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Temporal evolution of auto-ignition of ethylene and methane jets propagating into a turbulent hot air co-flow vitiated with NO_x

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ABSTRACT

In this paper, the temporal evolution of auto-ignition (AI) of C_2H_4 and CH_4 jets propagating into a NO_x vitiated hot co-flow at high velocity and turbulence was studied. Simultaneous temporally-resolved planar laser-induced fluorescence (PLIF) experiments of OH and CH_2O were carried out in a recently developed test rig for auto-ignition studies of turbulent non-premixed flows. Flame stabilization mechanisms were analyzed for both fuels at several operating conditions. The reaction progress of AI kernels as well as their apparent growth rate were evaluated. Results revealed that the stabilization mechanism (i.e. lifted flame or isolated kernel) strongly depends on the turbulent mixing, co-flow temperature and fuel composition. A further statistical analysis of the heat release rate (HRR) zones, calculated as the product of the CH_2O- and OH-PLIF signals, delivered an indication on the different AI characteristics of C_2H_4 and CH_4. An evaluation of the temporal evolution of the HRR for C_2H_4 jets provided a deeper insight about the reaction progress at different conditions of the co-flow, when AI was initiated by isolated kernels. Finally, estimations of the apparent growth rate of AI kernels indicated a faster propagation of C_2H_4 kernels when compared with those of CH_4.

1. Introduction

Auto-ignition (AI) of turbulent non-premixed flows is a phenomenon of great importance in the development of industrial combustion systems. AI is necessary to initiate the combustion in devices such as diesel engines, homogeneous charge compression ignition engines, and flameless combustors [1] and it needs to be avoided in applications such as lean premixed prevaporized gas turbines [2].

Important advances in understanding the phenomena involved in the turbulence–chemistry interactions during AI of flowing mixtures have been made substantially through two- and three-dimensional direct numerical simulations [2,3]. From the experimental side, studies of a fuel jet propagating into a hot co-flow have been carried out to mimic AI conditions similar to those during practical processes. Existing experimental facilities include cold jets of different fuels propagating into a vitiated air co-flow from lean combustion of hydrogen [4,5] or natural gas [6], and into a electrically-heated flow of air [7]. Besides, a novel plasma heater test rig for auto-ignition studies of turbulent non-premixed flows is now available [8].

Successful experimental advances in AI have been made by carrying out spatially and temporally-resolved measurements of velocity fields [9] and important scalars such as temperature [4,5], mixture fraction [5], and major and minor combustion species [10,11] using laser-based techniques. Collected experimental data is used to develop, validate and improve predictive models, to increase the understanding on AI phenomena, and to confirm fundamental findings achieved mainly through simulations.

Studies have revealed that the initiation and evolution of AI is influenced by specific physical and chemical properties of the flows as well as by turbulence–chemistry interactions. Therefore, time-resolved measurements are necessary to investigate the temporal evolution of AI events [2]. Ignition precursors from low-temperature reactions such as formaldehyde (CH_2O) and the

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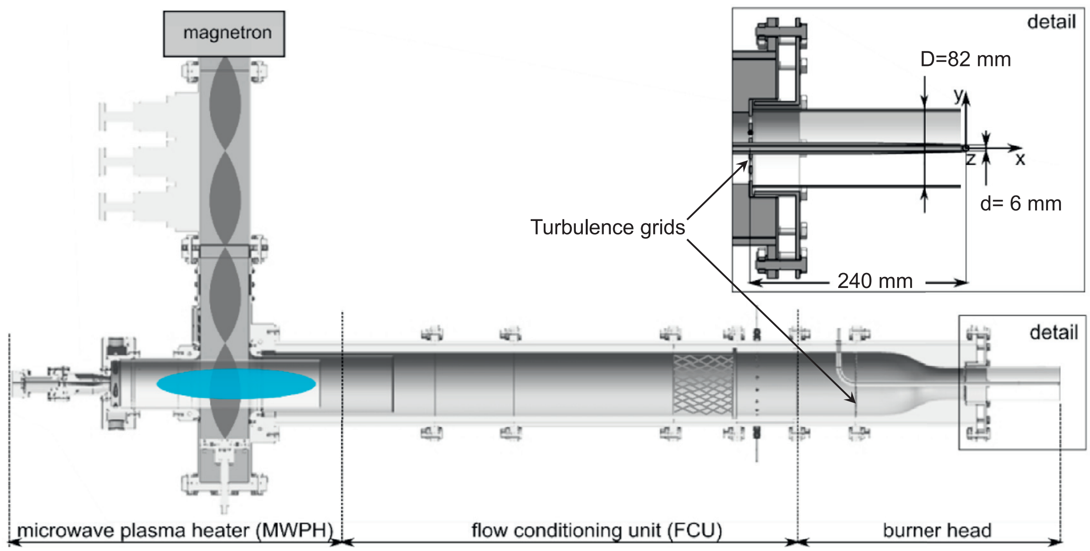

Fig. 1. Schematic cross section of the auto-ignition test rig. From left to right, the three main sections: microwave plasma heater (MWPH), flow conditioning unit (FCU) and burner head. Detail shows geometric boundaries at the exit of the burner head as well as the origin of the global coordinate system (*x*,*y*,*z*) located at the tip of the fuel lance.

hydroperoxyl radical (HO_2) play important roles in the initiation and flame stabilization mechanisms during AI processes [12–14]. Hence, simultaneous two-dimensional measurements of temperature, CH_2O and hydroxyl radical (OH) have provided a better insight into the nature of the processes involved during AI events [11,12]. Additionally, the product of quantitative images of CH_2O and OH has been used as a tool to semi-quantify and study the heat release rate (HRR) in non-premixed auto-igniting flames [11]. However, those measurements are only pseudo time series made of several single-shot images and time-resolved information on HRR during AI events is not yet available.

Moreover, there is still a gap of available experimental data for fuel jets propagating into co-flows at high temperatures, velocities and turbulence intensities [2,8]. In this paper, a study on the AI characteristics of ethylene (C_2H_4) and methane (CH_4) jets propagating into a NO_x vitiated hot co-flow of air at high velocity and turbulence was carried out. Simultaneous temporally-resolved planar laser-induce fluorescence (PLIF) measurements of CH_2O and OH allowed visualizing the low- and high-temperature reaction zones and their evolution with time. Flame stabilization mechanisms were analyzed for both fuels at several operating conditions based on the structure of the reaction zones and heat release rate distribution during AI events. A methodology for the evaluation of the reaction state and progress of AI kernels was implemented. Additionally, an evaluation of the apparent growth rate of AI kernels was performed by tracking their propagation and transportation in the flow field.

2. Materials and methods

2.1. Auto-ignition test rig

Experiments were carried out using a novel plasma test rig for auto-ignition of a fuel jet propagating into a hot turbulent co-flow. The test rig, schematically shown in Fig. 1, consists of three main sections: the co-flow of air is heated up by a microwave plasma heater (MWPH) (1), followed by a flow conditioning unit (FCU) (2) that shapes the flow profile and finally a burner head (3) including the fuel injection. The design allows having short heat-up times (from room temperature to 1300 K in ∼ 30 min.), reduced co-flow temperature variations (± 2 K), bulk exit velocities of up to 40 ms^{-1} with adjustable turbulence levels, and a top-hat temperature distribution in radial direction within the region of interest for AI studies. In addition, the variation of the co-flow and fuel compositions is possible. A detailed description of the test rig as well as its capabilities and limitations can be found elsewhere [8].

For the current setup, the fuel lance and the co-flow nozzle had inner diameters of 6 and 82 mm, respectively. Up- and downstream of the contoured nozzle, two turbulence enhancing perforated plates, with a hole diameter of 8 mm and a blockage ratio of 35%, were employed to control the integral length scale and to generate a turbulence intensity in the co-flow of ∼ 13% (at 1273 K) at locations where auto-ignition events initiate [8]. At the exit, the co-flow nozzle and the fuel lance were staggered by 5 mm to allow for full optical access directly at start of fuel injection. All measurements in the present study were spatially referred to the coordinate system (*x*,*y*,*z*) located at the tip of the fuel lance as shown in the detail of Fig. 1.

2.2. Operating conditions

Operating points of the test rig were defined by the Reynolds number of the jet (Re_{jet}), the co-flow control temperature ($T_{co-flow-ctrl}$), which was measured at the position of the second turbulence grid with an uncertainty of ± 2 K, and the Reynolds number of the co-flow ($Re_{co-flow}$) [8]. Methane (CH_4) and ethylene (C_2H_4) were investigated as fuels in the present study. The co-flow was mainly composed of N_2 and O_2. However, because air is heated up generating a high temperature plasma, the co-flow contained mole fractions of NO ranging from 4000 to 10,000 ppm, NO_2 from 100 to 1200 ppm and OH up to 28 ppm, depending on the temperature and bulk exit velocity of the co-flow. Inflow boundary conditions at the nozzle exit of the test rig such as temperature profile, co-flow composition and velocity field have been previously reported for selected operating conditions [8].