annular air[4] or substitute air.[5] The substitute air replaced nitrogen with argon or helium in composition. These two studies revealed that helium was the most stable, and argon the least stable among the three inert gases examined. Normal and substitute air had little, if any, influence on the liftoff characteristics of hydrogen jet diffusion flames.[4,5] The opposite trends in the liftoff velocities of hydrogen and methane jet diffusion flames using the same inerts are surprising. One additional note is that the laminar burning velocity has been recognized to be an important parameter in the liftoff of jet diffusion flames. The laminar burning velocity, however, increases with the substitute of helium in air for both hydrogen[4] and methane[9] flames.

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