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Autoignited laminar lifted flames of methane/hydrogen mixtures in heated coflow air

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ABSTRACT

Autoignited lifted flame behavior in laminar jets of methane/hydrogen mixture fuels has been investigated experimentally in heated coflow air. Three regimes of autoignited lifted flames were identified depending on initial temperature and hydrogen to methane ratio. At relatively high initial temperature, addition of a small amount of hydrogen to methane improved ignition appreciably such that the liftoff height decreased significantly. In this hydrogen-assisted autoignition regime, the liftoff height increased with jet velocity, and the characteristic flow time – defined as the ratio of liftoff height to jet velocity – correlated well with the square of the adiabatic ignition delay time. At lower temperature, the autoignited lifted flame demonstrated a unique feature in that the liftoff height decreased with increasing jet velocity. Such behavior has never been observed in lifted laminar and turbulent jet flames. A transition regime existed between these two regimes at intermediate temperature.

1. Introduction

Natural gas is one of the world's major energy sources, and has methane (CH_4) as its primary constituent. Since the C–H bond energy is relatively large, high temperatures are required for autoignition; around 1100–1200 K under diesel-like conditions [1,2]. This could limit the use of natural gas for diesel engines or low-temperature combustion engines. Recently, there has been a growing interest in hydrogen-enriched natural gas combustion, such as HCNG (or H_2CNG). This could extend the lean flammability limit, improve flame stability, reduce emissions, and decrease the ignition temperature. The effect of adding hydrogen on the ignition delay time and ignition temperature have been investigated previously [3–8].

The autoignition of hydrogen has been extensively investigated [9–13] in turbulent non-premixed jets. In a counterflow jet with heated air, the ignition temperature required to ignite a cold hydrogen/nitrogen fuel stream was investigated under varying conditions of turbulence level, fuel concentration, and pressure [14,15]. For methane/hydrogen mixture fuels in laminar counterflow with heated air, the ignition regimes were identified as: (1) hydrogen-assisted, (2) transitional, and (3) hydrogen-dominated [16].

Studies on autoignition in laminar jets are rather limited. Recently, lifted flame characteristics have been investigated in laminar coflow jets at elevated temperature [17,18]. When the temperature was low, conventional laminar lifted flames were stabilized for fuels with a Schmidt number Sc larger than unity (e.g. propane and *n*-butane) by having a tribrachial edge structure at the base of the lifted flame [19–23]. As the temperature was raised above a certain threshold, autoignition occurred and stationary lifted flames were stabilized for all the gaseous hydrocarbon fuels tested, irrespective of Sc, including methane, ethylene, ethane, propane, and *n*-butane. For methane jets, autoignited laminar lifted flames were observed when the initial temperature T_0 was greater than 940 K; a higher level than that required for the other gaseous hydrocarbon fuels tested [17,18].

The objective of the present study is to investigate autoignition behavior in laminar coflow jets, as the proportion of hydrogen in the methane/hydrogen fuel mixture is varied.

2. Experiment

The apparatus consisted of a coflow burner, a flow control system, and a heater assembly. The coflow burner had a central fuel nozzle made of stainless steel with an inner diameter d = 3.76 mm. The length of the nozzle was 750 mm; sufficient for the flow inside to be fully developed. The coflow air was supplied through a metal fiber, ceramic beads and a ceramic honeycomb, to produce a uniform flow. The effective inner diameter of the honey-

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comb was 133 mm. A Pyrex tube with inner diameter 133 mm was installed above the burner to prevent outer flow disturbance. A ceramic insulator 500 mm in length, 300 mm in diameter, and 80 mm thick was placed around the tube to minimize heat loss. The detailed inner structure of the coflow burner has been reported previously [17,18].

Chemically-pure methane (>99.95%), hydrogen (>99.99%), and nitrogen diluent (>99.99%) were supplied through a mixer filled with glass beads to ensure homogeneous mixing. Compressed air was used for the coflow. The flow rates were controlled by mass flow controllers. A cathetometer was used to measure liftoff height, which was defined as the distance between the nozzle tip and the base of the lifted flame. A digital camera and a high-speed camera were used for visualization.

The heater assembly had two pre-heaters in parallel and a main heater to control coflow air temperature. Compressed air passed first through the star-shaped pre-heaters (each 2.5 kW) and was then supplied to a cylindrical ceramic heater (7.5 kW), which also served as the inner surface of the burner body. The fuel nozzle was heated by the outer air and the ceramic heater.

To test whether the temperature of the heated coflow air was uniform, temperature measurements were taken along the axial and radial directions using K-type thermocouples with an outer diameter of 3 mm. The radial temperature was uniform up to 50 mm radial distance within limits of ±2 K. The axial temperature was also relatively uniform up to the edge of a lifted flame with a maximum deviation of 20 K. The temperature difference between the fuel and coflow air along the radial direction from the nozzle exit was within 10 K under all conditions of jet velocity (U_0) tested. Thus, the fuel and air temperatures were considered to be the same. The coflow velocity was fixed at V_{CO} = 1.1 m/s to maintain uniform temperature up to the edge of lifted flames. The flow velocity in the following was determined from the flow rate measurement considering density variation.

3. Results and discussion

A lifted flame for methane fuel does not exist in a laminar free or weak coflow jets at the room temperature condition [21–24], or at elevated temperatures below an autoignition temperature T_{ig} [18]. When the initial temperature T_0 was raised above T_{ig}, the flame was autoignited without requiring any external ignition source. In the present experiment, the methane/hydrogen fuel with nitrogen diluent produced autoignited lifted flames for T_0 > 940 K. For T_0 < 940 K, autoignition was not observed even without nitrogen dilution, i.e. where the initial fuel mole fraction $X_{F,0}$ = 1.0. The autoignition temperature for the stoichiometric fuel/air mixture $T_{ig,st}$ has been reported as 868.15 K for methane [25]. Considering the present jet configuration and nitrogen dilution, the observation of autoignited flames for T_0 > 940 K is reasonable.

In the following, the liftoff height characteristics of autoignited flames will be reported by varying the initial temperature, fuel mole fraction, and hydrogen ratio R_H, which is defined as $X_{H,0}/(X_{C,0} + X_{H,0})$, where the subscripts C and H indicate methane and hydrogen, respectively. Three ignition regimes were identified: (1) a hydrogen-assisted autoignition regime at relatively high temperature, (2) a regime in which liftoff height decreases with increasing jet velocity at low temperature, and (3) a transition regime at intermediate temperature.

3.1. Hydrogen-assisted autoignition regime

Direct photographs of autoignited stationary lifted flames for (T_0, U_0) = (980 K, 20.0 m/s) with R_H = 0.02, are shown in Fig. 1 for various values of $X_{F,0}$. For $X_{F,0}$ = 0.20 (a), the autoignited lifted flame

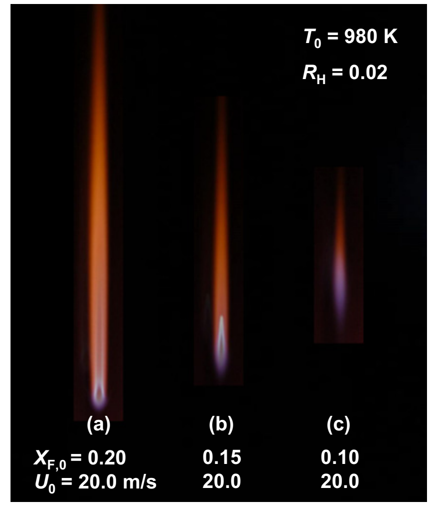

Fig. 1. Direct photographs of autoignited lifted flames at fixed (T_0, R_H, U_0) = (980 K, 0.02, 20.0 m/s) for $X_{F,0}$ = 0.20 (a), 0.15 (b), and 0.10 (c).

exhibits a tribrachial edge structure at the base similar to the one reported earlier [17], which consists of a rich premixed flame core, a lean premixed flame wing, and a trailing diffusion flame, all extending from a tribrachial point. The flame edge exhibits typical colors with a greenish-blue inner core of rich premixed flame and blue–violet rim of lean premixed flame. Note that a trailing diffusion flame typically has faint blue color since it is formed by the excess fuel, mainly CO and H_2, from the rich premixed flame and excess oxidizer from the lean premixed flame. The present trailing diffusion flame, however, has a reddish color, which can be attributed to water vapor as was observed for hydrogen flames [26,27] and autoignited lifted flames of methane at high initial temperature [18]. As $X_{F,0}$ decreases to 0.15 (b) and 0.10 (c), the flame gradually changes to a faint red–violet color without showing a distinct tribrachial edge structure. This behavior can be explained by the transition to the mild combustion regime [18,28].

The liftoff height behavior at T_0 = 980 K is first analyzed, where the temperature is sufficiently high for autoignition of methane fuel to occur without the addition of hydrogen. For $X_{F,0}$ = 0.20, the autoignited liftoff height H_L as a function of jet velocity is presented in Fig. 2 for various hydrogen ratios. The autoignited lifted flames exhibit a hysteresis behavior with jet velocity. For the pure methane fuel (R_H = 0), an autoignited nozzle-attached flame exists when U_0 is small. As the jet velocity increases, a direct blowoff

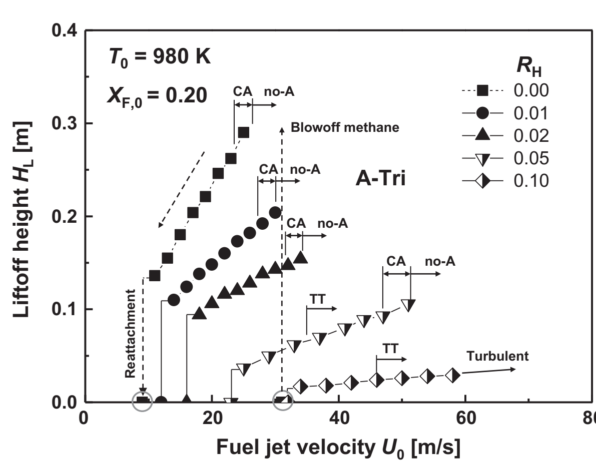

Fig. 2. Liftoff height with jet velocity for various R_H with T_0 = 980 K and $X_{F,0}$ = 0.20.