EFFECT OF BUTANOL BLEND ON IN-CYLINDER COMBUSTION PROCESS PART 2: COMPRESSION IGNITION ENGINE

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Abstract

To meet the future stringent emission standards, innovative diesel engine technology, exhaust gas after-treatment, and clean alternative fuels are required. Oxygenated fuels showed tendency to decrease internal combustion engine emissions. In the same time, advanced fuel injection modes can promote further reduction in pollutants at the exhaust without penalty for the combustion efficiency. One of the more interesting solutions is provided by the premixed low temperature combustion (LTC) mechanism jointly to lower-cetane, higher-volatility fuels.

In this paper, to understand the role played by these factors on soot formation, cycle resolved visualization, UV-visible optical imaging were applied in an optically accessed high swirl multi-jets compression ignition engine. Combustion tests were carried out using two fuels: commercial diesel and a blend of diesel with n-butanol. The fuels were tested at 70MPa injection pressure and different timings. At late injection timing coupled to high EGR rate (50%), the blends increased the ignition delay allowing operating in partially premixed LTC (PPLTC) regime in which the fuel is completely injected before the start of combustion. Strong reduction in engine out emissions of smoke and NOx were obtained with a little penalty on engine efficiency. This limitation was overcome operating at earlier injection timing in which a mixing controlled combustion (MCC) LTC regime was realized. In this regime, a good compromise between low engine out emissions and efficiency was achieved.

***Keywords**: optical diagnostics, combustion process, common rail CI engine, diesel/gasoline blend, diesel/butanol blend*

1. Introduction

Compression ignition engines are used worldwide because they achieve better fuel economy, lower carbon dioxide (CO2) emissions than conventional spark ignition engines fuelled by gasoline. However, these engines tend to be more costly and emit high levels of nitrogen oxides (NOx) and particulate matter (PM). While several technology options exist to decrease these exhaust pollutant emissions, the E.U. is promoting the development of Clean Diesel Combustion (CDC) technology, which refines several existing technologies into a unique engine design that is simultaneously clean, efficient, and cost effective. The key concept of CDC technology is the development of in-cylinder NOx and PM control, where NOx and PM emissions are reduced in the engine combustion chamber without penalizing the engine efficiency. One promising strategy is the Low-Temperature Combustion (LTC) that can be based on two different concepts: Homogeneous Charge Compression Ignition (HCCI) and Mixing Controlled Combustion (MCC) [1-6]. HCCI is a premixed combustion mechanism in which the equivalence ratio is less or equal to 1 ($\varphi \leq 1$). It is strongly dependent on kinetics, temperature, combustion timing as well as mixture preparation (early or late injection with high swirl). HCCI has the following potential limitations: difficult to control the combustion timing; possible knocking and high NOx and PM emissions at high loads; possible liquid fuel impingement on the in-cylinder surfaces; incomplete combustion at light loads (misfire, high UHC and CO). A different promising approach to reduce NOx and soot formation in diesel engines is the mixing-controlled LTC, a combustion mechanism in which the equivalence ratio is equal or higher than 1 ($\varphi \geq 1$). This concept is based on preserving the spray structure, but introducing a significant reduction in the equivalence ratio at the flame lift-off length cross section as well as in the combustion temperature. It can be realized in conventional diesel engines with appropriate fuel composition, modulation of injection and high level of EGR. The mixing-controlled LTC concept presents additional advantages compared to the HCCI, such as low combustion noise and the control of combustion phasing by the injection strategy. This combustion mechanism has been successfully explored in a low swirl engine [6] and in a quiescent constant-volume vessel. It was found a valid link between increased lift-off length and decreased soot formation. In order to verify this trend for multi-hole nozzles in realistic engine environment, optical investigations were carried out in a high swirl compression ignition engine operating under different combustion regimes. Recently, several researchers have studied the relationship between LTC regime and in-cylinder fuel reactivity. [7][8] A fuel like gasoline, more resistant to autoignition and an appropriate injection pressure and timing, can be very useful to realize it. [9][10] In fact, large amounts of exhaust gas recirculation (EGR) and high fuel injection pressure are common strategies to promote fuel and air mixing processes. High EGR reduces in-cylinder temperature and extends ignition delay while high injection pressure promotes fuel atomization and vaporization; both are beneficial for mixing process. [1][11] However, the application of high EGR reduces in-cylinder oxygen content, causing deterioration of combustion efficiency that leads to increased hydrocarbon (HC) and carbon monoxide (CO) emissions. To avoid the disadvantages of high EGR rates, a fuel with a lower cetane number and higher volatility can be considered. The resistance to autoignition of low-cetane fuels may provide an adequate ignition delay for mixing and faster vaporization that can increase mixing rate. In this way, a thorough mixing can be achieved without high EGR rates and worsening of combustion efficiency. Several researchers have investigated the relationship between LTC operational range and cetane number.[8] [12] In a light-duty diesel engine working at high loads, a low-cetane fuel allowed a homogeneous lean mixture with improved NOx and smoke emissions joint to a good thermal efficiency. Nevertheless, the growing energy demand and limited petroleum fuel sources in the world have guided researchers towards the use of clean alternative fuels like alcohols for their better tendency to decrease the engine emissions. [13][15] Alcohols have less carbon, sulphur content and more oxygen than traditional fossil-based fuels. On the other side, alcohol fuels, generally, produce higher evaporative emissions due to higher vapour pressures while their low energy density causes a drop in engine performance. However, the very low cetane number limits the usage of neat alcohols in diesel engines; they should be blended with diesel fuel without any modifications in the engine fuel system. There are many studies performed to observe engine performance and exhaust emissions by alcohol fuels blended with diesel fuel. Most of them concern the use of methanol and ethanol. On the other, n-butanol has more advantages than ethanol and methanol. Butanol is much less evaporative and releases more energy per unit mass than ethanol and methanol. Butanol has also a higher cetane number (12) than ethanol (8) and methanol (3) making it a more appropriate additive for diesel fuel. Butanol is less corrosive than ethanol and methanol and it can be blended with diesel fuel without phase separation. Finally, butanol can be produced by fermentation of biomass, such as algae, corn, and other plant materials containing cellulose that could not be used for food and would go, otherwise, to waste.

Even if the effect of butanol–diesel fuel blends on performance and emission of diesel engines was well studied [16][17][20], literature is poor about detailed description of the in-cylinder thermo-physical phenomena. In this paper two different low-temperature combustion (LTC) mechanisms (PPLTC and MCC), in an optical compression ignition engine, have been investigated. Blend with 80% of diesel and 20% n-butanol was tested. Optical diagnostics were applied to follow the combustion process changing injection timing and EGR rate. Their effect on the lift-off length and soot formation were studied. In-cylinder optical investigations were correlated with the engine parameters and with the engine out emissions, measured by conventional methods.

2. Experimental set-up

The experiments were carried out in an external high swirl optically accessed combustion bowl connected to a single cylinder 2-stroke high pressure common rail compression ignition engine. The main engine specifications are reported in Tab. 1. The external combustion bowl (50 mm in diameter and 30 mm in depth) is suitable to stabilize, at the end of compression stroke, swirl conditions to reproduce the fluid dynamic environment similar to those within a real direct injection diesel engine. The implication of "cylindrical bowl" is related to the peculiar design of the prototype engine that has a large displacement as an air compressor.

Tab. 1. Specifications of the engine

2-stroke single cylinder CI engine	
Cylindrical Bowl (mmxmm)	50 x 30
Bore (mm)	150
Stroke (mm)	170
Connecting Rod (mm)	360
Compression ratio	10.1:1
Air supply	Roots blower
Abs. intake air pressure (MPa)	0.217
Bosch Injector nozzle	7/0.141/148°
Injection pressure (MPa)	70

The main cylinder, connected to the external "swirled bowl" through a tangential duct, allows supplying compressed air flow to the bowl as the piston approaches TDC. The air flow, coming from the engine cylinder, is forced within the combustion chamber by means of a tangential duct. In this way, a counter clockwise swirl flow, with the rotation axis about coincident to the symmetry axis of the chamber, is generated. The injector was mounted within this swirled chamber with its axis coincident to the chamber axis; in this way the fuel, injected by the nozzle, is mixed up through a typical interaction with the swirling air flow. The combustion process starts and mainly proceeds in the chamber. As soon as the piston moves downward, the flow reverse its motion and the hot gases flow through the tangential duct to the cylinder and finally to the exhaust ports. The combustion chamber also provides a circular optical access (50 mm diameter), on one side of it, used to collect images and a rectangular one (size of 10 x 50 mm) at 90°, outlined on the cylindrical surface of the chamber, used for the laser illumination input. The injector was located on the opposite side of the circular optical access with the axis coincident to that of the combustion chamber. The common rail injection system was arranged by a solenoid controlled injector with a micro-sac 7 hole, 0.141 mm diameter, 148° spray angle. An external roots blower provided an intake air pressure of 0.217 MPa with a peak pressure within the combustion chamber of 4.9 MPa under motored conditions.

In the preliminary phase of the work, cycle resolved visualization of the spatial and temporal spray evolution were performed. The visualization was obtained using an 8-bit high-speed camera (Optronis CamRecord 5000 – 512 x 512 pixel) equipped with a 50 mm focal Nikon lens. The spectral range of the high speed camera extended from 390 nm to 900 nm. A camera region of interest was selected (440 x 440 pixel) to obtain the best match between the spatial and temporal resolution. This optical assessment allowed a spatial resolution around 0.15 mm/pixel and a frame rate of 5882 fps. The exposure time was fixed at 50 μs corresponding to 0.15 CAD at the engine speed of 500 rpm. The spray was back-illuminated by two 250 W halogen lamps in order to visualize the fuel jets still before the start of combustion.

To reach the target of the paper, UV-Visible digital imaging and chemiluminescence were applied. Previous works demonstrated that images of flame luminosity in the UV can be used to measure the lift-off length of diesel flames [21][23]. Even if several sources, including soot emission, may contribute to the total UV-VIS luminosity, the first exothermic reactions occur in the UV spectral range (<400nm). [21] Moreover, as reported in [24], the UV flame emission, below 350 nm, is governed by OH chemiluminescence. [25] The energetic reactions and high temperatures, which occur during stoichiometric combustion of typical hydrocarbon fuels, form excited state species that include excited state OH*. Once formed, OH* returns fast to its ground state, a fraction through chemiluminescent emission and through collisional quenching. OH chemiluminescence provides an excellent marker of the high heat release regions where it was generated.

Optical measurements have been performed, using an intensified CCD camera equipped with a quartz lens (UV-Nikon 78-mm), collecting the light emission that passes through the optical access of the combustion chamber. The electronically gated ICCD camera had an array size of 512 x 512 pixels with a pixel size of 19x19 μm and 16-bit dynamic range digitization at 100 kHz. The match between the ICCD and the lens allowed 185 μm spatial resolution. The camera spectral range spread from UV (180 nm) until visible (700 nm). The line-of-sight light emission measurements were performed in the whole ICCD spectral range. The ICCD is not a cycle resolved detector and each acquisition was carried out at a fixed crank angle of different engine cycles setting the exposure time at 5μs. The temporal difference between two images was 50μs. The intensifier gain was adjusted so that the brightest region of images was on the threshold of saturating the detector and it was the same for all the engine tests.

Single-jet experiments in well-defined ambient environments have provided valid relationship between flame lift-off length and soot formation. [21][23] In multi-jet realistic engine environments, the determination of lift-off length become more difficult due to in-cylinder swirling flows, the proximity of in-cylinder surfaces and interaction between adjacent jets. [22] To measure lift-off length from UV-VIS chemiluminescence, the luminosity along the axis of each liquid fuel spray was considered. The flame emission occurred spatially outside the envelope of the liquid scatter, appearing as a "bulge". [21][22][24] A 15% threshold in the luminosity, along the spray axis, was fixed in order to remove liquid scattering and evaluate the flame lift-off. Along each fuel jet axis an automated computer-based image-processing routine evaluated the distance from the combustion chamber centre to the first treated UV-VIS signal. The flame lift-off was obtained by the average on the seven directions. 2D chemiluminescence measurements were also performed by band-pass filters with 10 nm half height width, mounted in-front the UV Nikon lens. The filters were centered at 532 nm. The exposure time was set at 50 μs while the temporal difference between two images was 50 μs.

Tab. 2. Properties of tested fuels

Fuel Properties	Diesel	BU20
Density @ 15 °C [kg/m^3]	840	830.4
Viscosity @ 40 °C [mm^2/s]	3.2	2.2
Cetane Number	52.0	44.0
Net Heat Value [MJ/kg]	42.5	41.0
Carbon content [%]	87.0	80.2
Hydrogen content [%]	12.6	15.4
Distillation 50% Vol. [°C]	280	233
Distillation 90% Vol. [°C]	338	330

Visible wavelength flame emission is dominated by soot incandescence. It occurs farther downstream than the shorter wavelength UV emission [23]. Due to this spatial separation, soot flame lift-off was evaluated. The procedure was the same described for the UV-VIS emission. Finally, a post-detection processing of the optical data was realized. For each 16-bit image only the data in a selected region of interest corresponding to the combustion chamber were retrieved. Each image was converted in a numerical matrix. In this way it was possible to evaluate the luminous signals as integral on the whole combustion chamber. This procedure allowed also identifying the optical start of combustion for all the selected engine conditions. The procedure was applied to the filtered optical data in the visible (532 nm). The crank angle encoder signal synchronized the cameras and the engine, through a delay unit. The AVL Indimodul recorded the TTL signal from camera acquisitions together with the signal acquired by the pressure transducer. In this way, it was possible to determine the crank angles where optical data were detected. Results of the in-cylinder pressure have been computed averaging 300 consecutive engine cycles. Exhaust gaseous emissions have been acquired by the AVL DiGas 4000 analyzer for NOx (1 ppm resolution), the Smoke Meter AVL 415S was used for FSN and soot concentration (0.01 mg/m³ resolution) measurements. All combustion tests were carried out running the engine at the fixed speed of 500 rpm, injecting a fuel amount of 30mg ±1% at the pressure of 70 MPa. Tests were carried out setting the electronic injection timing (SOI) of 11 CAD BTDC, 3 CAD BTDC, 1 CAD ATDC and 5 CAD ATDC at two EGR rates, 0% and 50%.

Combustion tests were carried out using two fuels. The baseline fuel was the European low sulphur (10 ppm) commercial diesel with a cetane number of 52. The blend was composed by 80% of baseline diesel and 20% of n-butanol by volume and denoted as BU20. The main properties of the tested fuels are reported in Tab. 2.

3. Results and Discussion

Figure 1 displays typical in-cylinder combustion pressure for some selected engine conditions. The values in CAD of the pressure at start of combustion (PSOC) and Ignition Delay (ID) for both the fuels and all the operating conditions are listed in Tab. 3.

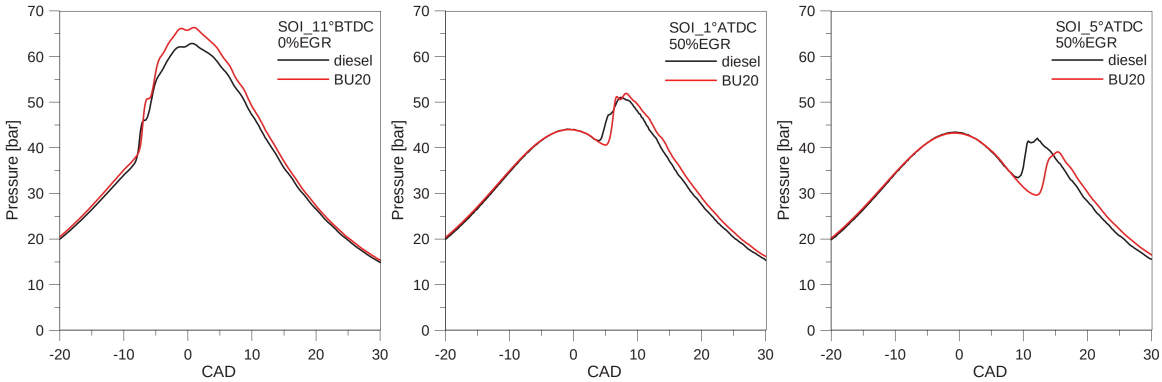

Fig. 1. In-cylinder pressure for diesel and BU20 for selected engine conditions

Tab. 3. Pressure start of combustion and Ignition Delay (ID) for all the operating conditions

SOI [cad atdc]	EGR [%]	Diesel PSOC [cad atdc]	Diesel ID [cad]	BU20 PSOC [cad atdc]	BU20 ID [cad]
-11	0	-8.5	1.5	-8.3	1.7
-3	0	0	2	0.3	2.3
1	0	4.3	2.3	4.7	2.7
5	0	9.3	3.3	10.1	4.1
-11	50	-7	3	-6.2	3.8
-3	50	0.4	2.4	0.8	2.8
1	50	4.9	2.9	5.5	3.5
5	50	10.4	4.4	11.7	5.7

It can be observed that the combined effects of lower cetane number of BU20, which gives a longer ignition delay with respect to diesel fuel, and its higher volatility contribute to increase the mixing time joined to a better mixed charge. Moving the SOI towards later start of injection a longer ignition delay may be observed. This trend is confirmed both at EGR=0 and 50% suggesting that the decrease in fuel cetane number increases the ignition delay for the low and high temperature conditions. SOI = 11 CAD BTDC gives a moderate higher pressure peak of BU20 compared to the diesel, both at EGR=0 and 50%. This effect is due to the larger amount of B20 fuel burnt during the premixed combustion because of the increased ignition delay. Retarding the SOI to 1 CAD ATDC, the MCC mechanism is observed for both fuels at EGR=50%.

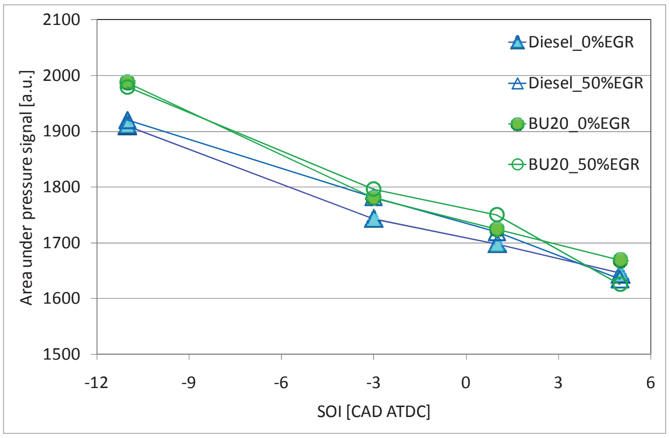

Fig. 2 - Pressure working area vs. the start of injection (SOI) for all the operating conditions

Moreover BU20 accomplishes a partial premixed low temperature combustion (PPLTC) mechanism. BU20 fully achieves the PPLTC at SOI= 5 CAD ATDC both at EGR=0 and 50%. The PPLTC regime was not attained for the diesel, although the ignition delay was increased up to 4.4 CAD for the case at EGR=50%. In this case, the total amount of injected fuel is delivered earlier than the crank angle at which the PSOC occurs. This condition gives an increase in the ignition delay that may contribute to reduce simultaneously NOx and smoke enhancing mixing before combustion. Regarding combustion efficiency, Fig. 2 shows the in-cylinder pressure working area, for the selected fuels and EGR rates versus the SOI. The working area decreases linearly retarding the start of injection at which an increase in ignition delay is matched. The limit value for engine stability and efficiency was reached at SOI =5 CAD ATDC, which gave an increase in the ignition delay, that enhanced the air-fuel mixing before combustion, realizing a partially premixed regime. At fixed SOI, BU20 gave a higher engine working area, due to the better fuel volatility and mixing rate than diesel fuel (about 5%). The average reduction in thermal efficiency between the tested fuels, comparing the SOI=11 CAD BTDC and SOI=5 CAD ATDC was lower than 20%, without any influence from EGR rates.

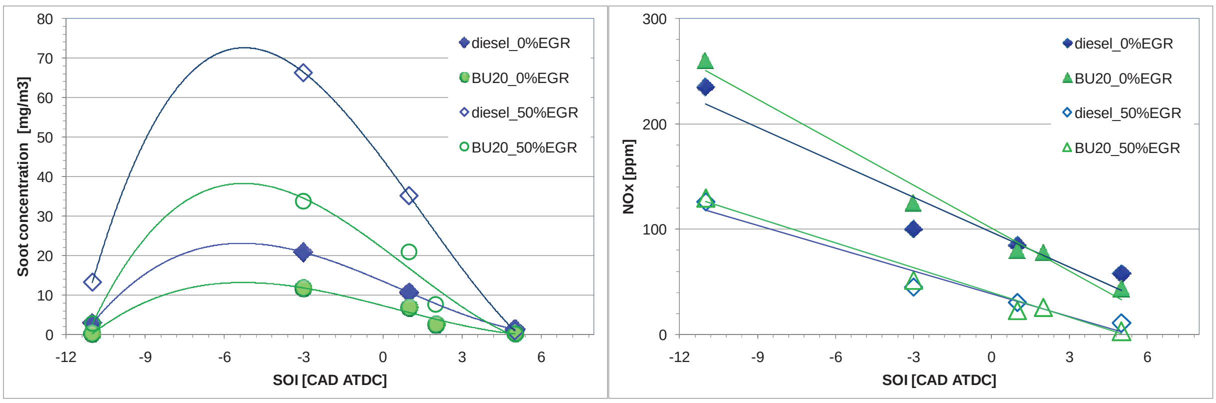

Fig. 3 – Engine exhaust emissions of soot (left) and NOx (right) vs. the start of injection (SOI)

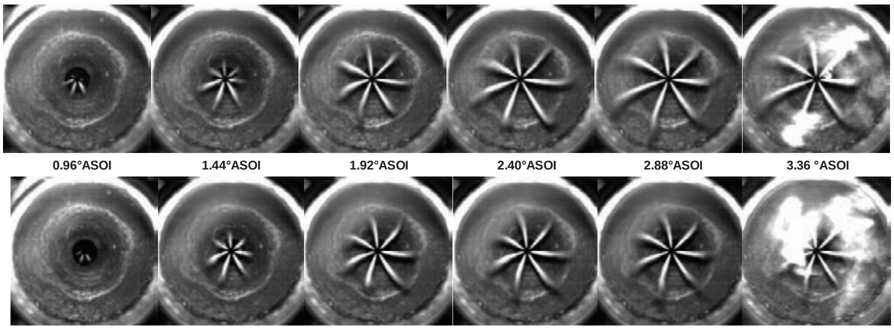

Fig. 4. Cycle resolved spray evolution for diesel fuel at SOI=11 CAD BTDC (up) and 1 CAD ATDC (down) at EGR=0%

One of the main targets of the premixed low temperature combustion is the reduction in engine out emissions without a significant penalty in fuel consumption. Fig. 3 shows engine out soot and NOx emissions versus the start of injection (SOI) for all the operative conditions. The blend BU20 allowed getting the best compromise between NOx and soot, at acceptable engine efficiency. At retarded SOC, the PPLTC mechanism was dominant: soot and NOx emissions were close to zero but the engine efficiency decreased. At early injection timing (11 CAD BTDC), the blend BU20 allowed to operate in mixing controlled combustion (MCC) supplying the highest working area and a good compromise between NOx and soot emissions. In particular, BU20 with EGR=50% guaranteed the best operative condition attaining a reduction in engine out emissions without a significant penalty in engine efficiency.

Regarding the optical investigations, Fig. 4 shows the time-sequence of the mixing controlled combustion (MCC) of diesel fuel without EGR, detected by the high speed cycle resolved camera for an early start of injection and a more retarded one. For both conditions, the fuel coming out from the nozzle proceeds toward the bowl wall interacting with the hot swirling air. The fuel sprays appear well separate without any interference between the jet tips. At a given distance from the nozzle, known as lift-off length, a fuel-rich premixed reaction zone develops in the internal region of the spray in which soot precursors are formed. The fuel rapidly burns, in a low oxygen and high temperature zone, creating suitable conditions for soot particles formation.

Figures 5-7 show the effects of tested fuels on the combustion evolution. For each selected sequence, the first image corresponds to the first well resolvable UV-VIS signal thus to the first exothermic luminescence reactions. The auto-ignition occurred near the tip of the fuel jets; after this time the flame went up the direction of the spray axis, following the stoichiometric air-fuel ratio path. Due to the strong swirl, the flame, previously induced, spreads in the combustion chamber dragged by the anticlockwise air motion. This had a stronger effect on the longer lift-off jets. For all the conditions, the ignition delay of BU20 blend was longer than the diesel fuel, at the same SOI and EGR values. The minimum ignition delay was measured for the SOI=3 CAD BTDC that corresponded to the highest smoke emission, for each condition more retarded SOI, the optical SOC increased about linearly retarding the injection timing, at EGR=50% and with fuels more resistant to auto-ignition (BU20). It should be noted that the spray wasn't detected for BU20 at the condition with SOI=5 CAD ATDC and both EGR rates.

To better understand the outcome fuel injection mode on the soot formation, a comparison between the visible wavelength luminosity and the related flame lift-off was evaluated. The results, obtained at 532nm, are shown in Fig. 8. It can be observed that the soot emission intensity diminishes with the increase in lift-off length. This result confirms the trend shown by other authors [24]. The soot emission and, consequently, the soot amount were linked to the lift-off following an exponential behaviour with a good agreement. It should be noted that, for BU20, it was not possible to evaluate the lift-off at SOI=5 CAD ATDC for both EGR rates. In particular, the BU20 provided similar effects at early injection and high EGR conditions. The soot emission fitting curves were always lower for blend than diesel, at fixed EGR in the same lift-off range. The rate of the soot reduction was dependent on fuel and temperature; the characteristic length of the exponential fits was always higher for blend than diesel, at fixed EGR. This effect was due to the simultaneous action of soot formation decrease and oxidation increase of the blend.

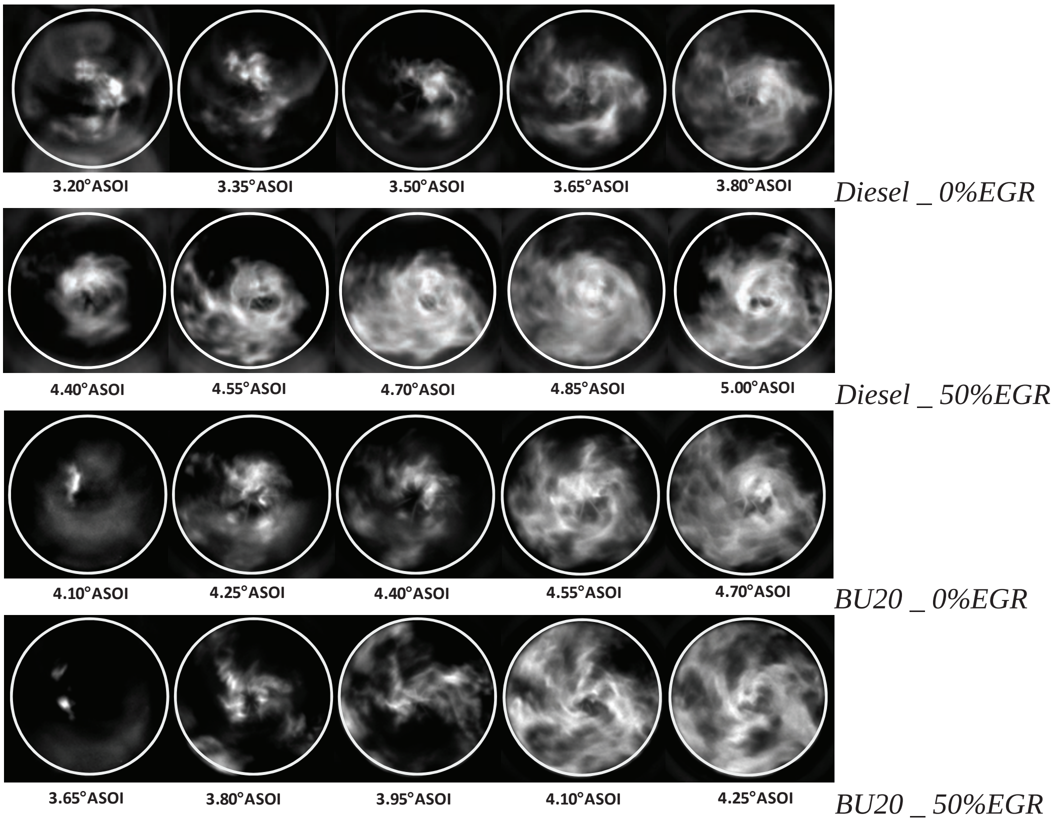

Fig. 5. UV-VIS flame emission for Diesel and BU20, SOI=11 CAD BTDC (0-50%EGR)

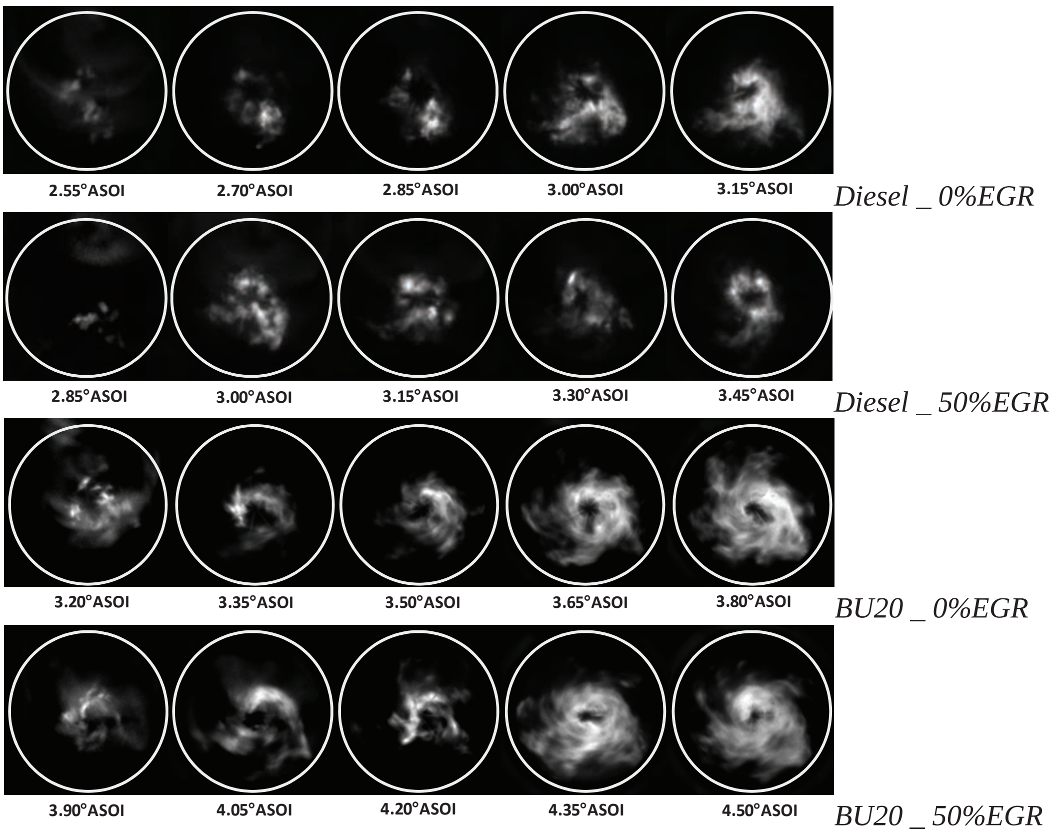

Fig. 6 - UV-VIS flame emission for Diesel and BU20, SOI=3 CAD BTDC (0-50%EGR)

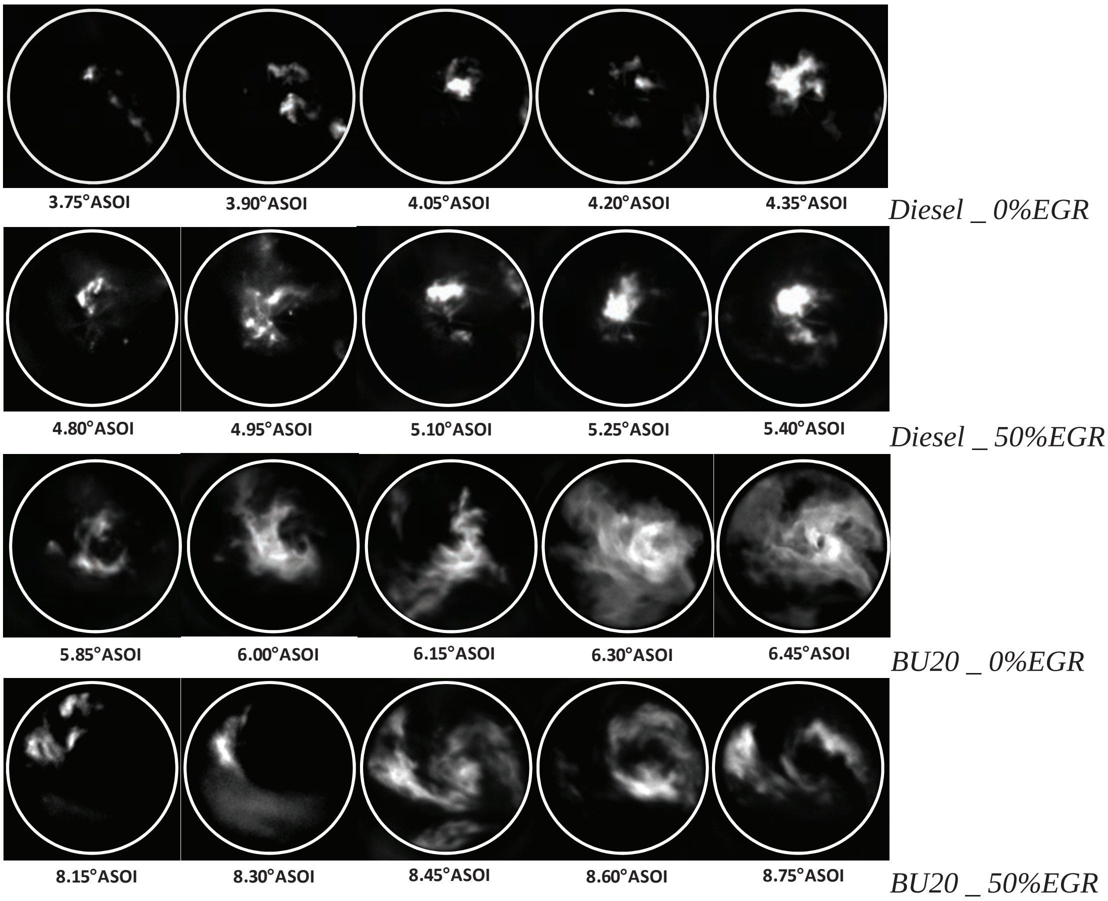

Fig. 7. UV-VIS flame emission for Diesel and BU20 fuel, SOI=5 CAD ATDC (0-50%EGR)

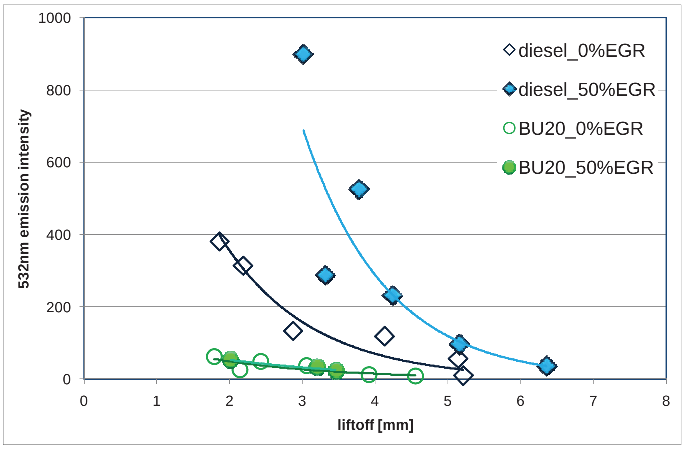

Fig. 8. Integral emission intensity versus the lift-off length measured by filtered data at 532 nm for all the selected operative conditions and fuels

4. Conclusions

Experimental methodologies based on cycle resolved visualization, UV-visible optical imaging and visible chemiluminescence were applied in an optically accessed high swirl multi-jets compression ignition engine. The engine was fuelled with a commercial diesel, a blend of 80% diesel with 20% n-butanol (BU20). Combustion process was studied from the injection until the late combustion phase fixing the injection pressure at 70MPa and changing the injection timing and EGR rate. In-cylinder optical investigations, correlated with conventional measurements of engine parameters and exhaust emissions, demonstrated that the blends increased the ignition delay particularly at late injection timing allowing operating in PPLTC regime in which the fuel is completely injected before the start of combustion. In this regime, strong reduction of engine out emissions of smoke and NOx were obtained. On the other hand this combustion regime reduced the engine efficiency. To overcome this limitation a mixing controlled combustion (MCC) LTC regime was realized by an earlier injection. In this regime, a good compromise between low engine out emissions and a good efficiency was demonstrated. The effects of the fuel quality and injection on the flame lift-off length and soot formation were studied. The increase in lift-off length well matched to a decrease of in-cylinder soot production. The BU20 blend, at 50% of EGR and late injection timing, allowed to operate in LTC regime in which a strong decrease of soot formation joined to reduce engine out emissions were obtained.

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