LIFTED FLAMES OF N-HEPTANE IN COFLOW JETS WITH INITIAL TEMPERATURE VARIATION

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Summary The characteristics of laminar lifted flames of *n*-heptane diluted with nitrogen have been investigated by varying the initial temperature in coflow jets. The result showed that the lifted flame in the non-autoignited regime has a tribrachial structure similar to the cases of gaseous fuels, and the liftoff heights are correlated reasonably with fuel jet velocity scaled by the laminar burning velocity. For the coflow temperature above 900 K, autoignited flames are formed that did not require any external ignition source. For smaller fuel mole fraction, mild combustion is observed. The liftoff heights of autoignited lifted flames could also be correlated with fuel jet velocity scaled by laminar burning velocity. While the correlation with the adiabatic ignition delay time is weak, which implied the insensitivity of the delay time with temperature variation in this temperature range.

INTRODUCTION

The stabilization of non-premixed jet flames has been one of the important factors for the safety and efficiency in practical combustors, as such the stabilization characteristics has been investigated accounting for various factors, including fuel type and nitrogen dilution. It has been shown that the stabilization of lifted flames in laminar jets is governed by a tribrachial structure, which consists of a lean and rich premixed flame wings and a trailing diffusion flame, all extending from a single location. The stabilization characteristics in high temperature autoignited regime have been studied for gaseous fuels, demonstrated the importance of ignition delay time. While studies with liquid fuels are rather limited. In the present study, the characteristics of laminar lifted flames of *n*-heptane have been studied experimentally in a wide range of initial temperature in coflow jets.

EXPERIMENT

The experimental apparatus consisted of a coflow burner and flow controllers, a heating system, and a measurement setup. The burner had a central fuel nozzle made of stainless steel with 3.76 mm in i.d. and 50 cm in length. The coflow air was supplied to the coaxial nozzle. A pyrex tube with 85 mm i.d. and 50 cm in length was placed on the coflow nozzle to confine heated coflow air. The fuel was *n*-heptane diluted with nitrogen. The flow rate of liquid fuel was controlled by a syringe pump. Gas flow rates were metered by mass flow controllers. To vaporize the liquid fuel, the fuel supply line was heated by rope heaters. The coflow air was heated by an inline heater and a coil heater. The temperature of heated air was measured at the exit of the coaxial nozzle with K-type thermocouples. The liftoff height was measured by a cathetometer and the flames were visualized by a direct photography.

RESULTS AND DISCUSSION

The characteristics of laminar lifted flames are investigated by varying the initial temperature T_0, fuel mole fraction $X_{F,0}$, and jet velocity U_0. When $T_0 < 900$ K, an ignition source is required to form a flame. At small U_0, the flame is attached to the nozzle (Fig. 1a). As the jet velocity increases, the flame is lifted off from the nozzle and is stabilized as a lifted flame. The lifted flame edge exhibits a typical trabrachial structure (Fig. 1b). The liftoff height H_L increases with U_0 nonlinearly, and at an excessive U_0, the blowout occurs. When observing the liftoff heights with U_0 at various fuel mole fractions and initial temperatures, the overall trend of liftoff heights in coflow jets agrees with the previous results for gaseous fuels. When the lifted flame edge is in the developed region of the jet, the slope of H_L versus U_0 is reasonably linear in the log-log plot, which indicates that there exists a relationship of $H_L{\sim}U_0^n$.
At specified T_0 and U_0, H_L decreases with $X_{F,0}$, and at specified U_0 and $X_{F,0}$, H_L decreases with T_0. These behaviors can be explained based on the balance mechanism between the local flow velocity and the propagation speed of edge flame. As $X_{F,0}$ and T_0 increases, the stoichiometric laminar burning velocity $S_L^0|_{st}$ which is strongly related to the propagation speed of the tribrachial flame increases, such that the liftoff height decreases. To emphasize the importance of the role of the laminar burning velocity through the propagation speed of tribrachial flame edge, the liftoff heights in the developed region are plotted in terms of the jet velocity scaled by $S_L^0|_{st}$ in Fig. 2. The result shows that the liftoff heights are correlated reasonably with H_L [m] $= 0.00672 \times (U_0/S_L^0|_{st})^{2.18}$. The result implies that the balance mechanism is still effective regardless of initial temperature in the non-autoignited regime.

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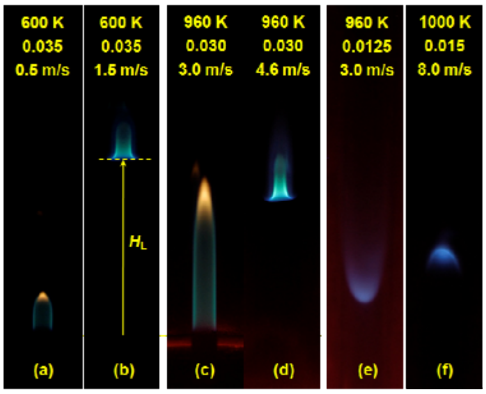

Figure 1. Direct photos of flames for various temperature and flow conditions.

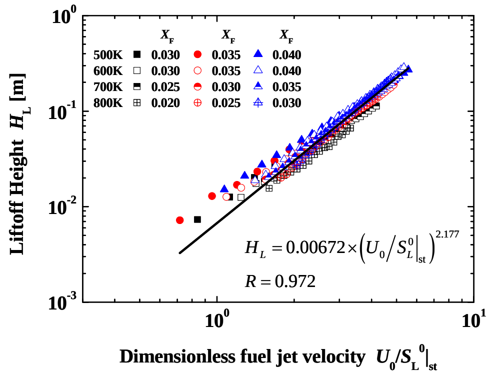

Figure 2. Liftoff heights of non-autoignited flames with scaled fuel jet velocity by $S_L{}^0|_{st}$.

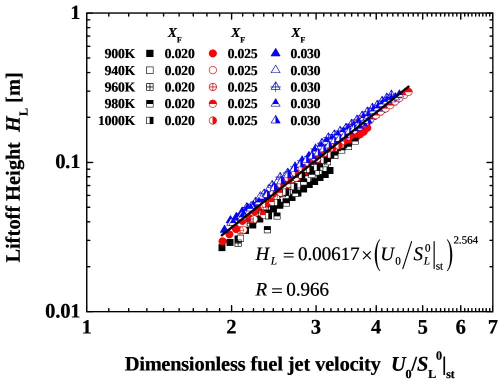

Figure 3. Liftoff heiths of autoignited flames with scaled fuel jet velocity by $S_L{}^0|_{st}$.

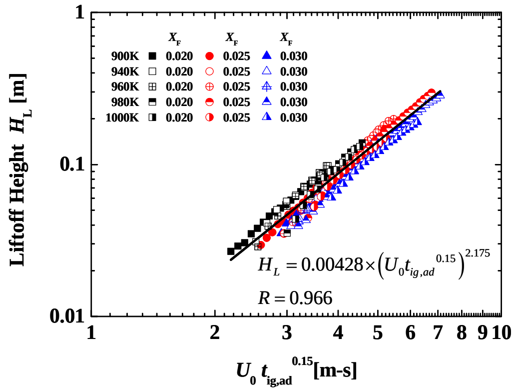

Figure 4.Liftoff heights of autoignited flames with scaled fuel jet velocity by $t_{ig,ad}$.

When T_0 > 900 K, a flame can be formed by autoignition without requiring any external ignition source. Figure 1c and d show the attached and lifted flame in the autoignited regime. The autoignited lifted flame (Fig. 1d) has a typical tribrachial edge structure similar to the non-autoignited flame (Fig. 1b). While for smaller $X_{F,0}$, the flame does not show a tribrachial structure and exhibited mild combustion behaviour (Fig. 1e and f). When focusing on the liftoff height of tribrachial flames in the developed region, H_L are correlated reasonably with $U_0/S_L{}^0|_{st}$ similar to the cases of non-autoignited flames (Fig. 3). The previous studies on the autoignited lifted flames with gaseous fuels have shown an excellent correlation of H_L with the square of adiabatic ignition delay time $t_{ig,ad}$ of the homogeneous mixture of fuel and air in stoichiometry. For a liquid fuel in this study, the correlation with $t_{ig,ad}{}^{0.15}$ is obtained, instead of $t_{ig,ad}{}^2$ for gaseous fuels. Based on the ignition delay time calculations, this result implies that the temperature range might correspond to the case with insensitive dependence on initial temperature. Future study is needed for the understanding of these flame characteristics, including the mild combustion behavior.

CONCLUSIONS

Lifted flame behavior of *n*-heptane fuel in the coflow jets has been studied experimentally by varying the initial temperature. In the non-autoignited regime, the lifted flame has a tribrachial structure similar to the cases of gaseous fuels. The liftoff heights can be correlated reasonably with the jet velocity scaled by the stoichiometric laminar burning velocity, regardless of the initial temperature. In the autoignited regime, the liftoff heights exhibited different behaviour as compared to previous gaseous fuels, demonstrating weak dependence on ignition delay time. While the liftoff heights are correlated reasonably with laminar burning velocity.

References

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