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Stabilisation of turbulent auto-igniting dimethyl ether jet flames issuing into a hot vitiated coflow

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Abstract

Experimental results focusing on understanding the role of autoignition in the stabilisation of turbulent lifted jet flames of dimethyl ether issuing into a hot vitiated coflow are explored in this paper. A stability map of the flame lift-off height as a function of coflow temperature and jet partially premixing ratios is reported, indicating a strong sensitivity of the mean and rms lift-off heights to the coflow temperature. A new experimental setup that utilises high repetition rate (10 kHz) joint OH and CH_2O PLIF combined with a third camera to track out of plane motion via chemiluminescence emission is employed. This allows the temporal dynamics of the flame base and autoignition kernels to be tracked at high spatial resolution over a spatial window of 20 mm (height) × 43 mm (width). To capture the temporal statistics of the flame over the full lift-off height range, a complementary, but not simultaneous, large field of view high-speed chemiluminescence imaging experiment was employed. The use of high-speed diagnostics is shown to be invaluable to understand the temporal dynamics of the flame base region, such as identifying and tracking autoignition kernels ahead of, and merging with, the main flame base. For low coflow temperatures, autoignition kernels are found to be fundamentally important to the stabilisation of the flame: small autoignition initiated kernels rapidly grow to form large flame kernels that eventually merge with the main flame base and in doing so rapidly establish a new lift-off height significantly upstream of the original flame base. For high coflow temperatures, autoignition kernels whilst still present, are significantly smaller in mean size and play a reduced role in the overall flame stabilisation. This leads to the conclusion that partially premixed flame propagation plays an increased role in overall flame stabilisation for high coflow temperature flames.

Keywords: Turbulent flame; Autoignition; Lifted flame stabilisation; Dimethyl ether; High speed PLIF

1. Introduction

Dimethyl ether (DME) is a promising alternative fuel and a possible replacement for conventional fossil fuel-derived diesel in compression ignition engines [1]. DME has several desirable combustion properties such as a high cetane number, low autoignition temperature and low

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sooting propensity due to the fuel bound oxygen. The kinetics of DME is significantly more complex with respect to low temperature and autoignition chemistry compared to simpler fuels such as methane and syngas due to DME's multiple chemical pathways leading to autoignition [2]. As such it is of great interest to study turbulence-chemistry interactions in DME flames where autoignition and low-temperature chemistry play an important role.

Experimentally, the study of turbulent autoignition utilising the configuration of a jet in a hot vitiated coflow as first reported by Cabra et al. [3,4] has revealed significant insight into the turbulent autoignition of hydrogen and methane flames. With a sufficiently large diameter hot coflow, flame stabilisation and autoignition over a range of regimes, conditions and fuels can be explored without the complication of entrainment and reaction quenching from cold ambient air [4–9]. The configuration of an electrically heat coflow of air that mixes with a fuel jet has also been shown to be a successful platform to study autoignition [9]. By investigating the effects of turbulent intensity, turbulent length scales and fuel type on the delay in autoignition, it has been shown that the autoignition delay increases with turbulence intensity and decreases with coflow temperature. This highlights the fact that autoignition is not only kinetically controlled but is also influenced by turbulence [9,10]. DNS studies have also found that autoignition locally occurs preferentially in regions of the most reactive mixture fraction combined with simultaneous low scalar dissipation rates [11–13]. The formation of autoignition kernels in regions of low scalar dissipation rates and for the most reactive (lean) mixture fraction has also been found experimentally [14,15]. The additional influence of pressure for DME turbulent combustion has also been highlighted by Fast et al . [16], showing that slow, low-temperature chemical kinetics dominate in the multistage ignition of transient pulsed DME jets issuing into temperature environments of 720 K.

Since autoignition is strongly dependent on chemical kinetics, monitoring radical species plays an important role in understanding the evolution of autoignition. CH_2O is often used as an indicator of low-temperature reactions [17], while OH can be used as a reaction zone marker. Their product is an indicator of the formyl radical formation rate, which has been shown to be proportional to the heat release rate in methane–air flames [18]. Utilising simultaneous OH and CH_2O PLIF, Gordon et al. [5] has studied methane autoignition kernel development in a vitiated hot coflow burner reporting a correlation between the build-up of high CH_2O levels with no OH upstream of the kernel formation region and flame base. Bhagatwala et al. [19] have shown that the product $[CH_2O][OH]$ is also a good surrogate for the heat release rate in a DME flame, a conclusion that is adopted in this study.

Autoignition is a strongly transient phenomenon, and as such it is highly relevant to study not only the spatial structure of the flame but also the temporal structure of the flame. The use of high speed 10 kHz OH^* chemiluminescence combined with OH PLIF imaging in a methane jet in a hot coflow has been used previously to determine the axial location of kernel ignition events and their respective ignition delay time and rate [20]. Based on high-speed chemiluminescence imaging, extensive analysis on the flame lift-off height and kernel formation was conducted by Oldenhof et al. [21], identifying that for certain flames, kernel formation and consumption in addition to advection was responsible for flame stabilisation.

This paper presents an experimental study of the turbulent autoignition of DME jets in a hot vitiated coflow burner. Both the minor species CH_2O and OH as well as chemiluminescence emissions are imaged simultaneously using high-speed 10 kHz diagnostics to provide a unique temporally and spatially resolved insight into the structure and stabilisation mechanism of the studied flames.

2. Experimental setup

2.1. Burner

The burner utilised in this paper is similar to that used by Cabra [3], however with some geometrical changes: the hot vitiated coflow has a diameter of 197 mm with ~1800 × 1.6 mm diameter holes to stabilise the lean H_2/air flames and the central jet inside diameter (D_j) is 4.45 mm. The coflow temperature is varied between 1200 K and 1500 K by changing the equivalence ratio of the hot coflow reactants, whilst maintaining a constant burnt velocity of 4 m/s for all cases. Utilising a coflowing wind tunnel of filtered ambient air with a velocity of 0.8 m/s, the 'valid cone' of the hot coflow, where the combustion of the jet mixture can be considered to be completely free from the influence of ambient air dilution and quenching, is measured to be 60 D_j.

In addition to varying the coflow temperature, the impact of partially premixing the DME in the central jet with air was studied for several partially premixing ratios as outlined in Table 1. Utilising air in the jet mixture compared to nitrogen, allows the variation of the adiabatic flame temperature at stoichiometric between cases to be minimised in addition to allowing a larger range of stoichiometric mixture fractions to be examined. The central jet bulk exit velocity was maintained at a constant 50 m/s for all experiments to ensure a consistent advection time scale for high speed imaging near the jet exit. In addition, the constant jet velocity maintains a similar convective time scale between flames allowing a clearer delineation of kinetic and autoignition effects. However as can be seen from Table 1, there is correspondingly a