Effects of Temperature and Oxygen on Spray and Combustion Characteristics of Diesel and Jet-A in a Constant Volume Combustion Vessel

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Abstract  
This work investigates the effects of ambient conditions on spray and auto-ignition characteristics of diesel and jet-A fuels in an optical constant volume combustion chamber using a single-nozzle fuel injector. The ambient conditions were varied for: five ambient O₂ concentrations (10%, 12%, 15%, 18% and 21%) and four different ambient temperatures (800K, 1000K, 1200K and 1400K). These conditions simulate different EGR levels and ambient temperatures in diesel engines. Liquid penetration is analyzed under reaction environment. Diesel liquid penetration is longer than that of jet-A, which results mainly from the lower boiling point of jet-A. First stage ignition (cool flame) delay increases when the ambient temperature decreases. The first stage ignition delay of jet-A is shorter than that of diesel, especially for low ambient temperature and low O₂ concentration. Effects of ambient oxygen and temperature are analyzed by developing correlations for the ignition delay. The results show that jet-A fuel has a more complicated relation between first stage ignition delay and ambient temperature.

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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, vehicles and equipment [1]. Jet-A and JP-8 specifications are generally the same except for the addition of four additives to JP-8: 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 with JP-8 and easy to get from a local retailer, jet-A was used in this work instead of JP-8.

Recently, emissions were measured in diesel engines to compare the jet fuel and diesel, such as NOx, soot and unburned hydrocarbon [4, 5]. The results showed that lower NOx and unburned hydrocarbon 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 will impede the execution of SFC. Since fuel spray characteristics affect the combustion and emission performance in engines significantly, the study of spray characteristics among different fuels becomes important, such as liquid penetration and spreading angle. In diesel engine design, liquid impinging on the wall should be avoided in most cases [6]. Therefore, the fuel liquid penetration is a key factor in air utilization. Simultaneous imaging of liquid spray and vapor fuel was performed by Kook and Pickett in a constant-volume chamber under typical in-cylinder conditions of diesel engines [7]. Their results showed that diesel liquid penetration was the longest one, followed by JP-8 and JP-A under 900K ambient temperature without reaction, and there was a very small difference between JP-8 and JP-A, what’s more, the same vapor penetration and spreading angle were found. Chen et al. [8] investigated the spray and atomization characteristics for diesel fuel and Jet-A under different injection pressure and normal ambient temperature. There is a lack of measuring liquid penetration for JP-A and diesel under high temperature reaction environment, so the measurement of liquid penetration for JP-A and diesel were performed over a wide temperature range from 800K to 1400K in this work.

Another parameter named ignition delay greatly determines the combustion and emission performances, and it is very sensitive to fuel type. Rothamer and Murphy [9] studied on the ignition delay for jet fuels and diesel fuel in a heavy-duty diesel engine. The results showed that there was no big ignition delay time difference between diesel and jet-A, a correlation was also proposed without considering O2 concentration effect. Ignition delay was also measured by Kumar and Sung [10] in a rapid compression machine, and ignition delay was divided into first stage ignition delay time and overall delay time. The results indicated that jet-A and JP-8 shared a similar value for the first stage ignition delay time, and JP-8 had a longer overall ignition delay time. It also pointed out that charge temperature was the major controlling parameter for the first-stage ignition delay. However, Vasu et al. [11] reported that ignition delay times are very similar for JP-8 and jet-A, increasing O2 concentration would lead to a shorter ignition delay. Since jet-A and JP-8 have the similar trend in first stage ignition delay time, jet-A was used in this paper to evaluate the first stage ignition delay instead of JP-8. More experimental data needed for the jet-A first ignition delay and this delay is very important for providing a datasheet related the overall ignition delay and validating the ignition model. Therefore, the first ignition delay for jet-A and diesel fuel was investigated in this work and two correlated equations were proposed by considering O2 concentration effect.

After a short review of jet-A and diesel fuel spray and auto-ignition, the liquid penetration and first stage ignition delay are needed to be addressed under varied ambient conditions. In this work, the measurements of jet-A and diesel fuels were conducted in an optically accessible constant volume vessel in terms of liquid penetration under reaction environment and first stage ignition delay time.

Experimental setup

Experiments were conducted in a constant volume combustion vessel with optical access via quartz windows under simulated, quiescent diesel combustion environments. More details about the combustion chamber can be found in previous publications [12, 13]; however, there are two important differences in the current work. First, the nozzle used in this study has one hole instead of six holes as used in [12], allowing detailed imaging of the flame. The nozzle diameter is 150 micrometers. Second, the optical windows were installed laterally along the spray axis in order to measure the flame development, as shown in Fig. 1. The total chamber volume is 0.95 liter, and the inner diameter of the window is 100 mm. Premixed combustion of acetylene occurred first to generate a high temperature, high pressure condition simulating the diesel environment at the start of fuel injection. Three different gases, acetylene, O2/N2 (50%/50%), and dry air, were used to formulate the proper mixture to achieve the desired ambient temperature and O2 concentration. The initial C2H2/ O2/N2 mixture was ignited by a spark plug. A pressure transducer was employed to measure the chamber pressure, which 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 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 reaction environment, which occurred approximately 2.5 ms after the injection triggering pulse. Details of the common rail fuel injection system and injection parameters are given in Table 1.

Diagnostics and Measurements

The chamber pressure was measured by a Kistler 6041A sensor coupled with a Kistler 5004 charge amplifier. Water cooling was provided to prevent the thermal shock effect. Liquid penetration and spreading angle were measured by capturing the images through a high-speed camera (Phantom v4.3) when spray under quasi-steady reaction environment. Broad-band natural luminosity (NL), mostly cool flame chemiluminescence, was obtained by an Andor intensified CCD (ICCD) camera to determine the first stage ignition delay time. Each condition was repeated five times for both the liquid penetration and first stage ignition delay.

Results and Discussion

The results and discussion is divided into three different sections. First, liquid penetration and spreading angle under reaction environment for varied ambient conditions are presented for diesel and jet-A. Second, first stage combustion (cool flame) delay are compared between the two fuels and this delay time correlation equations are deduced by adding two terms of O2 effect and ambient temperature into ignition delay equation in [19]. The liquid penetration and spreading angle with reaction environment images are obtained by averaging the liquid transient images over a different range for different ambient conditions, this range for each condition should be selected after the liquid fully develops and also before the intense NL occurs.

1. Liquid penetration and spreading angle under reaction environment

The liquid penetration was characterized by using a similar method in ref [14] for 800K ambient temperature. Since uniform diffused light was employed as background in the opposite direction of the camera in the liquid penetration measurement, liquid is dark and background is bright. A threshold value is defined as a ratio of the intensity difference between the liquid and the background to the background intensity. The liquid intensity is considered along the nozzle axis. 10% was selected as the threshold which is higher than the value in ref [14]. An example of 800K ambient temperature and 10% O2 concentration is used to show the liquid penetration which is indicated by a solid line in Fig 2. Since there is an overlap between the liquid jet and flame under high ambient temperature, the above method could not be used for 1000K and 1200K ambient temperature. The liquid penetration distance was chosen at the yellow area between the red and green areas, as shown in Fig 3.

Liquid penetration was normalized by the nozzle diameter for Jet-A and diesel, because the liquid length scales linearly with nozzle diameter [15]. The normalized liquid penetration for jet-A is shown in Fig 4. For a given O2 concentration, the jet-A liquid jet penetration decreases as ambient temperature increases, due to the fact that higher ambient temperature enhances the fuel vaporization and reduces the ignition time, especially shortens the flame lift-off [16]. Much more heat was transferred from the reaction zone to the liquid zone easily, and finally liquid penetration was reduced under such high ambient temperature. It can also be seen from Fig 2 and Fig 3, 10% O2 concentration condition is selected as an example. There is a vaporization zone between liquid zone and flame zone indicated by a dash circle for 800K ambient temperature, while no obvious transition area is shown for 1400K ambient temperature condition. On the other hand, the jet-A liquid penetration also decreases when O2 concentration tends to increase for a given temperature. It should be noted that liquid penetration should not be changed much without reaction environment, higher ambient temperature can also decrease the lift-off [17]; therefore, the distance between high temperature reaction zone and liquid zone was shortened as well, leading to a reduction of liquid penetration with more heat transferred into liquid zone. Diesel liquid penetration has a similar trend to jet-A liquid penetration, but it has a larger value in 800K ambient temperature, as shown in Fig 5. Under low ambient temperature and low O2 concentration, diesel jet penetration is longer than that of jet-A, such as 800K and 10% and 800K and 12%; however, diesel jet penetration becomes shorter than that of jet-A under high ambient temperature and high O2 concentration. Since jet-A has a lower boiling point compared to diesel, which can lead to a faster vaporization. More combustion heat can be introduced into liquid zone for jet-A which makes a shorter jet penetration compared to diesel under low ambient temperature, especially for 800K with a very large difference. As ambient temperature increases, it seems that the effect of boiling point becomes weaker. The diesel liquid penetration is lower than that of jet-A which could probably result from the fuel chemistry property. Because spray combustion is dominated by the fuel chemistry compared to the physical property [18] and the penetration depends greatly on the amount of heat, which is generated during the spray combustion and transferred into liquid zone.

2. First stage combustion analysis
First stage combustion (cool flame) images were captured by an ICCD camera to identify this combustion delay, which is defined as the time from the start of injection trigger to the first cool flame image. The time interval of 0.01 ms was selected to find the first natural luminosity image. Generally, two adjacent timing points will be repeated five times respectively. If the latter shows NL differentiated from the background and the former doesn’t, the time of the latter is recognized as the first stage combustion delay time (cool flame delay time). The cool flame delay times are shown in Fig 6 and Fig 7 for jet-A and diesel respectively. The delay time is decreasing as O\textsubscript{2} concentration decreases for a given temperature. Meanwhile, the delay time also decreases when temperature increases for a given O\textsubscript{2} concentration. The delay time for 800 K ambient temperature is much longer than that under other ambient temperatures for both fuels and the time difference becomes smaller when ambient temperature increases. The delay time for diesel is larger or equal to that of jet-A under all the conditions. The differences for 10% and 12% O\textsubscript{2} conditions with 800 K ambient temperature are much larger compared to other conditions. The boiling point effect can be minor under high ambient temperature and O\textsubscript{2} concentration, suggesting that physical property of different fuel plays an important role on the cool flame delay time under low ambient temperature and low O\textsubscript{2} concentration conditions, while the cool flame delay depends heavily on the fuel chemistry under higher ambient temperature and O\textsubscript{2} concentration. Two correlation equations are also proposed based on the measured data:

\[
Time = A \cdot \exp \left( \frac{E_a}{T} \right) \cdot p^n \cdot O_2^L \quad (1)
\]

\[
Time = A \cdot \exp \left( \frac{E_a}{T} \right) \cdot p^n \cdot T^n \cdot O_2^L \quad (2)
\]

where “Time” is the cool flame delay time, A is the constant, E\textsubscript{a}, n, m and L are the coefficients for temperature, pressure and O\textsubscript{2} concentration, respectively.

The two equations have a similar format with the one in ref [19], but two terms of temperature and O\textsubscript{2} concentration are added. In this work, effect of O\textsubscript{2} concentration is considered to characterize the cool flame delay time. In order to consider the physical phenomena during the first stage ignition period, such as vaporization and mixing process, additional term of T\textsuperscript{n} is added. A least square method is used to quantify the coefficients in the equations for the two fuels. The coefficients and the fitting curves are shown in Fig 8. By comparing the value of R\textsuperscript{2}, the diesel data fit well for Equation (1), while the jet-A data fit Equation (2). It is indicated that the cool flame delay time has a more complicated relation with temperature for jet-A compared to diesel, such as the term of T\textsuperscript{n} in Equation (2).

Conclusions

The spray and auto-ignition characteristics were studied in an optically accessible constant volume vessel under varied ambient conditions. The ambient temperature was changed from 800K to 1400K with 200K increment; O\textsubscript{2} concentration varied from 10% to 21% simulating the different EGR loads in engines. The findings and conclusions are summarized as follows:

- Liquid penetrations for both jet-A and diesel decrease as ambient temperature increases for a given O\textsubscript{2} concentration; meanwhile, it also decreases as O\textsubscript{2} concentration increases for a given ambient temperature under reaction environment. It could be explained by the amount of heat transferred from flame zone to liquid zone.
- Diesel liquid penetration is longer than that of jet-A, which mainly results from the lower boiling point of jet-A.
- First stage ignition delay was measured by capturing the first cool flame image. The results show that jet-A first stage ignition delay is shorter than that of diesel, especially for low ambient temperature and low O\textsubscript{2} concentration. Correlation equations are also proposed by adding two terms of temperature and O\textsubscript{2} concentration, jet-A is well fitted to Equation (2) by considering an additional temperature term of T\textsuperscript{n}.

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References

Figure 1. Experimental system: 1. fuel injector; 2. exhaust line; 3. chamber body; 4. quartz window; 5. plug/window retainer; 6. pressure transducer; 7. intake line; 8. metal plug; 9. spark plug; 10. combustion chamber; 11. high speed cameras (Phantom v4.3 or Andor ICCD camera).

Figure 2. The liquid penetration image under 10% O₂ concentration and 800K ambient temperature.

Figure 3. Example of defining the liquid penetration for high ambient temperature condition, ambient condition: 1400K ambient temperature and 10% O₂ concentration.

Figure 4. Jet-A normalized liquid lengths over a range of temperature and O₂ concentration.

Figure 5. Diesel normalized liquid lengths over a range of temperature and O₂ concentration.

Figure 6. Cool flame combustion delay time for jet-A over varied ambient conditions.

Figure 7. Cool flame combustion delay time for diesel over varied ambient conditions.
Figure 8. The comparison of experimental and fitting calculated results: (a) without $T^n$ for jet-A, (b) with $T^n$ for jet-A, (c) without $T^n$ for diesel, (d) with $T^n$ for diesel.

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<tr>
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Table 1. Details for the common rail injection system and injection parameters for jet-A and diesel.