

Effect of Injection Pressure on Ignition, Flame Development and Soot Formation Processes of Biodiesel Fuel Spray

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ABSTRACT

The effect of injection pressure ranging from 100 to 300MPa on the ignition, flame development and soot formation characteristics of biodiesel fuel spray using a common rail injection system for direct injection (D.I.) diesel engine was investigated. Experiments were carried out in a constant volume vessel under conditions similar to the real engine condition using a single hole nozzle. Biodiesel fuels from two sources namely; palm oil (BDFp) and cooked oil (BDFc) with the commercial JIS#2diesel fuel were utilized in this research. The OH chemiluminescence technique was used to determine the ignition and the lift-off length of the combusting flame. The natural luminosity technique was applied to study the flame development and the two color pyrometry was applied for the soot formation processes. Ignition delay decreased as the injection pressure progressed from 100 to 300MPa. This was as a result of the enhanced mixing achieved at higher injection pressures. The BDFp's higher cetane number facilitated shortest ignition delay when compared to the other fuels under all injection pressures. For all the fuels, the lift-off length increased as the injection pressure increased. The percentage of the stoichiometric air entrained upstream of the lift-off length by the BDFp was the lowest. The integrated, average natural luminosities and flame areas of the BDFp and BDFc were smaller at increasing pressures as compared to that of the diesel fuel flames. At the 100MPa injection pressure, the two color pyrometry measurements indicated that there was no significant difference in the integrated and averaged KL factors for all the fuels. At 200 and 300MPa injection pressures, the BDFp and the BDFc presented much lower integrated and averaged KL factors than diesel. The averaged flame temperatures of the BDFp and the BDFc were found to be

lower than that of diesel except at the 300MPa injection pressure. The oxygen contents in the BDFp and the BDFc fuels played a significant role on the soot formation process.

INTRODUCTION

Due to their low carbon dioxide emissions, compact high speed D.I. diesel engines could be attractive power sources for small engine applications. However, these engines are still capable of producing noxious substance such as particulate matter and NO_x at a time when emission regulations are becoming more stringent. Therefore in search of alternative fuels which can meet up with the stringent emission controls, studies on the spray, ignition and combustion of biodiesel fuels are important for small diesel engine technologies. Alternative fuels such as biodiesel are gaining more ground in many countries owing to the increased environmental awareness and the rising price of fossil fuels like diesel [1]. Biodiesel fuel is an environmentally clean and renewable energy source. It is usually produced from animal fats or vegetable oils by transesterification reaction. The oxygen content, which is about 11-15wt%, makes biodiesel to enhance the combustion process and reduce pollutant emissions from the diesel engine [2]. Biodiesel as an alternative fuel in diesel engines has a great potential of reducing CO , CO_2 , HC , PM , SO_x and PAH emissions with slightly increased brake specific fuel consumption (BSFC) and NO_x emission[1]. The major threat facing the use of biodiesel in diesel engine is the formation and control of NO_x emission. This is because this emission is closely related to the oxygen concentration in the biodiesel fuel. To this end, it has been proposed that the addition of cetane-improving additives and the decrease in the bulk modulus of biodiesel can be potential ways of decreasing the



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NO_x emission. Also by applying early injection timing, the NO_x emission can be reduced drastically [3, 4]. Numerous research works have been done on the spray and combustion characteristics of biodiesel fuel in diesel engine [5, 6, 7, 8, 9, 10]. Furthermore, the impact of high injection pressure as an effective method to improve the spray atomization and mixture preparation processes of diesel fuel in order to reduce particulate matter emissions has also been reported [11, 12, 13, 14, 15]. However, few studies have reported on the effect of high injection pressure on the biodiesel combustion and soot formation characteristics. Therefore this study investigated the characteristics of ignition and combustion of biodiesel fuel spray injected by a common rail injection system in a quiescent constant volume vessel. Injection pressures ranging from 100 to 300MPa and the ambient conditions typical of the diesel engine were used.

EXPERIMENTAL DETAILS

EXPERIMENTAL APPARATUS and METHODS

The experiments were conducted simulated quiescent conditions in a constant-volume vessel. Figure 1 shows a schematic cross section of the vessel. The vessel can produce the typical thermodynamic conditions in the combustion chamber of a diesel engine. The ambient temperature could be elevated to 900K with an electric heater fixed at the lower section of the vessel. The vessel has an internal diameter of 200mm. To provide an optical access, a quartz window with a diameter of 124mm is mounted on one side of the chamber while the other side is obstructed by a black metal block. The inside surface of the chamber is covered with a glass fiber insulator to avoid direct heat radiation from the heater. An

injector was installed at the center of the vessel's cover using an adapter, while the common rail was fixed on the top surface of the vessel's cover. A thermocouple was used to measure the ambient temperature inside the chamber. A manually operated piston screw pump (high pressure equipment co. Model 37-5.75-60) as shown in Fig. 1, was used to generate the injection pressure up to 300MPa in the common rail.

The injector was electronically controlled by the injector driver, while the common rail pressure was measured with pressure transducer. A pulse generator (Stanford Inc., DG 535) was used to synchronize the operation of the CCD camera and injection system. Auto-ignition was detected using the OH chemiluminescence imaging technique. The OH chemiluminescence was also used to determine the flame lift-off length. The natural flame luminosity technique was used to images which were use to analyze the flame development by the fuels undergoing combustion processes. For the soot formation experiments, the two color pyrometry technique (time-resolved, line-of-sight) was utilized to provide the flame structure, KL factor and temperature distributions. The KL factor characterizes the soot concentration in the flame. Figure 1 shows the experimental arrangement for the OH chemiluminescence, direct photography and the two color pyrometry imaging. With the aid of a UV-Nikkor lens (Nikkon, 105mm, f/4.5) attached to an image intensifier (LaVision Inc., HS-IRO), the OH chemiluminescence images were captured. OH band-pass filter of wavelength 313nm (10nm FWHM) coupled to the image intensifier was used to observe the OH chemiluminescence. The gain and gate of the image intensifier were adjusted carefully to acquire clear flame images and to avoid saturation of images. A visible lens (Nikkon, 210mm) with an aperture of f/11 to avoid saturation was used to obtain the natural luminosity images. For the two

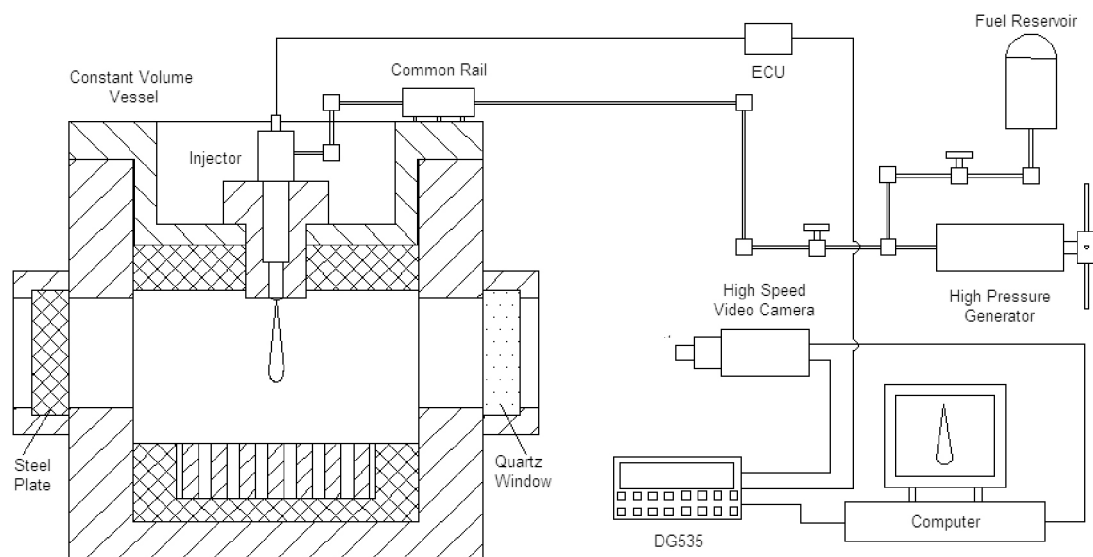


Figure 1. Schematic diagram of experimental apparatus

color pyrometry images, a visible lens (Nikon 105mm, f/4.5) was attached to the two color box and then coupled to the camera. The two color system was calibrated before it was used to capture two raw identical flame images at wavelengths of 650 and 800nm respectively. The Thermera HS4 software (Mitsui Optronics, version 4.61) was used to process the captured raw images, thus generating two-dimensional and line-of-sight false-color maps of flame temperature and soot concentration. This soot concentration, which is expressed as the KL factor, has been found to be proportional to the soot volume concentration [16]. To avoid saturation in the two color images, the aperture was changed to f/8.0. A frame rate of 10,000 fps, exposure time of 0.1ms and resolution of 512×512 pixels were used to capture all the images with the exception of the natural luminosity images which had an exposure timing of 0.001ms to avoid the saturation of the captured flame images.

EXPERIMENTAL CONDITIONS

The experimental conditions were determined by the real engine conditions. Two kinds of biodiesel fuels, namely BDFp

(from palm oil) and BDFc (from cooked oil) and the JIS#2 diesel were utilized in the experiments.

The JIS#2 diesel fuel was considered as the base fuel. [Table 1](#) presents the main properties of the three fuels while [Table 2](#) shows the list of the experimental conditions.

An ambient density of 15kg/m^3 was used to simulate engine conditions at a crank angle of -10° ATDC. Ambient temperature and pressure of 885K and 4.0MPa were maintained for the combustion conditions inside the constant volume vessel.

RESULTS AND DISCUSSION

OH CHEMILUMINESCENCE IMAGING

In obtaining information about the ignition and combustion characteristics of the fuels under investigation, the OH chemiluminescence imaging was carried out. In this work, the ignition delay is defined as the period from the start of injection to the time of the appearance of the first OH chemiluminescence flame. [Figure 2](#) presents the OH radical images of the ignition and combustion processes for the different fuels. As time

Table 1. Main properties of fuels

Fuel Property	JIS#2 Diesel	BDFp	BDFc
Density @ 15°C [kg/m^3]	830	874.4	885.1
Viscosity@ 30°C [mm^2/s]	3.36	5.53	4.45
Flash point [$^\circ\text{C}$]	>60	182	180.5
Flow point [$^\circ\text{C}$]	4	15	-5.0
Cetane number	58	64.6	51
Heating value [MJ/kg]	43.1	40.03	39.03
Sulfur content [ppm]	<10	<1	<3
Carbon content [wt%]	86.1	76.5	77.1
Hydrogen content [wt%]	13.8	12.3	12.0
Oxygen content [wt%]	<1	11.1	10.6

Table 2. Experimental conditions and nozzle specifications

Ambient Gas	Air
Density [kg/m^3]	15(-10° ATDC)
Pressure [MPa]	4.0
Temperature [K]	885
Injection	Common Rail System for D.I. Diesel Engine
Pressure [MPa]	100, 200 and 300
Duration [ms]	1.5
Nozzle	Single Hole
Hole Diameter [mm]	0.16
Hole Length [mm]	1.2

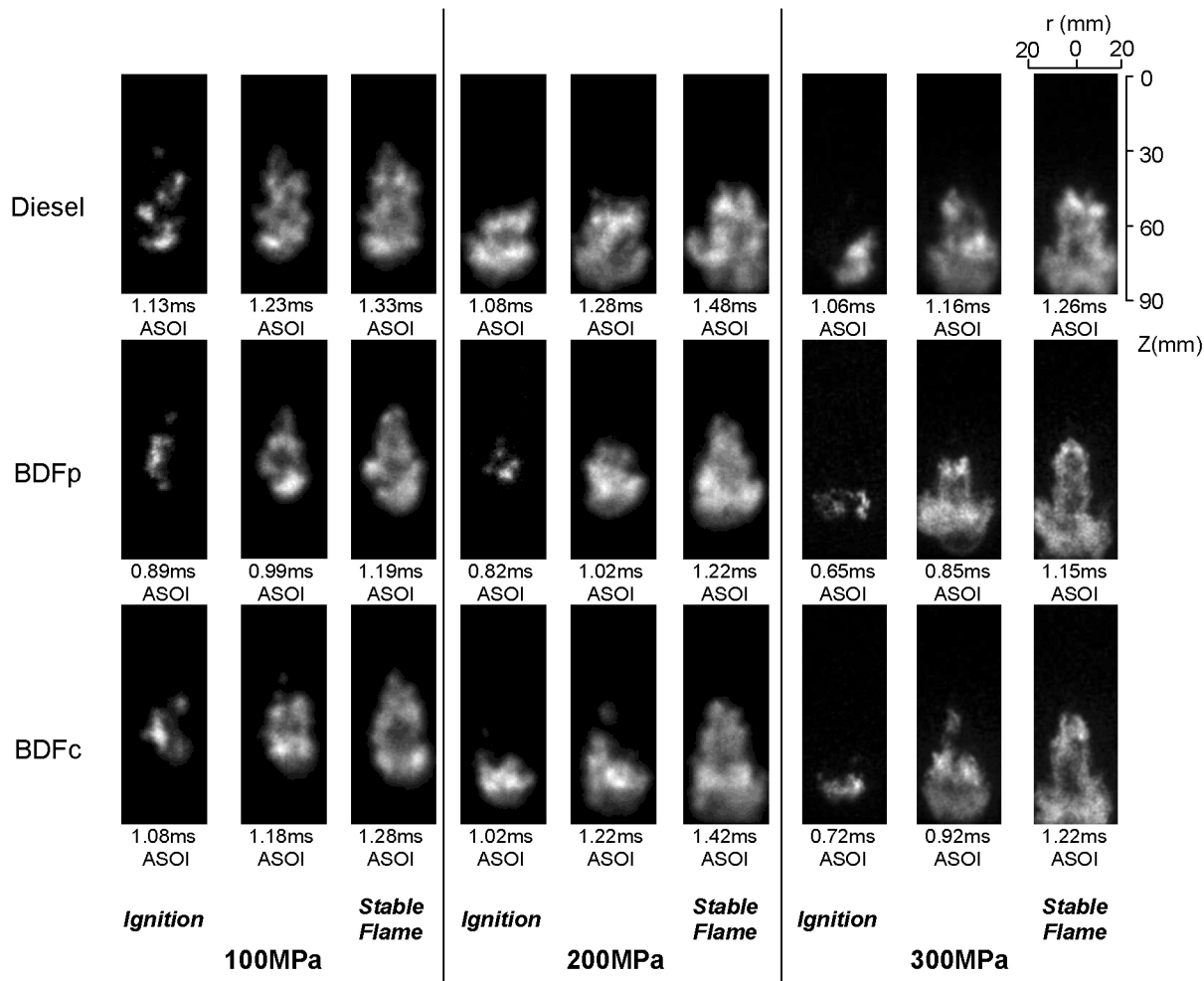


Figure 2. OH chemiluminescence images of ignition and combustion processes

proceeds, the flame size by the three fuel increased until a stable flame is formed. As shown in the figure, the flames move more downstream when the injection pressure increases from 100 to 300MPa. Also Fig. 3 shows the ignition delay of the BDFp, BDFc and diesel respectively under different injection conditions. The data were taken from a temperature range of 873K to 885K. From the analyses, the ignition delay decreases as the injection pressure increases from 100 to 300MPa respectively. This is as a result of the enhanced mixing achievable at higher injection pressure especially at 300MPa. Also the fuel type has effect on the ignition delay. One of the factors that could have an effect on the ignition delay is the cetane number [1, 17]. As shown in Table 1, the BDFp has the highest cetane number and this facilitated its shortest ignition delay when compared to the other fuels under all injection pressures. The diesel fuel ignition delay was the longest. The BDFc with a lower cetane number has a shorter ignition delay when compared to that of diesel. This is an indication that apart from the cetane number, other inherent factors could affect the ignition delay of combustible fuels.

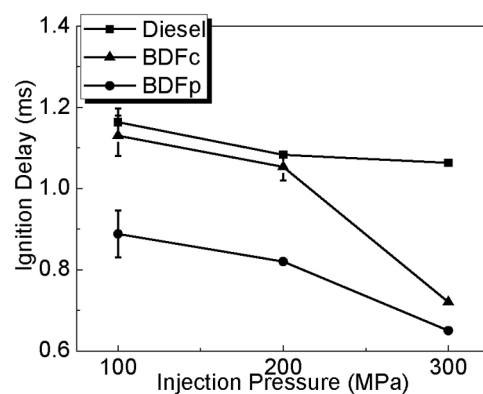


Figure 3. Variations of ignition delay with injection pressure

In Fig. 3, the flame stabilizes at a quasi-steady location significantly downstream of the injector tip. The distance from the injector tip to this initial flame location is referred to as the flame lift-off length. Fig. 4 shows the spatial variation of the

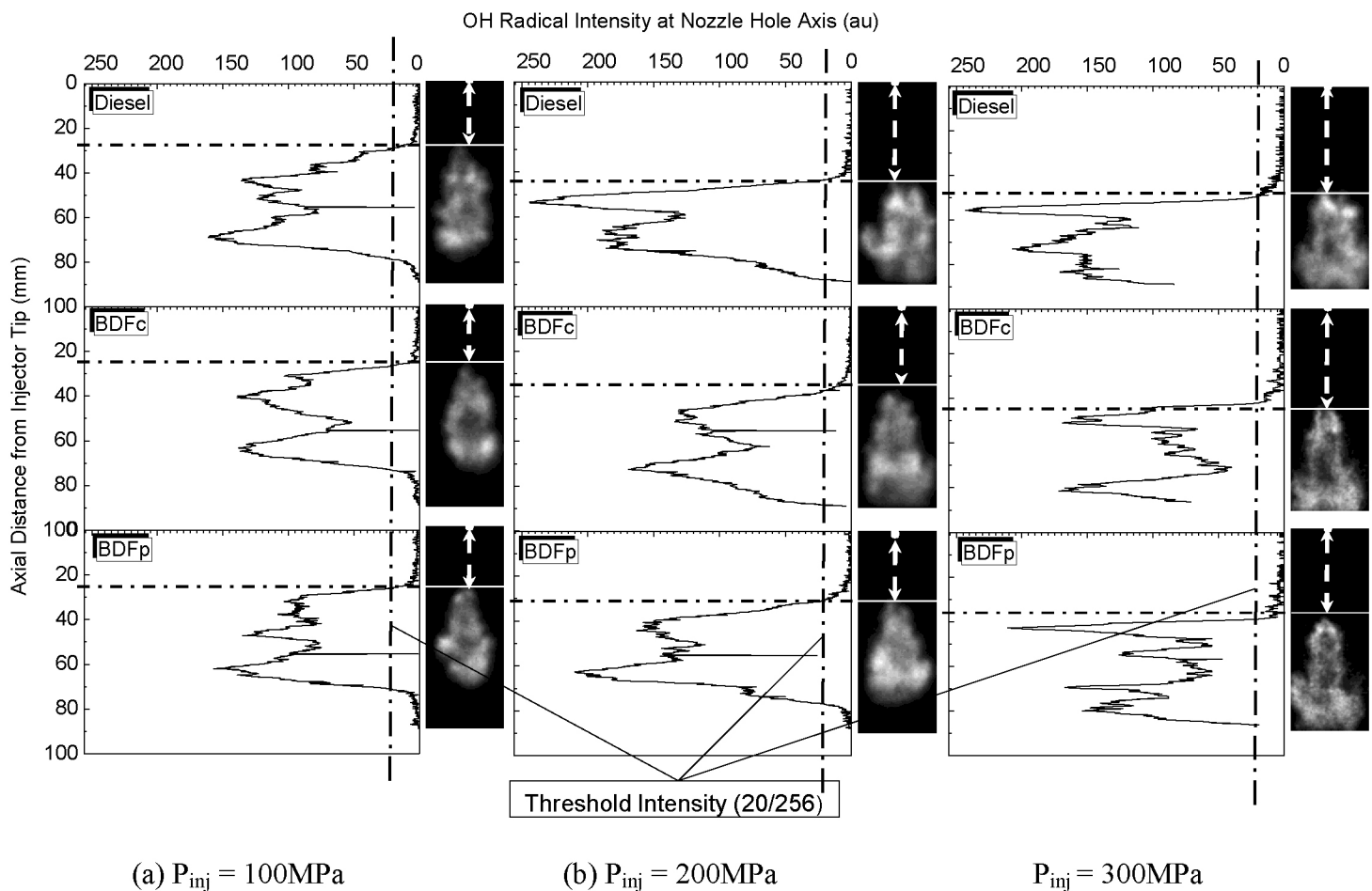


Figure 4. Variations of OH radical intensity at nozzle hole axis with the axial distance from injector at $P_{inj} = 100, 200$ and 300MPa

OH radical intensities measured downstream at the nozzle hole axis at the 100, 200 and 300MPa injection pressures.

The OH radical intensities were obtained by transforming the captured OH images into 8-bit grayscale images of the camera with a maximum intensity of 255 for white color. The distance between the injector and the top most part of the flame where the threshold intensity is 20 (8% of the maximum intensity) could be defined as the lift-off length. The threshold intensity was selected after observing a sudden increase in the intensity. The lift-off flame images are displayed to the right hand side of the graphical analyses of the relative intensities. The broken arrows on the images depict the lift off lengths obtained by the different fuels measured from the injector tip. Due to the turbulence nature of the flames, the OH intensity curves are not smooth. The OH radical intensity increases as the injection pressure increases to 300MPa for all the fuels. Also the lift-off length increased as the injection pressure increased.

For all the fuels, the lift-off length increases as the injection pressure increased. The effect is caused by the higher velocities in the spray as a result of increasing injection pressure, which

push the initial combustion zone (i.e., the lift-off length) farther downstream. At all injection pressures, the biodiesel fuels produced shorter lift-off lengths as compared to the diesel fuel with the BDFp producing the shortest lift-off length. Previous results showed that fuel with shorter ignition delays and higher cetane numbers have shorter lift off lengths [18, 19, 20]. Hence the same effect holds for the BDFp as compared to the other fuels at all injection pressures.

ESTIMATED AIR ENTRAINMENT UPSTREAM OF THE LIFT-OFF LENGTH

The air entrained upstream of the lift-off length has a great impact on the soot formation process which is expected to begin in the products of rich reaction zone. It can be estimated using the expression for the axial variation of the cross

sectional average equivalence ratio, $\bar{\phi}$, in a quasi-steady non reacting fuel jet whose model is as shown in Fig. 5. Full description of the model is beyond the scope of this research but can be found in [21]. The reciprocal of the equivalence ratio when multiplied by 100 gives an expression for the air entrained up to the lift-off location as a percentage of the total air required to burn the fuel being injected.