SPRAY AND COMBUSTION VISUALIZATION OF A DIRECT INJECTION DIESEL ENGINE OPERATED WITH DIGLYME FUEL BLENDS

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ABSTRACT

Experiments were conducted with a commercially available six cylinder, water cooled, turbocharged, direct injection diesel engine. The engine was operated with 15 PPM sulfur diesel (BP15) and blends of diesel with 20 wt.% diglyme (O-20), 40 wt.% diglyme (O-40) and 95 wt.% diglyme (O-95). These fuels were used for observing the effect of the fuel properties on injection timing, heat release, flame structure and luminosity. Visualization showed that the start of injection (SOI) event did not occur at the same time for all the fuels. The highest premixed burn peak and the lowest premixed burn peak were observed with BP15 and O-95 fuels, respectively. It is difficult to distinguish among the spray flames of BP15, O-20 and O-40. However, the flames with the much higher oxygen content O-95 fuel were non-luminous.

Keywords: Diesel, Injection, Combustion.

1. INTRODUCTION

The Environmental Protection Agency (EPA) has proposed an ultra low (15ppm) sulfur diesel fuel beginning in 2006. The introduction of ultra low sulfur diesel fuel might reduce particulate emissions, particularly the particulate matter (PM) associated with sulfates. Also, sulfur sensitive exhaust gas aftertreatment may be used to reduce other emissions from the exhaust gas [1]. Many studies have been performed with biodiesel and oxygenated diesel fuels and almost all of them showed a significant potential to reduce emissions [2-3].

Biodiesel and oxygenated fuel blends are currently of great interest and active research for PM reduction from diesel engines to meet future, stringent emissions regulations. Biodiesel fuels contain roughly 11 wt.% oxygen and the addition of oxygen containing hydrocarbons to diesel fuel offers an effective means to reduce particulate emissions [3]. The higher cetane number of biodiesel and many oxygenates may enhance combustion performance in compression ignition engines.

It is well established that diesel fuel properties have significant effects on engine performance and exhaust emissions [4]. However, there are differences in sensitivity to fuel property effects between older model engines and later model engines. Current production engines are less sensitive to changes in fuel quality so there is less opportunity to gain engine-out emissions improvements through changes in fuel formulation [5]. Sometimes it is very difficult to isolate the effects of one property from another, since the properties of diesel fuels are interrelated. Changing several fuel properties at a time may or may not provide synergistic effects on engine-out exhaust emissions.

In this paper, we present results from in-cylinder imaging in a Cummins 5.9L direct injection (DI) diesel engine using an engine videoscope system. The imaging studies provide a comparison of the fuel injection timing, ignition timing, spray formation and flame luminosity between different fuels.

2. EXPERIMENTAL

Experiments were conducted with a Cummins 5.9L, turbocharged, six-cylinder, 4-stroke, water cooled direct injection (DI) diesel engine. The experimental system consisted of an engine, dynamometer, controller, combustion analysis instrumentation, emissions analyzers and an AVL 513D engine videoscope. The engine was fitted with an electronic control module (ECM) that monitors engine performance and controls different events automatically, especially the SOI, injection timing advancement or retardation, etc. Figure 1 presents a schematic diagram of the engine and test cell instrumentation. Specifications of the test engine are shown in Table 1. The engine used a Bosch VP-44 type rotary distributor fuel pump. The injectors have 7 holes and a 152 deg spray cone angle.

Engine cylinder number six was selected for optical access and the cylinder head modified accordingly. An

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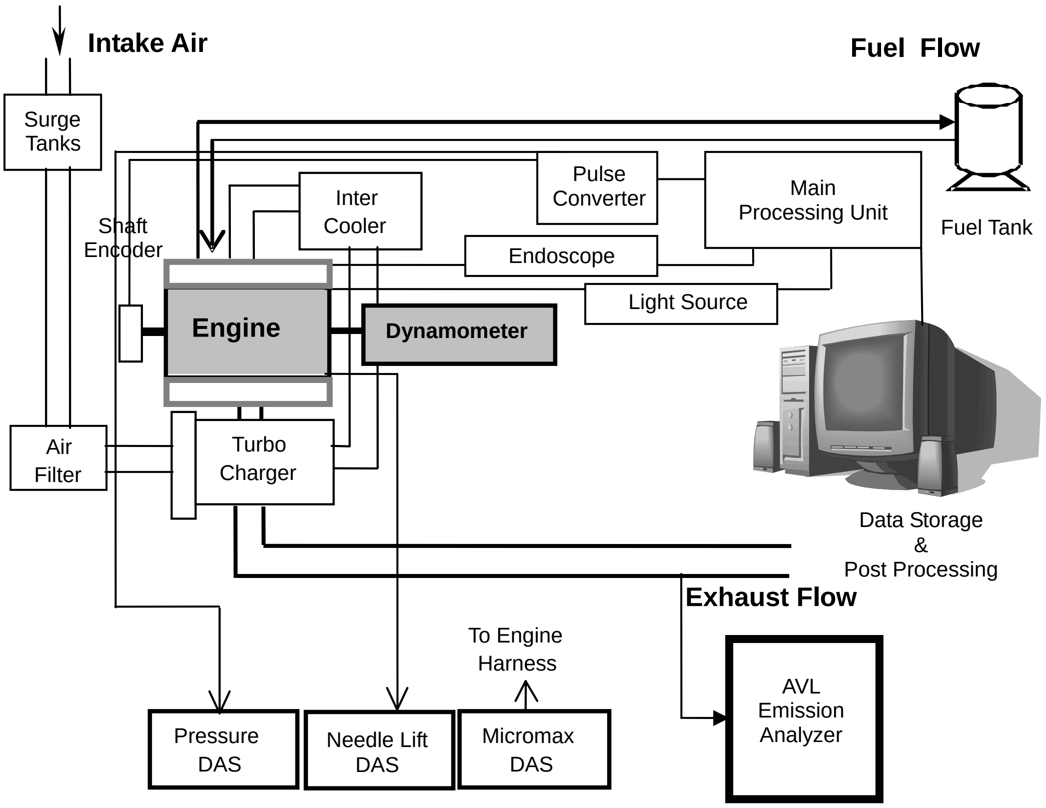


Fig 1. Schematic diagram of the experimental system

AVL 513D videoscope was used for capturing images of spray and combustion [6]. Optical access to the combustion chamber was prepared by installing two small windows in the cylinder head. The windows permit access for an external light source through one and an endoscope through the other. Figure 2-a shows how the light source and the endoscope are mounted in the engine.

Table 1: Specifications of the tested engine

Engine	Six-cylinder DI Diesel, MY 2000
Advertised Power	235 hp @ 2700 RPM
Bore X Stroke	102 mm X 120 mm
Compression Ratio	16.3
Displacement	5.9 L
Injection System	Bosch VP-44 Rotary Distributor Pump
Swirl Ratio	2.45
Aspiration	Turbocharged

Figure 2-b represents a sketch of the geometric relationship between the fuel injector and videoscope probes. Note that the viewing angle of all the endoscopes was 80 degrees. The depth of field was from 1 mm beyond the lens to infinity and therefore a sharp picture of the combustion chamber was obtained without any focus adjustment. The videoscope system is an integrated triggering and digital imaging system. The triggering system was operated with an AVL 364 angle encoder mounted on the engine crankshaft, enabling 0.1 CA degree resolution. A xenon bulb was used to illuminate the cylinder with a flash duration of 30 µs, and a radiometric light output of 328 mJ per flash. The image exposure duration was 62 µs. This videoscope system was only able to take one image per power cycle.

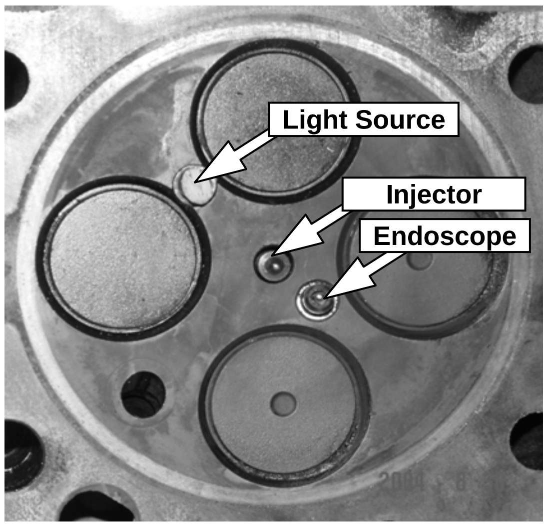


Fig 2(a). Endoscope and light source

Therefore, the images rely on cycle to cycle repeatability. Because of the rapid rate and intermittent process of window fouling inside the engine cylinder, roughly 10 imaging experiments were performed to obtain one clear sequence of digital images. For each fuel and blend considered, the images presented here are the most sharp and free from window fouling that were obtained after repeated trials. Each sequence of images presented here are from one imaging experiment, however as noted, the images are obtained in a given experiment by taking a picture at a given crank angle during one cycle and incrementing by 0.1 CA to take a picture at the next cycle. The AVL videoscope system includes post-processing software for image processing and analysis, which was used to obtain the data presented here.

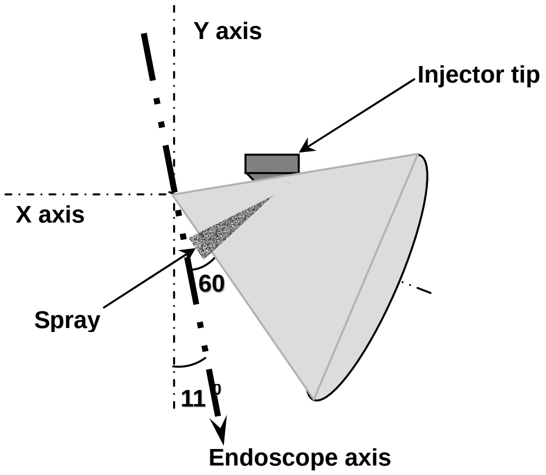


Fig 2(b). Geometric relationship between injector and videoscope probes

The windows installed into the cylinder head were designed to withstand the high temperatures and pressures prevailing within the combustion chamber and to stay clean under engine operating conditions, since the deposition of soot particles on the window surface would reduce visibility. However, it was not possible to operate the engine for very long before soot particles started to deposit on the window surfaces. Because the endoscope needs cooling to keep its maximum operating temperature below 110 ^{o}C, soot particles deposited onto the cold window surface due to thermophoresis. Generally, soot or PM emissions increase with increase in engine load. Soot deposition rate might increase at higher load conditions. To keep less deposition of soot particles on the window and light source, the engine was operated at a light load condition.

Four types of fuels were considered to perform these experiments and to observe the effect of the fuels on spray and combustion. An ultra low (BP15) sulfur diesel fuel with 15 ppm sulfur was considered for the base fuel along with three oxygenated blends consisting of 20 wt.% dyglyme blended with BP15 (“O-20”), 40 wt.% dyglyme blended with BP15 (“O-40”) and 95 wt.% dyglyme blended with BP15 (“O-95”) fuel. Table 2 shows some properties of the base and blended fuels. Cetane numbers of the fuels were derived from the ignition quality tester (IQT) and subscripts in Table 2 indicate IQT data.

For all the base and blended fuels, tests were performed at a steady state condition with the test engine operating at 45 ft-lb (10% rated load) and a constant speed of 1800 rpm. An extended 30 minute warm-up period at idle was used to bring the engine coolant to roughly 90 ^{o}C. Then, the engine was shut down and the endoscope and light source were installed in cylinder number six. After connecting all optical instruments, the engine was re-started and operated under automatic control. The control system was programmed so as to reach the desired speed and load in less than 10 seconds. Once the engine reached the desired speed and load, the spray and combustion images were taken and saved into the AVL high speed data acquisition system. Simultaneously, cylinder pressure and needle lift data were recorded for combustion and heat release analysis. A Leeds & Northrup “Micromax” data acquisition system logged the real-time engine speed, torque and power, lubricating oil and coolant temperatures, as well as, exhaust emissions via an AVL CEB II emissions analyzer.

Table 2: Selected fuel properties

Properties	BP15	O-20	O-40	O-95
Cetane Number	47.3 $_{IQT}$	56.5 $_{IQT}$	69.0 $_{IQT}$	184.0 $_{IQT}$
Density, gm/cm^3	0.837	0.85	0.87	0.92
Viscosity @ 40 C, cSt	2.48	1.85	2.5	0.848
Flash Point, C	63	58	57	55
IBP, C	167.4	166	165	162
Calorific Value, Btu/lb	18219	17420	16179	13320
Sulfur Content, wt%	0.0015	<0.0015	<0.0015	~0
Aromatic Content, wt%	21.2	< 21.2	<21.2	~0

3. RESULTS AND DISCUSSION

The following is a qualitative and quantitative analysis of the spray and combustion characteristics of BP15, O-20, O-40 and O-95. For all the results presented here, the engine was operated at 10% rated load (45 ft-lbs) at a constant speed of 1800 rpm.

Figure 3 shows spray images at 0.1 crank angle degrees (CAD) resolution and the SOI with BP15, O-20, O-40 and O-95. The O-20 showed the earliest start of injection among the fuels. The O-20 fuel showed 0.2 CAD advanced injection compared to BP15 diesel fuel. The start of injection event was retarded with O-40 and

O-95 compared to the BP15 and O-20. The O-40 and O-95 showed identical SOI at 5.3 deg. BTDC and both of them showed a 0.4 CAD retarded SOI compared to O-20 and a 0.2 CAD retarded SOI was observed compared to BP15 diesel fuel. The change in start of injection timing among the fuels might be due to the density differences of the fuels. The engine used in these experiments is a commercial engine fitted with an electronic control module designed to compensate injection timing according to the fuel properties such as density, calorific value, etc. The effects of density variation on start of injection timing might be more prominent with a mechanically controlled fuel injection system.

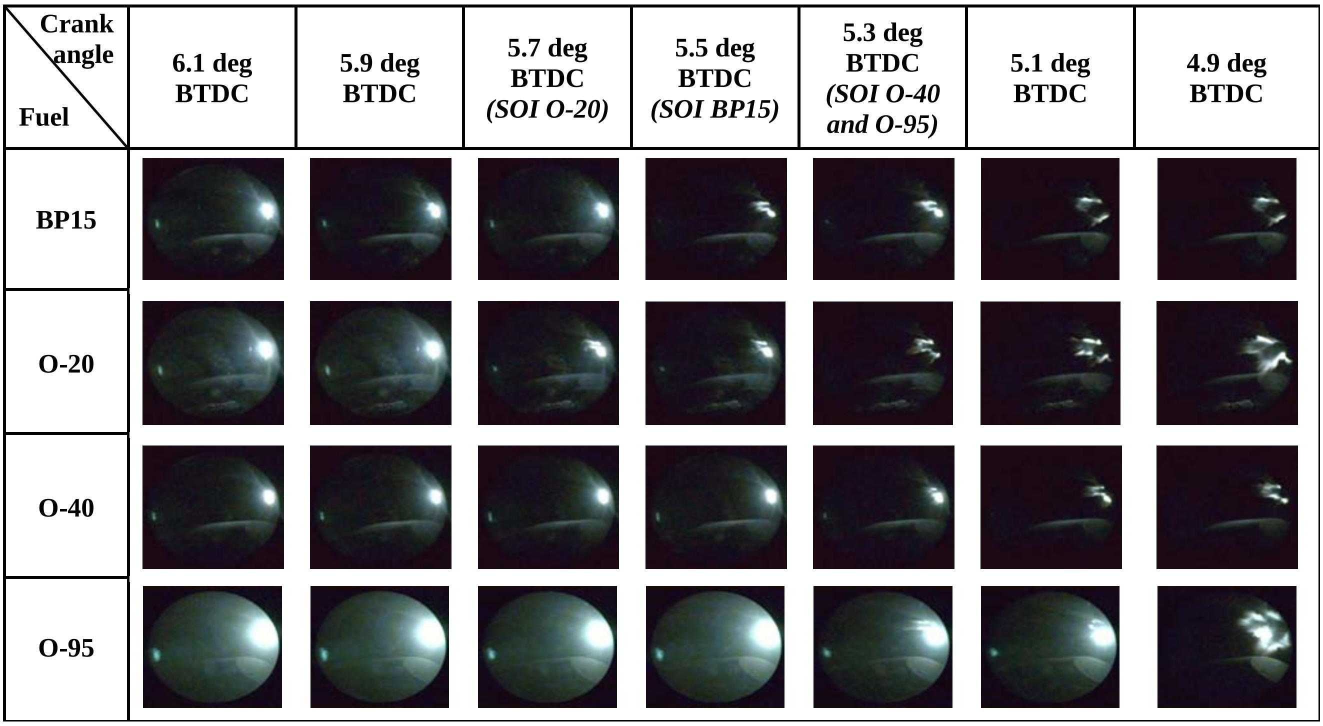


Fig 3. Start of injection with BP15 ultra low sulfur diesel fuel, O-20, O-40 and O-95

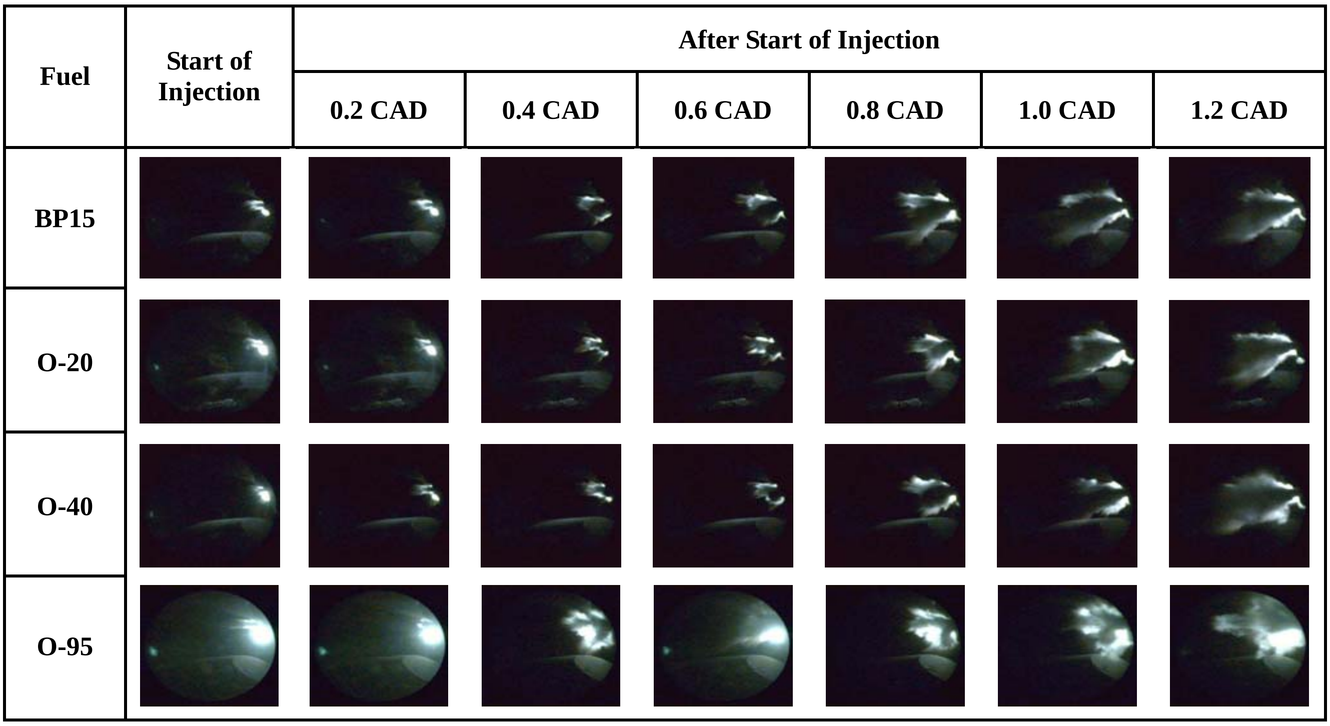


Fig 4. Spray penetrations with BP15 ultra low sulfur diesel fuel, O-20, O-40 and O-95

Spray penetration with all the fuels can be observed in Figure 4. Irrespective of actual crank angle position, the first column shows start of injection images and the rest show images after the start of injection with 0.2 CAD interval. Compared to all the fuels used in this study O-95 showed the lowest penetration. Spray penetration of BP15, O-20 and O-40 fuels are similar. However, this comparison may not be suitable when considering start of injection timing in CAD, since the observed start of injection of all the fuels did not happen at the same time in terms of CAD (Figure 3). Therefore, the length of penetration might change with cylinder pressure and temperature and the volatility of the fuels. Another difference between the base BP15 and O-95 is spray pattern. Soon after the start of injection with O-95, the initial spray angle is wider than the base, O-20 and O-40 fuels. From the spray images as shown in Figure 4, it is very difficult to quantitatively assess the change in spray angle among the fuels.

Figure 5 shows rate of heat release (ROHR) analysis of the fuels used in these experiments. The start of combustion is indicated by the CAD when the ROHR curve moves from negative to positive value. The ROHR analysis also indicated that the majority of the combustion was during the premixed burn (Figure 5). While the O-20 and O-40 blends contain fuel oxygen, it is difficult to distinguish between the spray flames of O-20, O-40 and the base BP15 diesel fuel. The early start of the heat release with O-95 is explained by its high cetane number (Table 2). Among the fuels, the highest premixed burn peak is observed with the base BP15 fuel, which is consistent with the cetane number of the fuels as shown in Table 2. In general, it seems that the NO_X emissions with O-40 and O-95 might be decreased due to the lower premixed burn peak with these two fuels. However, this statement may not be true at high load conditions. An earlier study was carried out under the AVL 8-Mode test protocol where gaseous and PM emissions can be found with base BP15 diesel fuel and some other biodiesel blends [7]. Blending oxygenates to base diesel fuel is a way of reducing tailpipe PM emissions. An example of low PM emissions with O-95 can be observed with PM deposition on the glass window and illumination tip (Figure 6).

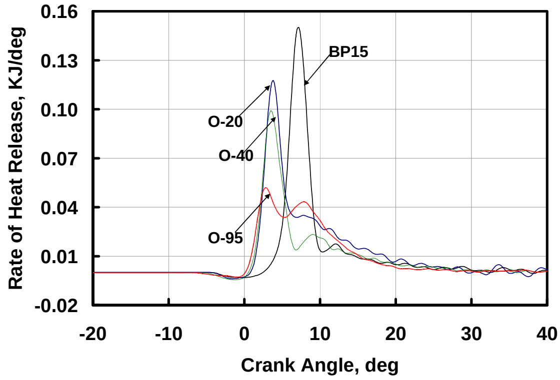
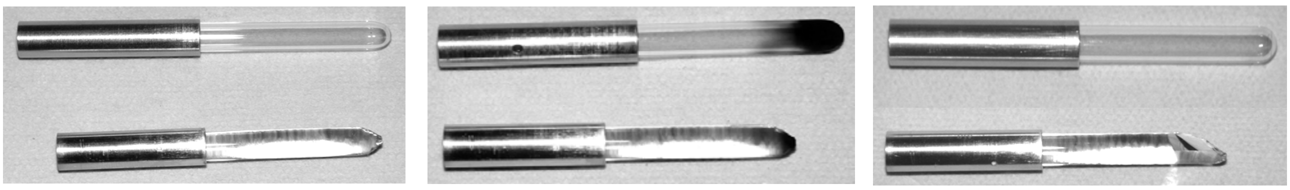


Fig 5. Rate of heat release analysis with BP15 ultra low sulfur diesel fuel, O-20, O-40 and O-95



(a) (b) (c)

Fig 6(a). Fresh window and illumination tip (b) soot deposition with BP15 (c) soot deposition with O-95

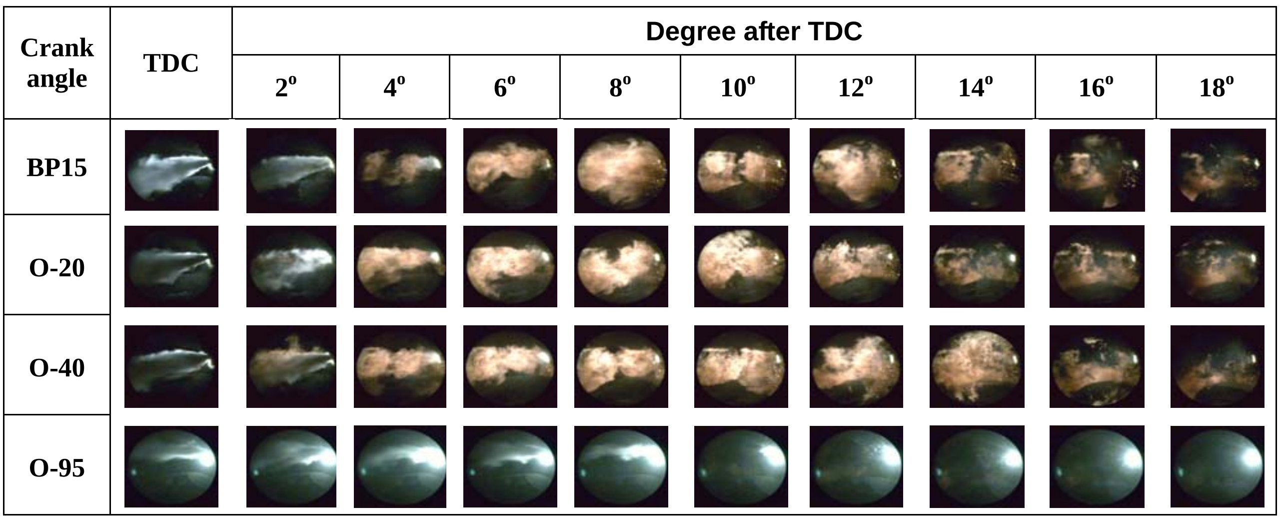


Fig 7. Combustion images from TDC to 18 deg ATDC of the combustion process with 2.0 CAD intervals with BP15 ultra low sulfur diesel fuel, O-20, O-40 and O-95

Figure 7 presents different combustion events for all the fuels starting from TDC to 18 deg ATDC at an interval of 2.0 CAD. The images of the spray and combustion are at a light load condition. Therefore, combustion is mainly controlled by the premixed burning phase. The ROHR analysis also indicated that the majority of the combustion was during the premixed burn (Figure 5). It is difficult to distinguish among the spray flames of BP15, O-20 and the O-40 fuel. However, the flames with much higher oxygen present in the O-95 fuel compared to O-20 were non-luminous, as observed by Beatrice et al. who demonstrated non-luminous flames with oxygenates [8].

4. SUMMARY

Experiments were conducted with base BP15 diesel fuel and three blends of diglyme with BP-15. In-cylinder visualization of spray and combustion was performed with these test fuels with 0.1 crank angle degree resolution. Findings from the present study can be summarized as follows:

1. The earliest start of injection event was observed with O-20 fuel. The start of injection event was retarded with O-40 and O-95 compared to base diesel fuel and O-20. The O-40 and O-95 show identical start of injection and 0.2 CAD retarded SOI compared to base BP15 fuel.

2. Combustion analysis showed that the earliest start of combustion occurred with the O-95 fuel. Among the test fuels, the highest premixed burn peak was observed with the lowest cetane number ultra low sulfur BP15 diesel fuel.

3. Combustion with O-95 was non-luminous.

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