Investigation of Entrainment during Combustion of Biodiesel Sprays

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Abstract

The oxygen ratio of a mixture is the amount of oxygen available in the reactants divided by the amount required for stoichiometric combustion, where "stable" species are neglected. The oxygen ratio at the lift-off length of a fuel spray stands for the oxygen entrainment up to the spray lift-off length as a percentage of the total oxygen required to completely burn the fuel being injected, and this has an important effect on combustion and emissions. The effects of ambient gas temperature on the flame lift-off length of direct-injection (DI) biodiesel sprays under quiescent conditions were experimentally investigated. This was determined from the time-averaged OH chemiluminescence imaging technique. Then the impacts of the observed lift-off length variations on oxygen ratio at the lift-off location were also studied. Pure diesel (B0), biodiesel (B100) and their blends (B20 and B50) were tested inside the constant volume combustion chamber capable of simulating the real diesel engine conditions with more flexibility in changing engine operating conditions. The effects of different ambient gas temperatures on spray lift-off length were investigated with fixed ambient density, oxygen concentration, injection pressure and duration. Then the oxygen ratio that occurs upstream of the lift-off length of the sprays was examined. The results show that as the ambient temperature increased, the lift-off length decreased for the four different fuel sprays. The reduction of the lift-off length from 800K to 900K ambient temperature is much larger than the reduction observed at higher temperatures. For different fuels, diesel spray had a more significant reduction in lift-off length as temperature increased when compared with B20, B50 and B100 sprays. With increasing biodiesel content in the fuel, the lift-off length increased under the same ambient temperature. The similar trends happened to the oxygen ratio at the lift-off length of sprays. The fuel sprays which had higher oxygen ratio at the lift-off length could burn more efficiently and have lower soot emission.

Introduction

Diesel engines, because of their higher thermal efficiency, will likely be increasingly more popular than gasoline engines in near future. However, the lever of NO_x and particulate matter (PM) emissions of diesel engines must be reduced to meet the stricter emission regulations. Many strategies, such as exhaust gas circulation (EGR) , high-pressure injection, electronically controlled injection, multiple fuel injections , redesigning the engine cylinder and the application of oxygenated fuels have been successfully applied on diesel engines to reduce the emissions.

Biodiesel is chemically known as mono-alkyl esters, long chain fatty acids derived from vegetable oils or animal fats, it can be used as an alternative fuel in diesel engines. It is nontoxic, biodegradable and environmentally friendly, and because of these it is getting more attention nowadays. They contain almost no sulfur and do not contribute to greenhouse gases due to their closed carbon cycle [1]. Furthermore, biodiesel can be blended with diesel at any percentage, and it can be used in the diesel engines with no or little modification. Alptekin and Canakci [2] concluded that the fuel properties of the biodiesel/diesel blends were similar to diesel at low concentrations for blends with up to 20% of methyl esters, while Phan and co-worker[3] reported that the physical properties for blends with less than 30 vol% of biodiesel are within EN14214 standard and could be used in diesel engines without a major modification. The engine particulate matter (PM) can be reduced significantly by using biodiesel or its blends as shown in many studies [4-7].

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Diesel spray usually stabilizes downstream of the fuel injector during the ‘quasi-steady period’ of the combustion process, which occurs between the end of the fuel spray premixed burn and the end of injection. The distance from the injector to the location of stabilization is known as the lift-off length(or height) [8]. It is believed that the air entrained from upstream will mix and react with fuel spray immediately downstream of the lift-off length. The lift-off length can then be used to represent the amount of air entrained from ambient into the fuel spray and it has a dominating effect on diesel combustion and emission formation processes. The oxygen ratio of a mixture is the amount of oxygen available in the reactants divided by the amount required for stoichiometric combustion, where “stable” species are neglected [9]. The oxygen ratio at the lift-off length of a fuel spray denotes the oxygen entrainment up to the spray lift-off length as a percentage of the total oxygen required to completely burn the fuel being injected, and this has an important effect on combustion and emission.

The flame lift-off length of diesel and oxygenated fuel sprays have been studied experimentally under various conditions [8,10-13]. However, the lift-off length and oxygen entrainment at the lift-off length of biodiesel and diesel/biodiesel blends have not yet been examined. In this study, the lift-off length of biodiesel and diesel/biodiesel blends spray were studied via experiments described below, consequently, the oxygen ratio were then determined.

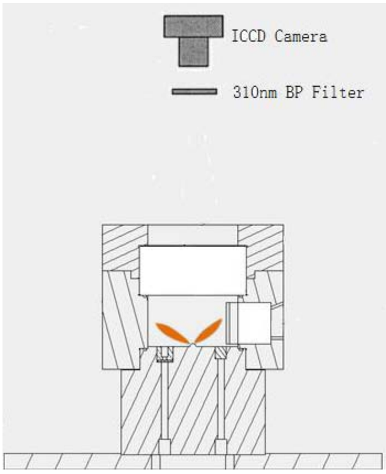

Figure 1. Experimental apparatus .

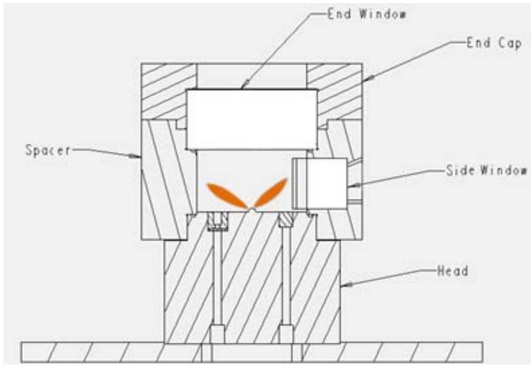

Figure 2. Schematic of combustion chamber.

Experimental Apparatus and Procedure

The experiments were conducted in a constant volume combustion chamber capable of simulating the combustion conditions inside a real diesel engine. By burning a lean premixed combustible mixture, an ambient similar to the compression stroke is achieved. A schematic of the experimental apparatus is shown in Fig. 1 and Fig. 2. The whole setup includes an ICCD camera, a 310 nm UV filter and a constant volume combustion chamber. Detailed discussion of the combustion chamber can be found in Xu et al. [14]. This combustion chamber provides more flexibility in changing the operating conditions, such as the ambient pressure, temperature, density, injection duration and injection pressure. As a result, a wide range of engine operation conditions can be studied. The combustion chamber was optimized for optical access and is fitted with a DI Caterpillar HEUI diesel injector. The bore of the chamber is 110 mm and its height is 65 mm. Other equipment needed for the experiments was installed in the chamber wall as show in Fig. 3. The maximum operating pressure allowed in the chamber is 18 MPa and the maximum chamber gas density is 30 kg/m^3.

The injector has six orifices with separate chambers for hydraulic oil and fuel. It is mounted in the head and pointing upward with the spray making a 22° ascension angle measured from the head surface. The chamber is heated with cartridge electric heaters to simulate engine-wall temperature of 375 K and to prevent water condensation on the windows. The end window on the top of the chamber is used for this study and one of the six spray jets is examined.

Gas were mixed and filled into the chamber to reach a density of 15 kg/m^3 for the test. In this experiment, 4 % acetylene, 30.6 % oxygen and 65 % nitrogen mixture was used. The resulting burned mixture contained 21 % oxygen. The spark ignited the mixture and brought rapid increase in pressure and temperature inside the chamber. The spray injection began when the pressure of the cooling burned mixture reached the preset conditions corresponding to the testing ambient temperatures. The large ambient temperature range is one of the advantages of a constant volume combustion chamber. The vent and vacuum operations followed at the end of the test and then another new cycle begins. Table 1 shows the operation conditions considered in this study; note that an operating condition of 1000 K ambient temperature and 15 kg/m^3 ambient density represents the typical diesel engine TDC environment. The 21 % ambient oxygen concentration corresponds to running the engine with no EGR.

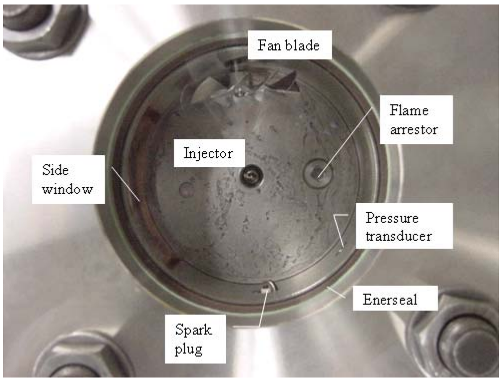

Figure 3. View of combustion chamber from the top of the end window.

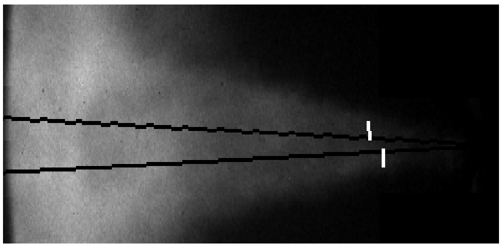

Figure 4. A time averaged image of natural light emission at 310 nm from a burning diesel spray injected into an ambient gas with a temperature and density of 1000 K and 15 kg/m^3. The pressure drop across the injector orifice was 134 MPa. Fuel was injected toward the left from one orifice of the injector at the right edge of the image. The horizontal length of the image is 55 mm. The lift-off length is marked along the two black lines, the average value of these two lift-off lengths is determined as the lift-off length of this image.(Fuel: B0)

Four different fuel or fuel blends: European low sulfur diesel fuel (B0), soybean biodiesel (B100), blend with 20 % (by volume) biodiesel (B20) and blend with 50 % (by volume) biodiesel (B50) were studied. Table 2 lists some of the important fuel properties of diesel and soybean biodiesel used in this study.

Measurement of Lift-Off Length

Naturally occurring OH chemiluminescence is adopted to measure the flame lift-off length because it occurs under high temperature and stoichiometric combustion conditions. The high temperature reactions occurring in the lifted diffusion flame produce a significant amount of the excited state of the OH (OH*). The chemiluminescence emitted from the OH* provides a marker of the high heat release region where it is generated, thus serving as an indicator of the location of the diffusion flame.

Table 1. Summary of experimental conditions.

Ambient gas temperature	800 to 1300 K
Ambient gas density	15 kg/m^3
Ambient oxygen concentration	21%
Injector	HEUI 300A
Nozzle type	VCO
Nozzle number	6 holes
Spray angle	140 deg included
Orifice L/D	6.2
Orifice diameter	0.145 mm
Orifice rail pressure	20 MPa
Pressure intensification ratio	6.7:1
Injection pressure	134 MPa
Injection duration	2.1 ms
Injection fuel amount	120 mm^3 at 23 MPa oil Pressure

One of the strongest bands of OH chemiluminescence occurs near 310 nm [15]. This band was selected for the determination of the lift-off length. The lift-off length is defined as the distance between the injector and the most upstream location of the 310 nm light in the images. In this study a 310 nm band pass filter with a 10 nm FWHM (Full Width at Half-Maximum) is used in front of the lens.

Image analysis code was developed to evaluate the lift-off length from the images such as the one shown in Fig. 4. Two lines were drawn to locate the first axial locations above and below the spray centerline with an intensity greater than a pre-selected threshold intensity, where the horizontal distance between the injector and the two axial locations were defined as the upper and lower lift-off length. The lift-off length of this image is then obtained by averaging the two values. The lift-off length for each testing condition reported in this study was obtained as the mean of 15 such measurements.

The threshold intensity for determining the lift-off length was 8 % of the camera dynamic range according to Siebers and Higgins [16]. The gate time was hold to 200 µs for each case but the camera intensifier gain varied with the maximum intensity of the image equaled 75 % of the camera dynamic range. The upper and lower lift-off lengths determined from the image in Fig. 4 were 12.4 mm and 11.2 mm , respectively, giving the lift-off length as 11.8 mm.

Table 2. European low sulfur diesel fuel and soybean biodiesel fuel properties.

Fuel Property	European Low Sulfur Diesel Fuel	Soybean Biodiesel Fuel
Specific Gravity	0.837	0.8853
Sulfur (ppm)	196	<3
Flash Point (°F)	130.4	>300
Boiling Point (°F)	396.3 (IBP) 518.0(50%) 671.9 (EP)	-
Viscosity	3.2 cPs (@40°C)	4.5cSt (@40°C)
Cetane Number	54.0	47.1

Estimation of Oxygen Ratio in Fuel Spray

To compare the oxygen entrainment from upstream of lift-off, the oxygen ratio (Ω) is calculated by an expression developed by Mueller [9]. A correlation is used to determine the oxygen equivalence ratio, φ_Ω , providing an accurate measurement of the mixture stoichiometry for fuel molecules contain oxidizer elements ,such as biodiesel, or for oxidizer molecules contain fuel elements. The oxygen ratio (Ω) stands for the oxygen entrainment up to the lift-off length as a percentage of the total oxygen required for complete combustion of the injected fuel.

$$\Omega = \frac{100}{\varphi_\Omega} = 100\,\frac{1 - \Omega_f\left[1 - \varphi(H) + \dfrac{\varphi(H)}{\Omega_{ox}}\right]}{\varphi(H) + \dfrac{1}{\Omega_{ox}}\left[1 - \varphi(H) - \Omega_f\right]}, \qquad (1)$$

where Ω_f is the oxygen ratio of the fuel, Ω_{ox} is the oxygen ratio of the oxidizer, the cross-sectionally averaged equivalence ratio at the lift-off length, $\varphi(H)$, is the amount of charge-gas entrained and mixed with the injected fuel spray upstream of the lift-off length [17]. The oxygen ratios of the fuel for B0, B20, B50 and B100 are 0, 0.011, 0.0225 and 0.0344, respectively, and $\Omega_{ox} \rightarrow \infty$ because the oxidizer in this study (molecular oxygen) contains no fuel elements. Although the model was developed for non-reacting sprays, equation (2) is reasonable for the combusting jet studied in this work since a diesel / biodiesel jet is non-reacting up to the lift-off length.

$$\varphi(H) = \frac{1}{\zeta_{st}} = \frac{2\,(A/F)_{st}}{\sqrt{1 + 16\,(H/x^+)^2} - 1}\,. \qquad (2)$$

In Eq.(2), ζ_{st} is defined as the percentage of stoichiometric air at the lift-off length excluding the oxidizer elements in the fuel, where H is lift-off length; $(A/F)_{st}$ is stoichiometric air-fuel ratio by mass, and x^+ is the characteristic length scale for the fuel [17] defined by: $x^+ = \sqrt{\frac{\rho_f}{\rho_a}}\,\frac{\sqrt{C_a}\cdot d}{a\cdot tan(\theta/2)}$. In the expression, d is the orifice diameter, C_a = 0.82 being the orifice area contraction coefficient, ρ_f and ρ_a are the injected fuel and ambient gas densities respectively, $\theta/2$ is the measured spreading half-angle of the fuel jet which can also be calculated (5.5°) [18]. The orifice area contraction coefficient accounts for the loss of flow area through an orifice resulted from vapor bubbles generation by cavitation reaching the orifice exit [19], "hydraulic flip" [20] and/or non-uniform velocity profiles at the orifice exit. The stoichiometric air-fuel ratios by mass for B0, B20, B50 and B100 are 14.37, 13.78, 13.21 and 12.65, respectively. The constant 0.75 was derived from a best fit of spray penetration data to a non-dimensional spray penetration correlation derived using conservation of mass and momentum principles applied to a spray [18].

Results and Discussion

The following section examines the effects of different ambient gas temperature and different fuel type on spray lift-off length, stoichiometric oxygen at the lift-off length and the oxygen ratio.

The effects of the ambient gas temperature and fuel type on lift-off length for the four fuels considered in this study are shown in Fig. 5. The pressure drop across the injector orifice, the orifice diameter, the ambient gas density and ambient oxygen concentration were 134 MPa, 0.145 mm, 15 kg/m^3 and 21 %, respectively. The injection duration was 2.1 ms for all cases. Fig. 5 shows that both the ambient gas temperature and the fuel composition have strong effects on the lift-off length. As the ambient temperature increased, the lift-off length decreased for all the fuels. This observation is consistent with the results reported by Siebers and Higgins [8]. The lift-off length increases as the amount of biodiesel increases due to the higher density, viscosity and flash point of biodiesel as shown in Table 2. When the ambient temperature increased from 800 K to 900 K, the lift-off length, for all fuels considered, decreased significantly. Further increment in temperature did not produce such an obvious drop in the lift-off length. Also noted from the figure is that the lift-off length drops more significantly against temperature for pure diesel versus biodiesel and their blends.

Fig. 6 shows the percentage of stoichiometric air entrained up to the lift-off length, determined by Eq. (2) using the lift-off length data from Fig. 5. As the ambient gas temperature increased, the total amount of air entrained upstream of the lift-off length decreased for the four fuel studied. This was resulted from the shorter lift-off length observed at higher ambient temperatures. The change in ζ_{st} and the change in lift-off length correlates linearly since the second term under the square root in Eq.(2) dominates for the conditions of studies in Fig. 6.

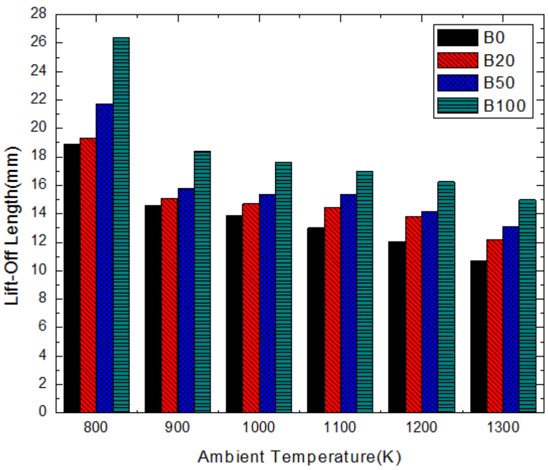

Figure 5. Spray lift-off length versus ambient gas temperature for different fuels. The columns in the same color represent the trend for each fuel.

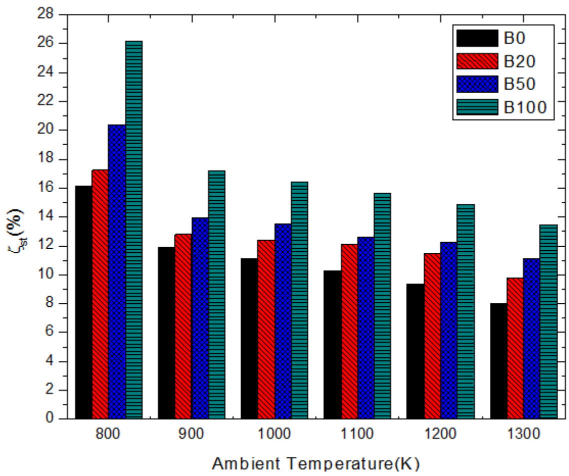

Figure 6. The percent of stoichiometric air entrained up to the lift-off length versus gas temperature for four different fuels. The columns in the same color represent the trend for each fuel.

Figure 7 shows the effects of the fuel composition and the ambient temperature on the oxygen ratio, determined by Eq. (1) using the lift-off length data in Fig. 5 and the stoichiometric air at the lift-off length in Fig. 6. The oxygen ratio provides an accurate measurement of mixture stoichiometry when fuel molecules contain oxidizer elements such as biodiesel in this study. The oxygen ratio (Ω) stands for the oxygen entrainment up to the lift-off length as a percentage of the total oxygen required to completely burn the fuel being injected. The oxygen entrainment up to the lift-off length is more accurately calculated using Eq. (1) than Eq. (2). Since there is no oxidizer elements in diesel molecules, $\Omega_f=0$ in Eq. (1), the stoichiometric oxygen, ζ_{st} , is then equal to the oxygen ratio, Ω , for pure diesel. While for the fuel blends B20, B50 and B100, Ω_f increases as the biodiesel content increases. The stoichiometric air, ζ_{st} , and the oxygen ratio, Ω , are different for biodiesel and its blends, with the later being larger as noted in Fig. 7. For example, at 800 K ambient temperature, the stoichiometric air for B20, B50 and B100 are 17.24093 %, 20.39286 % and 26.16588 %, respectively, while the oxygen ratio are 18.15128 %, 22.18402 % and 28.70577 % for B20, B50 and B100.

Lower soot emission is expected for sprays that entrained more oxygen prior to combustion. Therefore, combustion of fuels with higher oxygen ratio is likely to emit less soot.

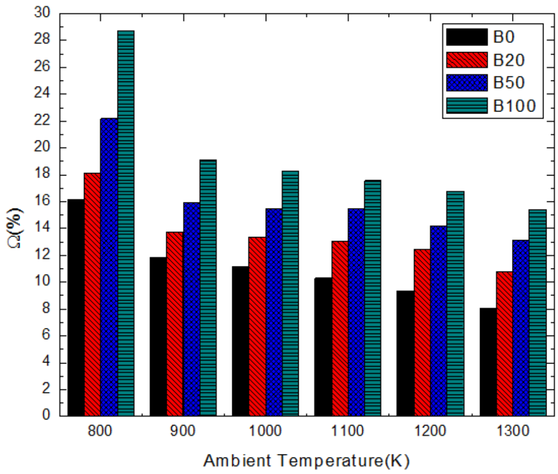

Figure 7. The oxygen ratio at the lift-off length versus gas temperature for four different fuels. The columns in the same color represent the trend for each fuel.

Conclusions

The effects of ambient gas temperature on the flame lift-off length of direct-injection (DI) biodiesel sprays under quiescent conditions were experimentally investigated. Then the impacts of the observed lift-off length variations on oxygen ratio at the lift-off location were also studied. Pure diesel (B0), biodiesel (B100) and their blends (B20 and B50) were tested inside the constant volume combustion chamber. The effects of different ambient gas temperatures on spray lift-off length were investigated with fixed ambient density, oxygen concentration, injection pressure and duration. Then the stoichiometric air and oxygen ratio that occurs upstream of the lift-off length of the sprays were determined.

From the experimental results, the following conclusions were obtained:

1. As the ambient temperature increases, the lift-off length decreases for the four different fuel sprays. The reduction of the lift-off length for an increase of the ambient temperature from 800 K to 900 K is much larger than the reduction observed at higher temperatures. For different fuels, diesel spray has a more significant reduction in lift-off length as temperature increases when compared with B20, B50 and B100 sprays.
2. When the biodiesel content in the fuel increases, the lift-off length increases under the same ambient temperature mainly due to the higher density, viscosity and flash point of biodiesel.
3. The total amount of air entrained upstream of the lift-off length decreases as the ambient gas temperature increases because of shorter lift-off length at elevated ambient temperatures.
4. The stoichiometric air, ζ_{st} , is equal to the oxygen ratio, Ω , for pure diesel because it contains no oxidizer elements. For B20, B50 and B100, the oxygen ratio is larger than the stoichiometric air.
5. Less soot emission is possible when burning fuel that has a higher oxygen ratio.

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Nomenclature

a a constant with a value of 0.75
C_a orifice area contraction coefficient
d diameter
H lift-off length
x^+ characteristic penetration length
ρ_a ambient gas density
ρ_f injected fuel density
θ measured spreading half-angle of the fuel jet
Ω oxygen ratio
Ω_f oxygen ratio of the fuel
Ω_{ox} oxygen ratio of the oxidizer
$\varphi(H)$ cross-sectionally averaged equivalence ratio at the lift-off length
φ_Ω oxygen equivalence ratio
ζ_{st} stoichiometric oxygen at the lift-off length

Subscripts
a represent area or ambient gas
f fuel
ox oxidizer
st stoichiometric

Superscripts
$+$ downstream of the fuel jet

Abbreviations
(A/F) air/fuel ratio
EGR exhaust gas recycle

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