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# The role of temperature, mixture fraction, and scalar dissipation rate on transient methane injection and auto-ignition in a jet in hot coflow burner

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ABSTRACT

The transient injection and subsequent auto-ignition of a methane jet issuing into a laminar coflow of hot exhaust gas from a lean premixed hydrogen air flame was studied using high-speed planar Rayleigh scattering, yielding two-dimensional measurements of mixture fraction, temperature and scalar dissipation rate with high spatio-temporal resolution. The temporal development of the mixing field between the transient fuel jet and the surrounding coflow prior to the occurrence of auto-ignition was examined at a sampling rate of 10 kHz. The impact of the transient jet development on numerical modeling of this test case is discussed. It was found that auto-ignition occurred after the jet transitioned from a transient state into the steady state, thus eliminating the need to model the complete transient fuel injection when the primary focus is on the onset of auto-ignition.

Simultaneous high-speed OH* chemiluminescence from two viewing angles was applied to gain 3D-information of the ignition kernel location. This information allowed the selection and analysis of ignition events where the initial kernel formed inside the laser light sheet. Detailed analysis of the dynamics of a single ignition event, as well as statistical analysis of multiple ignition events based on a joint probability density approach, indicated that the ignition kernels occurred at very lean mixture fractions and at locations with low scalar dissipation rates.



## 1. Introduction

The mixing and auto-ignition of (cold) fuel in a hot oxidizer stream is of great technical importance in several combustion systems, including internal combustion engines operating under diesel or homogeneous compression charge ignition (HCCI) conditions, gas turbine combustors employing FLOX®, MILD or reheat combustion, and scramjet applications. Auto-ignition in lean premixed gas turbine combustion can lead to the establishment of a flame in an undesired region such as the mixing section and therefore lead to combustor damage [1]. Similarly, auto-ignition must be prevented in the mixing duct of reheat combustors, where fuel is injected into the lean (diluted) combustion products of a primary combustion stage [2]; in spark-ignition internal combustion engines to avoid knock; and in flammable material storage. Additionally, auto-ignition can play an important role in the flame stabilization in combustors with high recirculation, such as swirl-stabilized combustors [3] or FLOX® combustors [4]. In MILD combustion [5] and High Temperature Air Combustion (HiTAC) [6] the temperature of one or all of the reactants is higher than the auto-ignition temperature of a stoichiometric mixture [5–7] and thus auto-ignition can contribute significantly to the flame stabilization. Finally, it has been noted that in scramjet applications with flameholders auto-ignition plays a significant role in the flame stabilization mechanism due to the transport of hot gases into a lower-speed location.

Due to the complexity of the underlying physical and chemical processes, auto-ignition remains a challenging field of research. While auto-ignition is a transient process, the majority of previous experimental studies in turbulent flows have focused on stably burning lifted jet flames which are stabilized by auto-ignition. Here, continuously-fed fuel jets were studied, either issuing into hot air [8,9], or into a coflow of hot, vitiated combustion products [10–17]. The latter configuration is termed jet in hot coflow or JHC, and has gained significant research interest in recent years [18].

Cabra et al. [10,11] performed point-wise Raman/Rayleigh/laser-induced fluorescence measurements in nitrogen-diluted hydrogen

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and in methane jets with vitiated coflow temperatures between 1045 K and 1350 K. They measured peak temperatures as an indicator for heat release conditioned on the mixture fraction at different axial locations. For the lower axial locations it was found that heat release occurred at mixture fractions much leaner than the stoichiometric mixture fraction, while for the higher axial locations, heat release occurred at values close to the stoichiometric mixture fraction.

Temperature imaging via Rayleigh scattering in JHC configurations has been performed by Medwell et al. [14] and Gordon et al. [15]. Both studies used simultaneous OH and $CH_2O$ planar laser-induced fluorescence (PLIF) to gain information about ignition-kernel formation and flame stabilization mechanisms. Medwell et al. [14] found a strong influence of the coflow oxygen content on the peak temperature in the reaction zone. Gordon et al. [15] observed isolated ignition kernels corresponding to a rise of temperature and $CH_2O$ concentration; however, OH was not present in all ignition kernels, indicating auto-ignition (and not flame propagation) is a primary mechanism behind lifted flame stabilization. With the recent development of high-speed laser measurement and imaging techniques [19–21], new insights into the mechanisms governing auto-ignition has been gained in transient systems [17,22–31]. In the current work, high-speed laser-based measurements are used to reveal details of the roles of temperature, mixture fraction, and scalar dissipation rate on auto-ignition within a JHC configuration.

One approach to study auto-ignition is with the use of transient jets via pulsed fuel injection. However, to understand auto-ignition in such a transient system, first the behavior of the transient jet has to be studied in detail. The first attempts to derive scaling laws for transient jets (i.e., jet penetration depth) were made by Witze [32]. It was shown that the centerline velocity of an impulsively-started jet reached the steady-state jet value very quickly (after a few milliseconds) and thus it was concluded that transient jets can be treated quasi-steady. The jet penetration was found to scale linearly with time until the jet tip reaches a certain distance from the nozzle exit; afterwards, the jet penetration scales with the square root of time [33]. Soulopoulos et al. [34] performed scalar dissipation rate measurements in a starting jet and found that high values of scalar dissipation rate were concentrated at the jet boundary as well as at random regions in the jet body.

Sadanandan et al. [22] studied the ignition of near-stoichiometric hydrogen/air mixtures by means of hot exhaust gas jets using high-speed Schlieren imaging and planar laser-induced fluorescence of OH. The ignition was observed to occur near the tip of the exhaust gas jet and no ignition was observed at the periphery of the jet, where the strain rate is expected to be high. Fast et al. [23] studied the auto-ignition of a transient dimethyl ether jet in a high-pressure environment using high-speed shadowgraphy imaging. They observed a two-stage ignition process. Johannessen et al. [31] studied auto-ignition in unsteady hydrogen/nitrogen jets in a hot coflow using high speed Schlieren imaging and microphone probes. It was found that the ignition frequency was dependent on the nitrogen mole fraction in the jet. Oldenhof et al. [17] studied the ignition of impulsively-started natural gas jets issuing into a hot vitiated coflow. Initially, a laminar flow phase was observed, followed by a rapid transition to a turbulent phase after a few milliseconds. No flame reactions were observed in the initial laminar phase. Flame structures were only observed in regions with velocities close to the coflow velocity and it was concluded that transport of coflow fluid into the jet periphery governs the auto-ignition time.

One difficulty in many of the previous experiments was the accomplishment of well-defined boundary conditions; for example, providing a homogeneous gas distribution within the coflow or knowledge of the temperature of the fuel jet. Other difficulties are out-of-plane effects. When observing an ignition kernel with planar laser measurement techniques, it is of great importance to know whether this ignition kernel formed within the measurement plane or if it formed outside the measurement plane and was convected into the measurement plane by transport processes. Arndt et al. [28,29] studied the auto-ignition of a transient fuel jet issuing into a hot vitiated coflow with well-defined boundary conditions using high-repetition-rate planar laser diagnostics and high-speed imaging. Chemiluminescence imaging from two viewing angles was used to reconstruct the downstream location of an auto-ignition kernel as well as its position relative to the measurement plane. Recently, Ma et al. [35] used high-speed tomographic chemiluminescence to study the ignition dynamics in a Mach 2 combustor following spark ignition and the subsequent spatio-temporal evolution of ignition kernels.

The aforementioned studies have yielded insight into the statistics of auto-ignition time and location, but no major information has been available concerning the role of turbulence or turbulent mixing. As described in a review paper by Mastorakos [36], direct numerical simulations (DNS) of igniting mixing layers with simplified [37–41] and detailed [42–46] chemistry have shown that auto-ignition occurs away from the stoichiometric mixture fraction at the so-called most-reactive mixture fraction. In the case of cold fuel issuing into an environment of a hot oxidizer, two competing mechanisms determine the mixture fraction at which ignition initially occurs. For very lean mixture fraction conditions, the mixture temperature is high, while the fuel concentration is low. For richer mixtures, the fuel concentration increases, but the mixture temperature decreases. The optimal composition with the shortest ignition delay time is called the most-reactive mixture fraction. However, DNS in turbulent mixing layers has shown that not all locations with the most-reactive mixture fraction ignite at the same time [36]. This finding was supported from previous experimental results [28,29], where auto-ignition was observed in the form of localized ignition kernels. In DNS, fluctuations of the scalar dissipation rate were found to play a key role in determining the probability of auto-ignition in transient systems; here, ignition occurs first in localized kernels at locations with minimal scalar dissipation rates [42,44–46], as is found in the cores of vortices [38–40]. Kerkemeier et al. [47] performed 3D direct numerical simulations with detailed chemistry of a hydrogen plume that ignited in a hot, turbulent coflow. In this study ignition occurred in the form of auto-ignition spots at the most reactive mixture fraction and at locations with low scalar dissipation rate, far downstream of the fuel injector. While previous DNS studies have highlighted the importance of the mixture fraction topology and scalar dissipation rate fluctuations in the auto-ignition process, no previous experimental studies have examined the role of the mixture fraction and scalar dissipation rate on auto-ignition.

In order to study effects of turbulence and mixing on auto-ignition experimentally, time-resolved measurements of mixture fraction and temperature fields with sufficient spatial resolution prior to the onset of auto-ignition are necessary. Due to the limited pulse energy of continuously-operating high-repetition-rate laser systems, only a subset of well-established laser-based imaging techniques have been applied at high acquisition-rates. In JHC configurations, only PIV and OH PLIF in combination with flame emission and Schlieren imaging have been employed at kHz rates. With the development and continued improvement of pulse-burst laser systems [48], methods requiring high laser pulse energies, such as planar Rayleigh scattering for mixture fraction or temperature imaging [49–52], or major species concentration via Raman scattering [53] have become possible at multi-kHz acquisition rates.

In the current study, the High-Energy Pulse-Burst Laser System (HEPBLS) at Ohio State [50,54] was employed to study the mixing

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