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An experimental study of flame and autoignition interactions of *iso*-octane and air mixtures

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ABSTRACT

Recent modifications to the University of Michigan rapid compression facility (UM RCF) were made to allow direct imaging of flame/autoignition interactions using compression to initiate autoignition chemistry and a spark plug to initiate simultaneous flame development. The experimental data in this study quantify the effects of spark-initiated flame propagation on autoignition of *iso*-octane/O_2/inert gas mixtures at well-defined initial conditions. The work leveraged the controlled environment of the UM RCF, in which temperature, pressure, and composition are nominally uniform and well-known at the end of compression. Flame initiation by the spark plasma, flame propagation, and autoignition were monitored using high-speed optical imaging of chemiluminescence and *in situ* pressure time histories. End-of-compression temperatures from $T_{EOC} = 942–1012$ K were considered, while the end-of-compression pressures were nominally constant within the range of $P_{EOC} = 7.8–9.5$ atm. The fuel-to-O_2 molar equivalence ratio was varied from $\phi = 0.20–0.99$ and dilution, defined as the molar ratio of inert gases to O_2 in the reactant mixture, was varied from inert:O_2 = 3.76–7.47 to determine the effects on flame/autoignition interactions as well as to identify the lean flammability limit of the mixtures as a function of dilution. Flame propagation is generally expected to decrease autoignition delay times by compression heating the unburned portion of the mixture. The effect of flame propagation was maximized in these experiments by igniting the mixtures early during the autoignition process. Later spark timings had small to negligible effect on the autoignition delay time. Dilution had significant effect on the lean flammability limits, increasing from a lean limit of $\phi = 0.35$ at air levels of dilution to $\phi = 0.65$ at inert:O_2 dilution of 7.5. The flammability limit was well correlated with the theoretical adiabatic flame temperature of each experiment. The propagation rates of flames successfully initiated by the spark plasma were determined from the imaging data and were $\sim$1 to 12 m/s. The magnitude of the propagation rates and the effect on the time integrated temperature scaled with the energy content of the mixtures as indicated by the theoretical adiabatic flame temperature.

1. Introduction

Advanced modes of internal combustion (IC) engine operation have potential to dramatically improve IC engine efficiencies while simultaneously lowering engine emissions [1–5]. Advanced engine operating strategies include low temperature and fuel lean conditions, which enable higher compression ratios and may reduce the need for exhaust gas after-treatment [2–5]. Homogeneous charge compression ignition (HCCI) is a low temperature combustion strategy that has been the focus of numerous experimental and computational studies in the past decade. Several excellent articles review research progress on HCCI and other advanced engine strategies including discussions of important limitations of current scientific understanding [2,5], demonstration of operating modes [2,4,5], and advances (existing and required) in related engine technology [2,4,5].

Methods of advanced combustion in IC engines often encompass mixed modes of combustion, in which flames and autoignition processes are simultaneously contributing to combustion and heat release rates. For example, during spark-assisted compression ignition (SACI), a spark plug is used to initiate a flame into the nominally homogeneous or partially stratified fuel/air charge in an internal combustion engine. SACI has been demonstrated to expand high and low load operation beyond HCCI boundaries

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[6–8]. However, methods to optimize SACI and other mixed modes of combustion are limited by the lack of fundamental understanding of flame propagation and autoignition interactions at conditions relevant to advanced engine strategies. Moreover, advanced combustion strategies like HCCI, SACI and gasoline direct injection (GDI) often consider highly dilute operation as a means to achieve high efficiency goals and meet emerging and more strict emissions requirements. These strategies typically target either (globally) fuel lean or stoichiometric conditions. The combination of high levels of dilution and fuel lean reactant mixtures is particularly challenging, as flame propagation and heat release rates decrease dramatically compared to undiluted stoichiometric conditions.

There is also a significant lack of fundamental combustion data, such as flame speeds and flammability limits at the state and reactant mixture conditions important to advanced combustion in IC engines. This gap complicates optimizing engine operation, especially the development and validation of theory and models which accurately describe mixed modes of combustion like SACI. Consequently, the objective of the current study is to experimentally characterize flame and autoignition interactions of *iso*-octane (an important reference fuel) and air mixtures at premixed, moderate temperature (925–1000 K) and pressure (>7.5 atm) conditions relevant to advanced engine strategies. The technical approach of this study leverages the well-defined mixture and state conditions that can be created using a rapid compression facility (RCF). Previous studies have demonstrated the value of RCFs as experimental platforms for providing important insights into the effects of mixture stratification on spark ignited flames during direct injection of the fuel [9–13]. Much has been learned from these previous RCF studies, including the effects of spark and fuel timing on mixture stratification and the resulting flame propagation [9–13]. The focus in the current work differs fundamentally from these previous studies as the focus is on flame/autoignition interactions at conditions with nominally homogeneous initial conditions, where thermal and mixture stratification have been minimized prior to spark igniting the mixture. Specifically, the effects of flame propagation on the autoignition delay time are determined in this study and the flammability limit for lean, dilute, premixed *iso*-octane air mixtures is determined. Measurements of flame propagation rates were also made for mixtures in which flames were successfully initiated and sustained in the test gas mixture.

2. Experimental approach

All experiments were conducted using the University of Michigan rapid compression facility (UM RCF) which has been used for numerous autoignition studies, including extensive characterization of *iso*-octane autoignition [14–17]. The UM RCF is essentially a chemical reactor that creates nominally uniform temperature and pressure conditions using a free piston to compress a test gas mixture. The test section of the UM RCF provides excellent optical and physical access to interrogate the gases during autoignition. The technical approach used in this study compared autoignition data with and without the use of a spark plug to initiate flames during the ignition delay time. The autoignition characteristics of the mixtures were determined using the pressure time history, and the characteristics of flame propagation were determined using high-speed imaging. The spark/autoignition experiments were also used to identify flammability limits as a function of dilution for fuel lean *iso*-octane air mixtures.

2.1. Rapid compression facility details

Details of the dimensions, operating procedure, and results of RCF characterization studies have been described previously and can be found in Donovan et al. [18] and He et al. [15]. The key features are highlighted here: the UM RCF consists of a driver section, driven section, test section, a sabot or free piston, a globe valve, and a mixing manifold. The driver section is separated from the driven section by a fast acting hydraulic globe valve assembly. Due to the high pressure differential across the globe valve assembly, a thin (0.05 mm thick) and scored plastic (Mylar) sheet is placed between the vacuum side of the valve assembly and the driven section to prevent air leaking into the evacuated driven section. The RCF achieves desired thermodynamic conditions through compression heating of the test-gas mixture by the sabot. The sabot consists of a solid plastic (Delrin) body with a brass counterweight located in the posterior and a detachable disposable nosecone made of deformable ultra-high molecular weight polyethylene. The sabot design includes two u-ring seals to minimize blow-by of the driver gases into the driven section during compression of the test-gas mixture.

As shown in Fig. 1, downstream of the driven section is the test manifold, which consists of the converging, extension, and test sections. The converging section traps the cold boundary layer gases outside the test section to maximize test times at high temperatures and pressures, by minimizing fluid mixing and heat losses. The critical dimensions of the extension section are the internal diameter of 5.08 cm and the axial length of 8.05 cm.

A new test section was fabricated from 316L stainless steel for this study to allow a spark plug to be mounted in the test section. The critical dimensions of the test section are the internal diameter of 5.08 cm and the axial length of 5.88 cm. For each experiment, the sealed test volume consists of the test section volume and part of the extension section volume. The nosecone seals the test section by an annular interference fit in the extension section, resulting in a nominal test volume of 186.1 cm^3. The test section is sealed using a polycarbonate endwall, 12.7 mm thick, and a load distribution plate that allows optical access for end-view imaging. Polycarbonate is more durable than quartz and polycarbonate provides comparable transmission efficiency to quartz in the visible spectrum, where the transmission efficiency of quartz is $\sim$90% and of polycarbonate is 85–90% in the wavelength range 390–700 nm.

The pressure time histories for each experiment were measured using an amplified high-speed transient piezoelectric pressure transducer (Kistler 6045A transducer and Kistler 5010B charge amplifier). As shown in Fig. 1, the pressure transducer was mounted on the bottom of the test section (i.e. at the piston or end view 6 o'clock position), and the spark plug was mounted at the 11 o'clock position. The orientation of the transducer and spark plug are not expected to effect the results of this study. The information is provided to orient the imaging data. All data except the camera imaging results were recorded using a 32 bit data acquisition system (National Instruments cDAQ-9172) operating at 100 kHz and collected using a custom data acquisition program (LabView, 2011).

2.2. Spark ignition system details

The spark ignition system used in this study is similar to traditional electronic ignition systems used in automotive applications. The spark plug is a production flat seat iridium tip model (NGK IX BKR6EIX-11) set with a 1.1 mm gap between the central and ground electrodes. The central electrode sits 5 mm proud relative to the wall of the test section. An ignition module (Wells DR178) was used to signal an ignition coil (Accel 140024) with a maximum discharge voltage of 48,000 V. The ignition coil was powered by a regulated power supply capable of 12 A output (Pyramid PS-14KX 13.8 V) and connected to the spark plug using a spiral wound, silicone-sleeved, low resistance conducting spark plug