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Autoignited lifted flames of dimethyl ether in heated coflow air

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ABSTRACT

Autoignited lifted flames of dimethyl ether (DME) in laminar nonpremixed jets with high-temperature coflow air have been studied experimentally. When the initial temperature was elevated to over 860 K, an autoignition occurred without requiring an external ignition source. A planar laser-induced fluorescence (PLIF) technique for formaldehyde (CH_2O) visualized qualitatively the zone of low temperature kinetics in a premixed flame. Two flame configurations were investigated; (1) autoignited lifted flames with tribrachial edge having three distinct branches of a lean and a rich premixed flame wings with a trailing diffusion flame and (2) autoignited lifted flames with mild combustion when the fuel was highly diluted. For the autoignited tribrachial edge flames at critical autoignition conditions, exhibiting repetitive extinction and re-ignition phenomena near a blowout condition, the characteristic flow time (liftoff height scaled with jet velocity) was correlated with the square of the ignition delay time of the stoichiometric mixture. The liftoff heights were also correlated as a function of jet velocity times the square of ignition delay time. Formaldehydes were observed between the fuel nozzle and the lifted flame edge, emphasizing a low-temperature kinetics for autoignited lifted flames, while for a non-autoignited lifted flame, formaldehydes were observed near a thin luminous flame zone.

For the autoignited lifted flames with mild combustion, especially at a high temperature, a unique non-monotonic liftoff height behavior was observed; decreasing and then increasing liftoff height with jet velocity. This behavior was similar to the binary mixture fuels of CH_4/H_2 and CO/H_2 observed previously. A transient homogeneous autoignition analysis suggested that such decreasing behavior with jet velocity can be attributed to partial oxidation characteristics of DME in producing appreciable amounts of $CH_4/CO/H_2$ ahead of the edge flame region.

1. Introduction

Dimethylether (DME) is an oxygenated fuel which has drawn attention recently for various applications such as automotive engines because of its low particulate emission and high cetane number characteristics, suitable for compression ignition engines. DME can be produced from natural gas. For small/medium natural gas wells, conversion of methane into DME can be economical for transportation, considering compression and evaporation of natural gas during transportation processes. DME can also be produced through coal gasification.

The autoignition temperature of DME is 508 K [1], which is very low compared to other hydrocarbons including methane. Thus, DME can be a candidate as an ignition improver [2–6]. DME fuel exhibits negative temperature coefficient (NTC) region which is attributed to two-stage ignition, and features an increase in ignition delay time as temperature increases. Various studies investigated this phenomenon at high pressure conditions [7–9]. Ignition delay times representing fuel reactivity have been measured experimentally [10–14] and kinetic mechanisms have been developed [15–21] to be utilized in numerical simulations.

Ignition delay times are typically measured for homogeneous mixtures in shock tubes and rapid compression machines. While typical autoignition in practical combustion systems such as in diesel and premixed charge compression ignition engines occurs under inhomogeneous conditions. However, studies on the relation between ignition delay times measured under homogeneous conditions and autoignition phenomena under inhomogeneous conditions are limited. Recently, a canonical jet configuration was adopted to investigate the relation between chemical ignition delay time and physical flow time by studying the characteristics of autoignited laminar lifted jet flames in high-temperture coflow

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air for various hydrocarbon fuels [22–27]. The autoignited lifted flames exhibited two distinct structures: tribrachial edge and mild combustion. In the autoignited lifted flame with tribrachial edge, three distinct branches of a lean and a rich premixed flame wings along with a trailing diffusion flame are exhibited, all extending from a tribrachial point [28–30]. The autoignited lifted flame with mild combustion structure with highly diluted fuel is characterized by its faint blue luminosity [22,31]. Such a flame is characterized as the initial temperature T_0 is larger than the autoignition temperature and $(T_f - T_0) < T_0$, where T_f is the flame temperature, corresponding to the enthalpy increase by heat release is smaller than the initial enthalpy [31]. For both flame structures, the ignition delay time was found to be a key parameter for the stabilization of autoignited lifted flames [22,23]. Recently, autoignition characteristics of lifted laminar jet flames of DME have been studied numerically at elevated pressures and temperatures [32–34], revealing a unique polybrachial flame structure, which is attributed to the role of methoxymethylperoxy radical ($CH_3OCH_2O_2$) in DME combustion. However, a systematic experimental study of DME flames under autoignition conditions in jet configuration has not been conducted yet.

Formaldehyde (CH_2O) is an important intermediate species which is formed at early stage of ignition processes through a low-temperature oxidation pathway, which can be visualized by adopting a laser-induced fluorescence (LIF) technique. Thus, a CH_2O PLIF measurement could provide a progress of autoignition process. Several CH_2O-LIF studies have been conducted for various flame configurations including premixed flames [35], non-premixed flames [36], channel-flow catalytic reactor [37], and homogeneous charge compression [38]. The combination of OH-LIF and CH_2O-LIF images has been utilized to identify the flame heat release region [39].

In the present study, autoignited laminar lifted flames of DME with high-temperature coflow air are studied experimentally at the atmospheric pressure condition. This fuel is selected since it is an oxygenated fuel with strong low temperature kinetics, unlike other hydrocarbon fuels investigated previously [22–26]. The structure of DME lifted flame is studied and CH_2O PLIF measurement is conducted. The liftoff heights of autoignited DME flames are analyzed and the role of ignition delay time is investigated. A unique behavior, having a decreasing liftoff height with increasing jet velocity, is reported. Such behavior was never observed for autoignited lifted flames with single component hydrocarbon fuels, while it was observed for binary mixture fuels of CO/H_2 and CH_4/H_2 [24,40]. Partial oxidation characteristics of DME fuel are discussed to explain such a behavior.

2. Experiment

The apparatus consisted of a coflow burner, a flow control system, a heater assembly, and a planar laser-induced fluorescence (PLIF) setup, as schematically shown in Fig. 1. Details of the burner have been reported previously [22]. A stainless-steel fuel nozzle with the inner diameter of $d = 3.76$ mm was placed at the center of the coflow burner. Its length was 750 mm for the flow to be fully developed. A metal fiber, ceramic beads, and a honeycomb were utilized to ensure flow uniformity of the coflow air whose diameter is 133 mm. To minimize the heat loss, a ceramic cylindrical insulator was placed around the air coflow as a confinement, whose length was 500 mm with the outer diameter of 300 mm. For a visualization purpose, three quartz windows were installed.

The fuels were supplied through a mixer filled with glass beads for homogeneous mixing of fuel and nitrogen diluent, which were chemically pure grade of DME (> 99.60%) and nitrogen (> 99.99%). Propane fuel (> 99.95%), exhibiting weak low temperature kinetics, was also used for a comparison in the PLIF measurement. Compressed air was used for the coflow. Gas flow rates were metered by mass flow controllers.

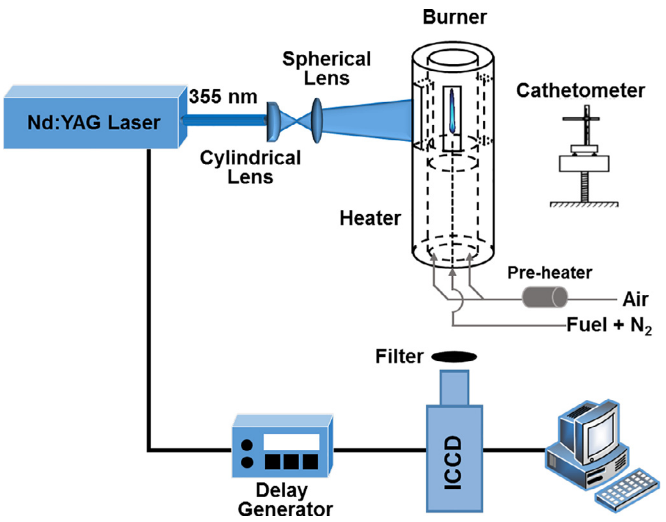

Fig. 1. Schematic of experimental setup.

The heating system had a pre-heater and a main heater to control coflow air temperature. The air passed through the pre-heater with star-wound shape first and then the preheated air was supplied to the ceramic heater, which also served as the inner surface of the burner body. Heat exchange between the heated coflow air and the fuel nozzle occurred inside the ceramic insulator. The temperatures of the heated air and fuel were measured at the exit of the coaxial nozzle and fuel nozzle exit, respectively, with sheathed K-type thermocouples. The temperature difference between the air and fuel was less than 10 K, such that the fuel temperature could be regarded as the same as the coflow air temperature. Details of the effect of radiation in the thermocouple measurement were discussed previously [22–26], which was negligibly small in the initial temperature measurement, typically less than 1000 K.

The coflow velocity was fixed at $V_{CO} = 1.1$ m/s to maintain a uniform temperature up to the edges of lifted flames. Details about temperature uniformity have been reported previously [22–26]. Liftoff heights were measured by a cathetometer.

For the PLIF measurement of CH_2O, a third-harmonic of Nd:YAG laser (Quantel, Brilliant) was used to excite formaldehyde at 355 nm (rotational transitions within the $\tilde{A}^1A_2 - X^1A_1 4_0^1$ vibronic manifold) [41]. The 6 mm-diameter UV pulsed laser beam (10 Hz) was supplied with an energy of 170 mJ/pulse to ensure an excitation of formaldehyde. Then, the beam was expanded to form a thin laser sheet (3 cm width) for visualizing a 2D image of CH_2O PLIF. This was accomplished by combining plano-convex cylindrical and spherical UV fused silica lenses with focal lengths of 15 and 75 cm, respectively. The formaldehyde fluorescence was detected using an ICCD camera (Princeton Instrument) with a UV lens, together with a combination of long- and short-pass filters (400–450 nm) placed in front of the camera to collect the formaldehyde fluorescence. This broadband absorption-detection was selected to ensure high formaldehyde signal [41,42]. The interference of PAH fluorescence can be neglected because they are saturated at high laser excitation energy while the formaldehyde fluorescence is expected to be in the linear regime [41,42]. The number of accumulated single shot images was fixed at 20 for all cases to compare the qualitative CH_2O intensities for different cases. The excitation laser energy/pulse was fixed for all cases. The laser system and camera were synchronized using a delay generator and a computer software. A digital camera was used to capture visible images of flames.

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