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Spray combustion of Jet-A and diesel fuels in a constant volume combustion chamber

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ABSTRACT

This work investigates the spray combustion of Jet-A fuel in an optical constant-volume combustion chamber under different ambient initial conditions. Ambient temperature was varied at 800 K, 1000 K, and 1200 K and five different ambient O_2 concentrations were used, spanning 10–21%. These ambient conditions can be used to mimic practical diesel engine working conditions under different fuel injection timings and exhaust gas recirculation (EGR) levels. Both transient and quasi-steady state analyses were conducted. The transient analysis focused on the flame development from the beginning to the end of the combustion process, illustrating how the flame structure evolves with time. The quasi-steady state analysis concentrated on the stable flame structure and compared the flame emissions in terms of spatially integrated intensity, flame effective area, and intensity per pixel. The transient analysis was based on measurements using high-speed imaging of both OH* chemiluminescence and broadband natural luminosity (NL). For the quasi-steady state analysis, three flame narrow-band emissions (OH* at 310 nm, Band A at 430 nm and Band B at 470 nm) were captured using an ICCD camera. Based on the current Jet-A data and diesel data obtained from previous experiments, a comparison between Jet-A and diesel was made in terms of flame development during the transient state and spatially integrated intensity, flame effective area, and intensity per pixel during the quasi-steady state. For the transient results, Jet-A shares a similar flame development trend to diesel, but featuring a narrower region of NL and a wider region of OH* with the increase of ambient temperature and O_2 concentration. The soot cloud is oxidized more quickly for Jet-A than diesel at the end of combustion, evident by comparing the area of NL, especially under high O_2 concentration. The quasi-steady state results suggest that soot is oxidized effectively under high O_2 concentration conditions by the wider region of OH* in the downstream locations where only OH* emission is observed. The intensity of OH* is higher for Jet-A than diesel under low O_2 concentration but lower under high O_2 concentration. The intensity of NL is higher for Jet-A for all the conditions investigated. However, the intensities of Band A and Band B are lower for Jet-A for all these conditions. Based on the imaging of multiple-band flame emissions, the spray flame structures were further analyzed for the two fuels under both low temperature and conventional combustion modes. Conceptual flame structures were proposed to complement the previous conceptual models for spray combustion under different combustion modes.

1. Introduction

The single-fuel concept (SFC) proposed by the United States Armed Forces specifies a single fuel, F-34 (Jet Propellant 8 (JP-8)), to be used for battlefield military aircraft, ground vehicles, and equipment [1]. Compared to the commonly used jet fuels in civil aircrafts (such as Jet-A and Jet-A1), JP-8 specifications are generally the same except for the addition of certain types of additives, including an antioxidant, a static dissipater, a corrosion inhibitor, fuel system icing inhibitor, and a lubricity improver [2,3]. Since Jet-A has very similar components to JP-8 and is easy to get from a local retailer, Jet-A was used in this work in place of JP-8. In past years, pollutant emissions were measured in diesel engines fueled with jet fuel and diesel, such as NO_x, soot, and unburned hydrocarbon [4,5]. The results showed that lower NO_x and unburned hydrocarbon emissions were obtained from jet fuel combustion, but higher engine-out soot emission was observed. High soot emission can lead to an obvious infrared signature in military application, which impedes the execution of SFC. Therefore, spray combustion

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for jet fuel needs to be investigated in order to reduce soot emission.

Low temperature combustion (LTC) is treated as an effective and advanced method to reduce soot and NO_x in the diesel engines [6–10]. Soot formation of diesel spray combustion has been studied under different diluted conditions [11]. It has been demonstrated that LTC is the most promising technology for future diesel engines with simultaneous reduction of soot and NO_x emissions [12]. During a typical diesel spray combustion event, OH, CH, HCHO, and C_2 radicals or other intermediate species are generated and can be used for identifying the active reaction regions [13]. Mancaruso et al. [14] investigated auto-ignition and combustion in the homogeneous charge compression ignition (HCCI) mode in a diesel engine. They showed that the presence of OH radicals was a reason for soot reduction during the HCCI combustion process. Simultaneous OH and formaldehyde laser induced fluorescence (LIF) measurements were performed in an HCCI engine with a port fuel injection system by Collin et al. [15] and they found that the formaldehyde signal was constant until the main heat-release started, and OH was formed in the areas where the formaldehyde signal disappeared. OH radicals were shown to be effective in oxidizing the soot in the downstream region of a diesel spray combustion plume [16]. The concepts of conventional and low-temperature spray combustion were discussed and compared by Musculus et al. [17]. Conventional diesel combustion was dominated by the mixing controlled combustion with high flame temperatures, which generally occurred under high O_2 concentration and high ambient temperature (such as 21% and 1000 K or above); while the low-temperature combustion mode with low O_2 concentration and low temperature was controlled by a large amount of premixed combustion. Consequently, the identification of different radicals associated with different combustion modes by using multi-band emission measurements is beneficial to further understanding the spray combustion process, particularly for the low temperature combustion mode.

In addition, differences exist in both physical and chemical properties for jet fuel and diesel and they greatly affect the combustion process of these fuels. Many experiments have been conducted in real engines or well-controlled combustion devices [18–24]. Simultaneous imaging of liquid spray and vapor fuel was performed by Kook and Pickett for different fuels in a constant-volume chamber under typical diesel engine in-cylinder conditions [18]. Their results showed that diesel liquid penetration was the longest, followed by JP-8 and Jet-A, under 900 K ambient temperature without reaction, and there was a very small difference between JP-8 and Jet-A. Ignition delay data for jet fuel were measured in a heavy-duty diesel engine [19,20], shock tube [21,22], rapid compression machine [23] and constant volume chamber [24] by different research groups. These results showed that JP-8 had a longer overall ignition delay time than diesel. The combustion and emission characteristics were compared by Nargunde et al. [25] and Papagiannakis et al. [4]. Their results showed that JP-8 led to a better combustion efficiency, improved fuel economy, and reduced NO_x but with a higher soot emission compared with diesel fuel. In-cylinder soot evolution under low load conditions was studied in an optical engine with JP-8 and ultra-low sulfur diesel (ULSD) by Yu et al. [26]. JP-8 produced less engine-out soot emission compared to ULSD, meanwhile, less soot optical thickness (KL factor) was also found for JP-8 during the whole cycle with lower soot temperature. The comparison of Jet-A and diesel has included spray, combustion, and emission aspects, such as liquid penetration, ignition delay, combustion efficiency, NO_x and soot; however, details of the combustion process are still needed, such as regions of different reactions and different active radicals during combustion process, which is essential to reducing pollution emissions from spray combustion.

In this work, a multiple-spectrum imaging approach was employed to visualize different flame emissions under varied ambient conditions. From the experimental results in the literature, 1000 K was considered as a typical ambient temperature for diesel spray combustion. Three ambient temperatures of 800 K, 1000 K and 1200 K were selected to cover different combustion modes in diesel engines including the low temperature combustion and conventional combustion modes. Five ambient oxygen concentrations were employed to simulate the effects of different levels of dilution, namely exhaust gas recirculation rates, in diesel engines. The spray combustion process was investigated in a constant-volume chamber based on the imaging of OH^* (310 nm) chemiluminescence, broadband natural luminosity, 430 nm narrow-band flame emission (Band A), and 470 nm narrow-band flame emission (Band B) with different band pass filters. The OH^* chemiluminescence was used to identify the high temperature combustion regions involving OH radicals. The broadband natural luminosity is mainly due to soot luminosity and it was used to identify soot formation locations and late stage oxidation events. Band A was chosen to capture CH^* chemiluminescence, and Band B was chosen for partially showing HCHO chemiluminescence [13]. It should be pointed out that both Band A and Band B emissions can be overwhelmed by soot radiation when there is a significant amount of soot in the flame. During the low-temperature combustion modes with little soot, however, Band A and Band B can show the activities of these two radicals. A comparison was then performed for the current Jet-A results with our previous No. 2 diesel results [16,27,28].

2. Experimental setup

Experiments were conducted in a constant-volume combustion vessel with optical access via a quartz window under simulated, quiescent diesel combustion environments. Details about the combustion chamber can be found in previous publications [27,28]. The injector nozzle used in this study has one orifice, allowing detailed imaging of the flame. The orifice diameter is 150 μm. The optical window was installed laterally along the spray axis in order to measure the flame development, as shown in Fig. 1(a). Gas supply system and fuel delivery system are shown in Fig. 1(b) and (c), respectively. The total chamber volume is 0.95 L, and the inner diameter of the window is 100 mm. Premixed combustion of acetylene mixtures occurred first to generate a high-temperature, high-pressure condition simulating the diesel environment at the start of fuel injection. Three different gases, acetylene, O_2/N_2 (50%/50%), and dry air, were used to formulate a proper mixture to achieve the desired ambient temperature and O_2 concentration. The initial $C_2H_2/O_2/N_2$ mixture was ignited by a spark plug. The chamber pressure was measured by a Kistler 6041A pressure sensor coupled with a Kistler 5004 charge amplifier. Water cooling was provided to prevent the thermal shock effect. The chamber pressure was used for calculating the ambient temperature at the time of fuel injection. The fuel injection pressure was maintained at 100 MPa using a common rail fuel system. The entire operation process was controlled by a LabView program. The injection duration was set at 4.0 ms for all the cases in order to achieve a quasi-steady state flame, which occurred approximately 2.5 ms after the injection triggering pulse for most conditions. Details of the common rail fuel injection system and injection parameters and ambient environments are summarized in Tables 1 and 2. Selected fuel properties are shown in Table 3 [29,30]. The major compositions of the two fuels used in this study are shown in Fig. 2. It is seen that Jet-A has more components with lower molecular weight than diesel and it is expected that Jet-A