Effect of Fuel Injection Pressure on Performance and Emission Characteristics of a Compression Ignition Direct Injection Engine Fuelled With Waste Cooking Oil Biodiesel Mixture

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Abstract- In the recent years, biodiesel has become a promising solution to the rapid depletion of the fossil fuel reserves as well as to the alarming amount of discharged pollutants. But inherent properties such as low volatility, high density and high viscosity have been pointed at for inducing most of its drawbacks. Many studies have been undertaken in order to inhibit these deficiencies. Hence, the aim of this study is to investigate the effect of varying injection pressure on performance and emission characteristics of a four-cylinder, four-stroke, compression ignition direct injection engine fuelled with mineral diesel fuel and 20%, 40% and 60% waste cooking oil biodiesel blends (B20, B40 and B60). To that end, five injection pressures were tested: the original 200 bar, 220 bar, 240 bar, 260 bar and 280 bar. Experiments were conducted in accordance with the procedure dictated by DIN 70020. This study revealed that implementing the injection pressure up to 240 bar induces significant improvement in the performance characteristics for all tested fuels to varying degrees. The B20, under this optimized injection pressure was found to offer the best performances characteristics. Increasing injection pressure has proven its worth within a restricted limit. Indeed, for 260 bar and 280 bar, for all tested fuels, performance and smoke level characteristics were found to be dwindling.

Keywords- Diesel engine, waste cooking oil biodiesel, kinematic viscosity, performances, smoke opacity

1 Introduction

In order to meet 2020 renewable energy targets, strong banded partnerships have been built between engine manufacturers, energy suppliers, legislators and researchers. They are teaming up in the fields of improving fuel economy, reducing exhaust emissions and optimizing renewable alternative fuels use in internal combustion engines. Energy targets are subdivided in two major criteria; security and sustainability [1].

Beyond protecting the environment and boosting the economy, countries worldwide are seeking energy security in adopting biodiesel fuel. the EU countries faced the obligation of lowering their dependence on imported mineral fuels while remaining highly mobile. Lowering reliance on imported fuels by relying on locally available sources, thus establishing energy security, became the driving force of promoting biofuels [2]. According to the European automobile manufacturers association (ECEA), biodiesel is one of the two most widely used biofuel blending components gaining momentum today [3].

True it is, biodiesel produced from waste cooking oil transesterification is a first-generation biofuel, but it does comply with the requirements of the Renewable Energy Directive II (RED II directive), and also helps to fulfill the sustainability criteria as cited in Allen B. report [2]. Indeed, the production of this kind of biofuel does not impair food security.

The biofuels directive of the EU parliament 2003/30/EC is the first legal framework which provided backing for the initial steps taken by biofuels in the automotive fuel market. Between this directive and its supersede: the in-affect directive: 2009/28/EC, biofuels have been gaining ground in transport sector. The 2009/28/EC directive proposed a new proportion by 2020. In the transport sector, the EU aims to increase the minimum percentage of fuels coming from renewable sources up to10% [4].

Reaching this challenging goal leads to help reducing greenhouse gas emissions and to improve the EU security of supply. Actually, biodiesel fuels have to be within the limits of the standard EN 14214: 2008. This standard, as well as its homologue ASTM D6751, have become since the backbone of biofuels industry.

Biodiesel fuel is preferred as a renewable diesel engine fuel [5,6]. However, numerous researches conducted on diesel engines fuelled with biodiesel, reported that high viscosity characteristic is deriving in an improper combustion process and proposed increasing injection pressure as a technological solution to this drawback. Therefore, the objective of this study is to experimentally investigate the effect of high-pressure fuel injection implementation on performance and emission characteristics of a direct injection diesel engine fuelled with waste cooking oil biodiesel mixture.

2 Experimental Apparatus and Procedure

2.1 *Test fuels properties*

In this study, diesel as baseline was provided by “Société Nationale de Distribution des Pétroles AGIL S.A”. Biodiesel was provided by BIODEX S.A, which is a certified company based in Tunisia for biodiesel production. This company holds the International Sustainability & Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RBS) certification. Biodiesel was produced from waste cooking oil (WCO) and methanol by transesterification process [9]. The waste cooking oil methyl ester (WCOME) physical-chemical parameters meet the requirements of EN 14214:2008. The analysis report provided by the supplier is summarized in Table 1.

Table 1. Main specifications of tested WCOME

Property	**EN 14214:2008 Limits**		**Test method**	**Analysis result**
	Min.	**Max.**		
Ester content (%m/m)	96.5	–	EN 14103	99.6
Density @ 15 °C (kg/m^3)	860	900	EN ISO 12185	882.9
Viscosity @ 40°C (mm^2/s)	3.5	5	EN ISO 3104	4.272
Flash point PM-procedure A	101	–	ENISO2719	>140
Cetane number	51	–	ASTMD7668	54.3
Total contamination (mg/kg)	–	24	EN 12662	<6
Methanol content (% m/m)	–	0.20	EN 14110	0.08
Monoglyceride content (% m/m)	–	0.80	EN 14105	0.6
Diglyceride content (% m/m)	–	0.20	EN 14105	0.15
Triglyceride content (% m/m)	–	0.20	EN 14105	0.02
Free glycerol (% m/m)	–	0.02	EN 14105	<0.010
Cold filter plugging point (°C)	–	Country specific	EN 116	-2

2.2 *Viscosity measurement*

Detrimental effects of biodiesel’s high viscosity have been reported in several studies [7, 8, 9, 10]. During the atomization process, fuel is forced through a small orifice under high pressure and atomized into very fine droplets. This process helps increasing the surface between compressed air and fuel which leads to a better mixing and to a subsequent combustion. In the other hand, fuels characterized by high viscosity, like biodiesel, tend to form large droplets when atomized next to the nozzle exit which leads to a poor atomization during spray phase and interferes with complete combustion [11]. Authors reported fuel high viscosity role in decreasing the spray tip penetration, contracting the spray angle, diminishing the injection velocity and in wearing the fuel pump and injectors. Those factors derive in a poor combustion, in increasing exhaust emissions and smoke opacity, and in tending to form engine deposits on fuel supply system and components [12, 13]. Hence, this research focus was narrowed on the kinematic viscosity of biodiesel and on the effect of injection pressure (IP) increase on inhibiting deficiencies induced by this property.

BX refers to a a blend including X% volumetric biodiesel.

kinematic viscosity of baseline mineral diesel, B10, B20, B30, B40, B50, B60, B70, B80, B90 and B100 was measured. For each sample, the kinematic viscosity measurement test was conducted two times in order to match the requirements of BS EN ISO 3104: 1996. The average value of experimental data was taken as quintessential value. Fig.1 shows viscosity measuring system using OMNITEK "Spectro-Visc", serial number 5.300.20346. The analysis conforms to the precise requirements of ASTM D445, D446, D7279 and ISO3104: 1996. The temperature of the thermostatic bath, for the integrality of tests, was fixed at 40°C.

Fig.1. Kinematic viscosity measuring system

The viscosity of biodiesel can be estimated from mixing laws such as the Grunberg-Nissan and Katti-Chaudhri law, which was originally proposed by Arrhenius [14]. The law is expressed in mathematical form as written in the following equation:

$$Ln\,(V_{mix}) = x_1\,Ln\,(V_1) + x_2\,Ln\,(V_2) \qquad \textbf{(1)}$$

where, V_{mix} is the kinematic viscosity (mm^2/s) of the mixture, V_1 and V_2 are kinematic viscosities (mm^2/s) of components 1 and 2 and x_1 and x_2 are the mass or volume fractions of components 1 and 2.

2.3 *Test engine set up and measurement instrumentation*

For this experimental investigation, a four-cylinder, four-stroke compression ignition direct injection engine was used. Its major specifications as well as the fuel injection system's are shown in Table 2. As shown in Fig.3, the test engine and the hydraulic dynamometer are interfaced to a control panel. The test rig is provided with the necessary equipment which measures fuel consumption, temperature and pressure of lubricating oil and coolant water. The smoke opacity level was monitored using a computerized smoke meter.

Table 2. General specifications of the test engine

Engine:	
Make:	LAND ROVER
Type:	DI, diesel engine, turbocharged, intercooled, 4 cylinders in-line
Bore (mm):	90, 47
Stroke (mm):	97,00
Displacement (cm):	2495
Compression ratio:	19.5: 1 + 0.5: 1
Valve timing:	
IVO/IVC (°CA):	16°BTDC/ 51° ATDC
EVO/EVC (°CA):	42° BTDC / 13° ATDC
Fuel injection system:	
Injection pump:	BOSCH rotary type
Injectors:	
Type:	Hole type injectors
Number of nozzle orifices:	5
Nozzle holes diameter	0.26 mm
Nozzle hole angle:	145°
Nozzle opening pressure	200 bar

2.4 *Dynamometer*

The hydraulic dynamometers are first and foremost used as loading units for performance testing of combustion engines on engine test stands. They absorb the mechanical energy of the driving engine and allow its load with torque. The mechanical energy is turned into warmed-up cooling water [16]. The test engine was coupled with a hydraulic HORIBA SCHENCK D400 type dynamometer. It has been verified that the power range of the testing engine is well supported by the chosen hydraulic dynamometer. The dynamometer's braking power is controlled through the cooling water filling level. The torque measurement is ensured by a load cell fitted with pendulum body support. Torque measuring hysteresis error < 0.2%. The speed is digitally acquired at the shaft of the dynamometer via a toothed wheel and a pulse generator with measuring error of ± 1 revolution per minute (rpm).

2.5 *Smoke meter*

Smoke opacity is related to the amount of particulate in the exhaust gas, i.e. the amount of unburned carbon and polycyclic aromatic hydrocarbon [17]. The smoke opacity of exhaust was measured as a percentage using the TEXA fume analysis chamber which is an optical absorption diesel smoke meter type [16]. Its opacity measurement range is from 0 to 99.9% with a resolution of 0.1.

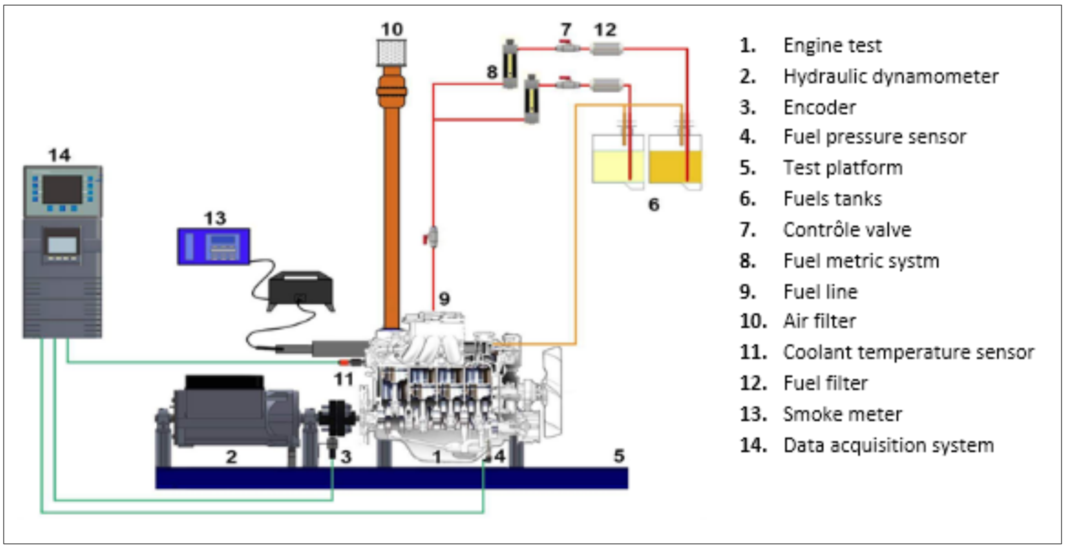

Fig.3. Schematic of experimental system

2.6 Experimental conditions and test procedures

The experimental investigation has been carried out according to the strict procedure dictated by DIN 70020. The experimental design was as follows. Five test batteries have been carried out. During every battery, we fix the IP and we vary the fuel (baseline Diesel Fuel (DF) then B20, B40 and B60). The first battery was performed at the original fuel injection pressure which is 200 bar. The second at 220 bar, the third at 240 bar, the fourth at 260 bar and the last array of experiments has been performed at 280 bar. Fig. 4. shows the five sets of injectors used in this experimental investigation.

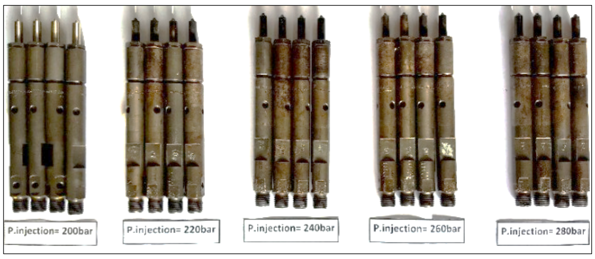

Fig.4. Sets of injectors used in tests

During all the experimental phase, the management of the test engine, the data acquisition and the supervision were fully operated in a manual mode. The engine start, the increase of engine revolutions, the decrease of engine revolutions and the engine complete shutdown were manually controlled from behind the operating panel of the engine test bench.

Initially, the IP of the engine was, as set by the manufacturer, 200 bar and the fuel used was the baseline diesel. The engine was warmed up until the temperature and the pressure of the lubricant oil respectively reached 75 °C and 2.5 bar and kept with small or no variations. As DIN 70020 standards require, the engine speed was then gradually increased from 1800 rpm to 4000 rpm. After engine stabilized in 4000 rpm, a progressive deceleration was applied. During this deceleration, from 4000 rpm until 1800 rpm, at every 200 rpm, net power, net torque and specific fuel consumption were recorded. The same testing procedure was also performed to the engine operated with B20, B40 and B60.

To conduct the next four batteries of tests, the 200 bar original injectors set have been replaced by the 220 bar set, then by the 240 bar set, the 260 bar set and finally by the 280 bar injectors set. With each set of injectors, the same testing protocol has been maintained: starting with baseline diesel, before switching with biodiesel blends: B20, B40 and B60.

Let's highlight that the test engine operated under enhanced strain marked, inter alia, by running under variable speeds, various loads, several fuel types and especially numerous IPs imposed by this research. The mentioned conditions are different from the standard operating ones imposed by the engine constructor. Therefore, instead of the permanent monitoring of the exhaust temperature, the engine lubricating oil pressure and temperature, the cooling water circulating through the engine block jackets and the cylinder heads temperature via the control panels of the test bench, a dual laser, 1% of reading accuracy, infrared thermometer was used to detect and localize any possible engine overheating.

3. Results and Discussion

For all blends, experimentally measured values and predicted values of kinematic viscosity with equation (1) are plotted in Fig.2. Comparison reported a maximum absolute error of 0.0746%.

This implies that, for this WCO biodiesel, Arrhenius law can be used with confidence to estimate the kinematic viscosity of the biodiesel blend.

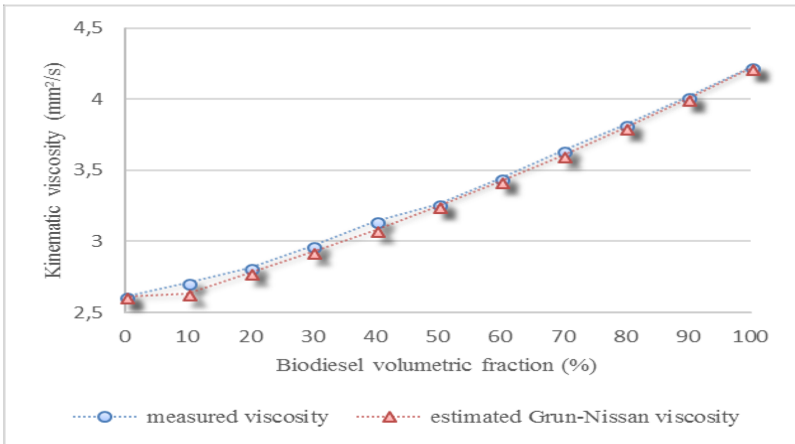

Fig.2. Kinematic viscosity variation with biodiesel fraction (measured and estimated)

Kinematic viscosity measurements have shown that:

- The B100 viscosity is full well within the EN 14214 specifications. Indeed, B100 viscosity is 4.22 mm²/s and the EN 14214 requires that it has a value between 3.5 and 5 mm²/s. the fossil diesel has a kinematic viscosity of 2.6 mm²/s. In this case of study, the viscosity of biodiesel is 1.6 times higher than of diesel at 40°C [18].
- Kinematic viscosity values of all tested blends were higher than of diesel; they were within 2.70 mm²/s and 4.01 mm²/s. As a matter of fact, the blend's kinematic viscosity was increasing with the biodiesel volume fraction. Regarding the close kinematic viscosity of B10 to diesel's, let's highlight that the diesel properties standard EN NF 590:2009 allows the blending of up to 7% fatty-acid methyl-ester (FAME) with conventional diesel.

Yet, despite the obvious effect of blending with mineral diesel in improving the viscous characteristic of biodiesel blends, it remains unsatisfactory as regards the substitution aim of fossil diesel by biodiesel which explains the aim of investigating implementing high pressured fuel injection.

3.1. Engine performance characteristics

The evaluation method for power correction was DIN 70020. This method indicates the reference atmospheric condition of pression and temperature P_0 and T_0. The correction factor *cf* used for measured data is as described in the equation (2):

$$C_f = \left(\frac{P}{P_0}\right) * \left(\frac{T_0}{T}\right)^{0.5} \quad (2)$$

where

- P_0: reference air pressure = 1.01325 bar.
- P: current air pressure during the measurements = 1.016 bar.
- T_0: reference temperature equal to 293 °K.
- T: current air temperature on the intake occurring during the measurements = 296.1°K.

The correction factor was then 0.998.

Figure 5 to Figure 7 respectively show the effect of varying injection pressure on power, torque and specific consumption of diesel fuel and WCOME blends. Furthermore, at a given injection pressure (200 bar, 220 bar, 240 bar, 260 bar and 280 bar), the effect of WCOME blends is respectively displayed in each of (a), (b), (c), (d) and (e) graphs.

The engine ran satisfactorily throughout the following batteries of tests: with the 200 bar, 220 bar, 240 bar and 260 bar IP. For these IPs, neither surfaces overheating, nor abnormal engine vibrations or noises were reported. But, during the last 280 bar IP test battery, and especially within the range of 2600 rpm and 4000 rpm, remarkable vibrations were noticed. A maximum of 23 % higher lubricant oil temperature was registered.

The Fig.5. (a) and the Fig.6. (a) graphs show that, at the original IP of 200 bar all tested WCOME blends offered reduced power and torque performance compared to baseline DF. The reported decrease of power achieved a maximum value of 3.6% as compared with DF. This can be attributed to biodiesel blend percentage properties such as the higher kinematic viscosity [18], the higher density, the lower volatility and the lower heating value compared to baseline diesel fuel (approximately 13% lower compared to DF as reported in [19]), which resulted in a poorer atomization compared to DF. Concerning the specific consumption, it increased along with the increase of WCOME concentration, which is plotted in Fig. 7(a). These results were in conformity with measurements obtained in [20].

The Fig. 5 (b) and the Fig. 6 (b) indicate that a 10% rise in IP value (from 200 bar to 220 bar) generated an overall rise in power and torque for both types of fuels: DF and WCOME blends. For baseline DF a 0.8 % rise in maximum power at 4000 rpm, and a 0.98 % rise in maximum torque at 2000 rpm were recorded. In the same way, for B20 a 0.2 % rise in power and a 0.86 % rise in torque; for B40, a 0.25 % rise in power and a 0.86 % rise in torque; for B60 a 0.22 % rise in power, and a 0.47 % rise in torque at the same mentioned speeds were recorded. But power performances of B20, B40 and B60 remained below DF's (Fig. 7(b)) describes a decrease in specific consumption for all tested fuels compared to 200 bar. At low rpms, specific consumption of B20 mildly matched the specific consumption of baseline DF. The positive impact on both power and torque which has been observed was attributable to the increasing of engine combustion efficiency with increased IP which, in turn, can be ascribed to better volumetric efficiency and atomization rate. The reduction of calorific value of test blends with increasing concentration of WCO biodiesel vis à vis baseline DF, made that the DF held the best performance characteristics.

When we increased IP further to 240 bar, power and torque performances found to be slightly increasing compared to IP 220 bar. Analyzing Fig. 5(b), Fig. 5(c), Fig. 6(b) and Fig. 6(c) leads to conclude that B20, under the IP of 220 bar as well as under the IP of 240 bar, in the range between 2200 rpm and 3200 rpm, offered optimal performances compared to DF, to B40 and to B60. In term of specific consumption, the Fig. 7(c) indicates that the IP of 240 bar was found to be optimum condition for B20.

The three first sets of experiments showed that the incrementation of IP assisted in reducing the high kinematic viscosity effects. As a matter a fact, high kinematic viscosity of the WCOME blends is held responsible for generating not only a smaller spray angle and poorer air entrainment, but also in lowering injection velocity, which itself is due to the increase of droplet size in the WCOME blends vis à vis DF's [19]. Increasing the IP up to 240 bar, had demonstrably improved the atomization process. The proper atomization led to a better fuel-air mixing assignable to finer spray droplets formation which is an asset unto itself, promoting higher performances combustion [23].

When we augment IP furthermore to attain 260 bar, power and torque performances were found to be dwindling for all fuels compared to those recorded at 240 bar IP. The trend followed by both power and torque (improvement with the IP incrementation), came to an end with the 260 bar IP.

Besides, at 280 bar, a sharp loss of power performance was reported not only for DF but also for B20, B40 and for B60. The decline was observed at low and high engine speeds. The 280 bar IP was accompanied with a considerable performance loss of 12% in power, 23% in torque and a significant increase in specific consumption especially at high rpms as plotted in the Fig. 7(e). This trend is observed due to the combined effect of the fuel injection duration shortened with rising IP and of the fuel spray characteristics deterioration because of higher fuel viscosity especially for higher concentrated WCOME fuels (B40 and B60). Indeed, higher volumetric percentage of WCOME in tested fuels causes atomization and mixing issues which offsets combustion improvement [21,22].

At the specific tested IP of 280 bar (Fig. 5(e), Fig. 6(e)), let's accentuate that the higher the volumetric proportion of WCOME is, the better performances were, and this, for all engine speeds. Among DF, B20, B40 and B60, the highest power and torque values were recorded when B60 was used.

In one hand, increasing the IP does also mean decreasing the ignition delay [21]. Too high injection pressure decreased the possibilities of homogeneous mixing and combustion efficiency [9], which was translated in a sharp loss of performances. But, in the other hand, in this case of study, the higher the proportion of BD is, the better the performances were at high injection pressure which was reflected in Fig. 5(e) and Fig. 6(e)

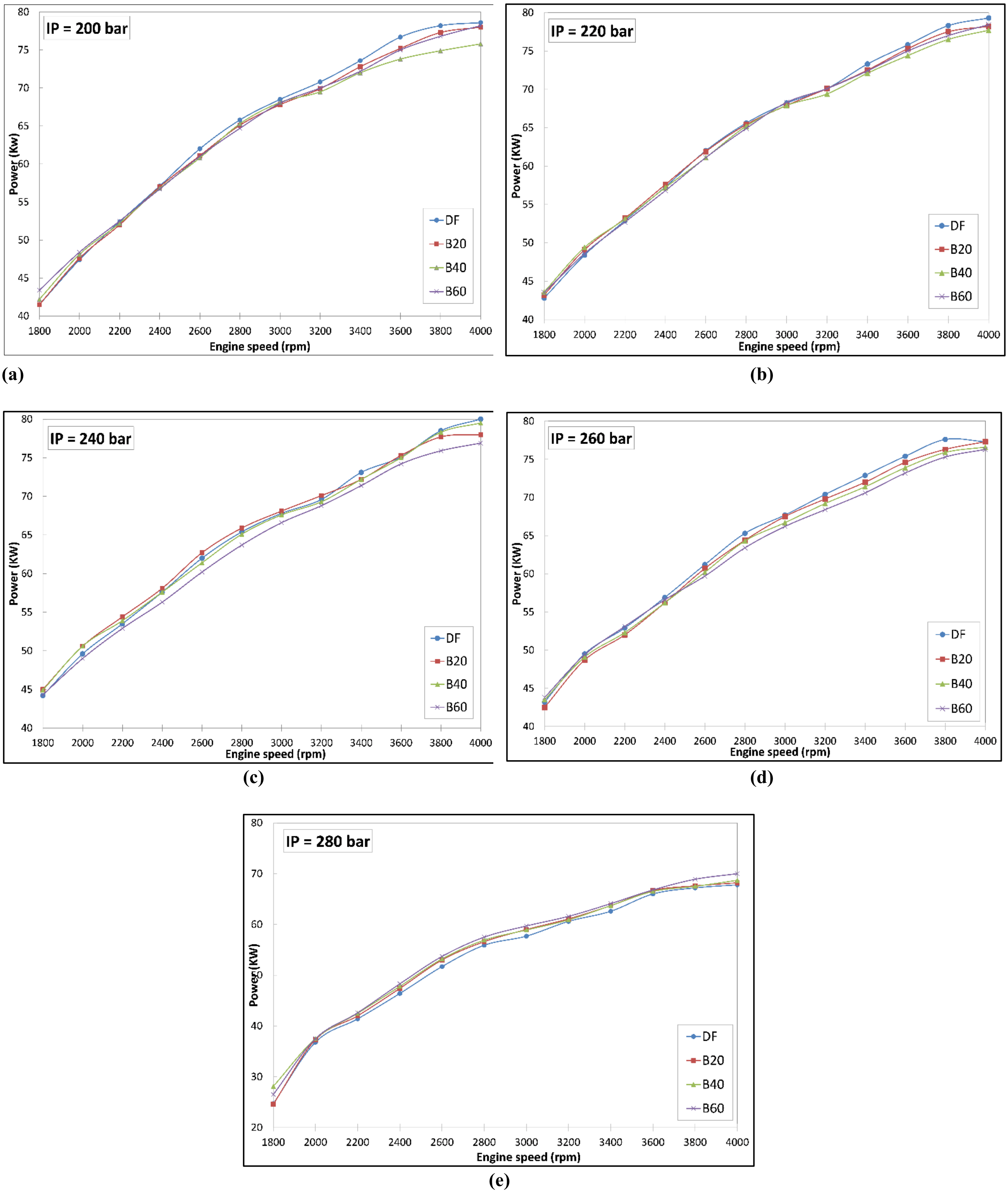

Fig.5. Power of DF and WCOME blends at different injection pressures

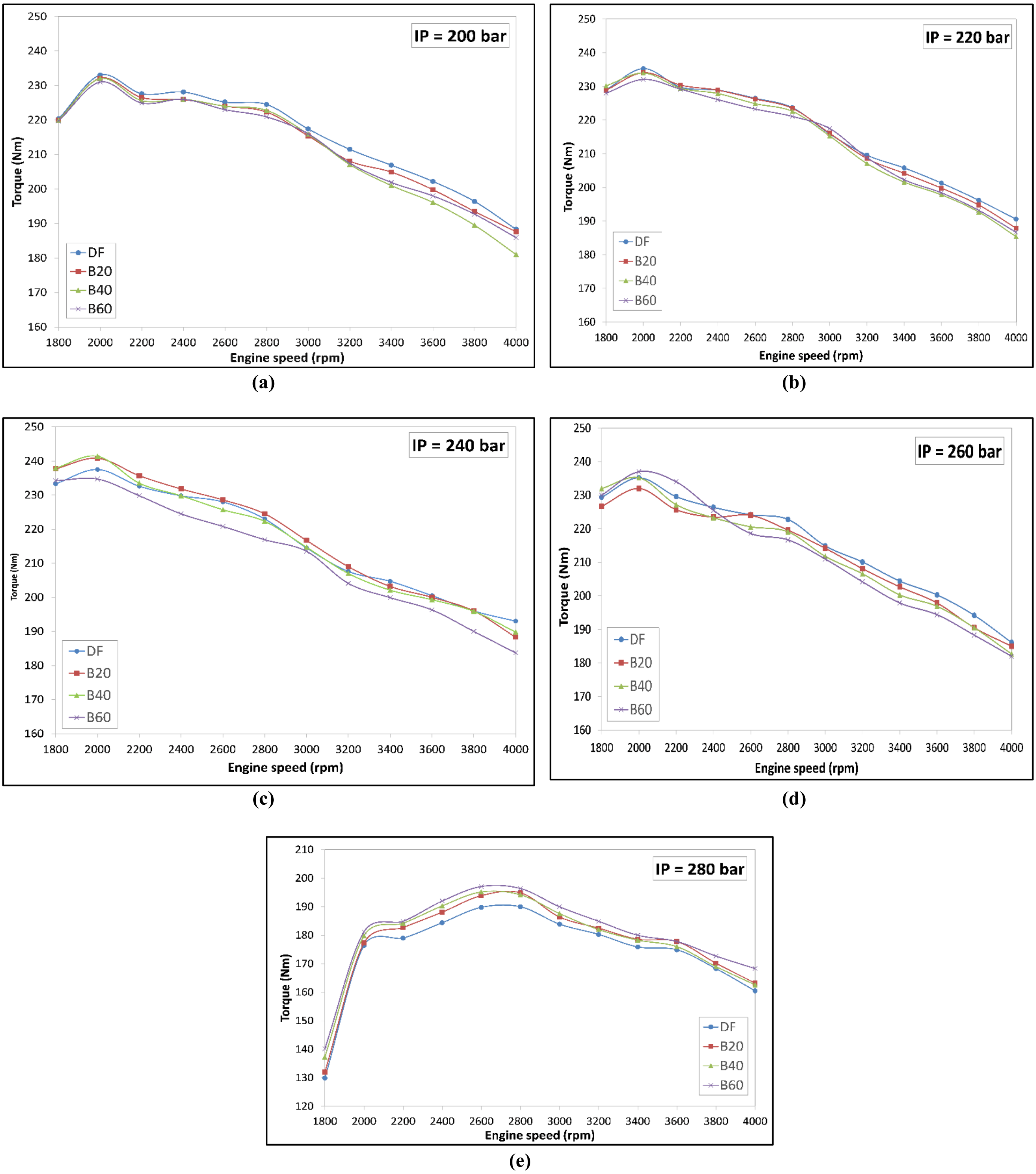

Fig.6. Torque of DF and WCOME blends at different injection pressures

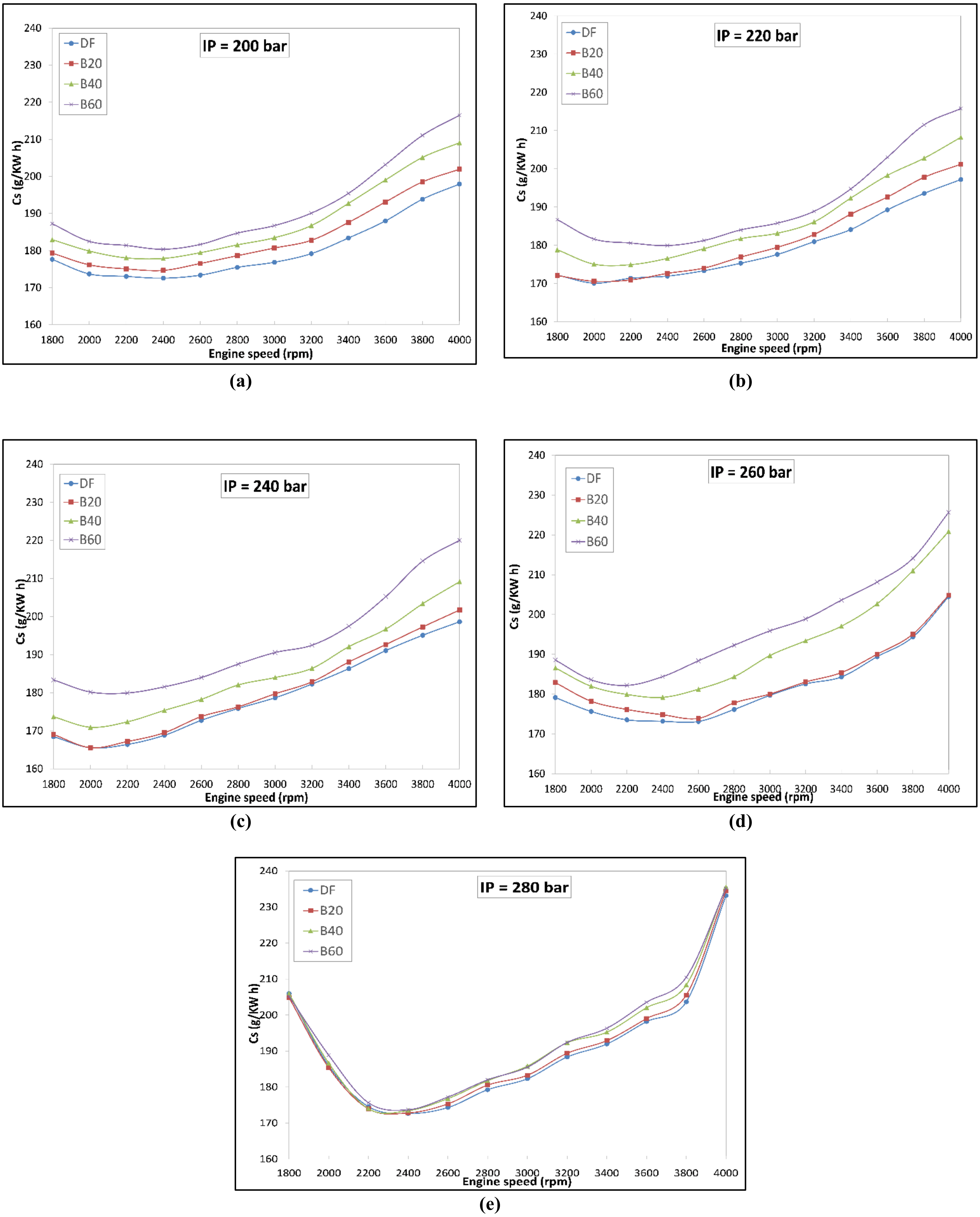

Fig.7. Specific consumption of DF and WCOME blends at different injection pressures

3.2. Smoke emission characteristics

Smoke formation results from unburned carbon in addition to polycyclic aromatic hydrocarbon [19,24]. The smoke emission variance with different fuel blends and injection pressures is plotted in Fig. 8.

- For DF: Implementing the IP of 10% had a positive impact on smoke discharged by the test engine while fueled with baseline DF. A decrease of 4.32% was registered compared with the original IP. But beyond 220 bar, smoke emissions levels increased [25].
- For B20: The overall optimum smoke opacity of 30.4% was obtained with 220 bar under B20. This can be attributed to the following factors. First, compared to baseline DF, the 20% volumetric BD contributed by its oxygen contents in the enhancement of the oxidation process of the injected fuel [26]. Second, raising IP up to 10% improved atomization as well as mixture formation process as a result, smoke emissions have reached the optimum level [19, 23].
- For B40 and B60: The important oxygen content could not perform its role properly in oxidation process and has been weakened under the high kinematic viscosity effect of both of B40 and B60. At all tested IPs, the smoke emissions of B40 and B60 were higher than those of DF. Indeed, even with aid of increased IP, the discharged smoke emissions have reached a non-conventional maximum of 85% for B60 at 280 bar IP.

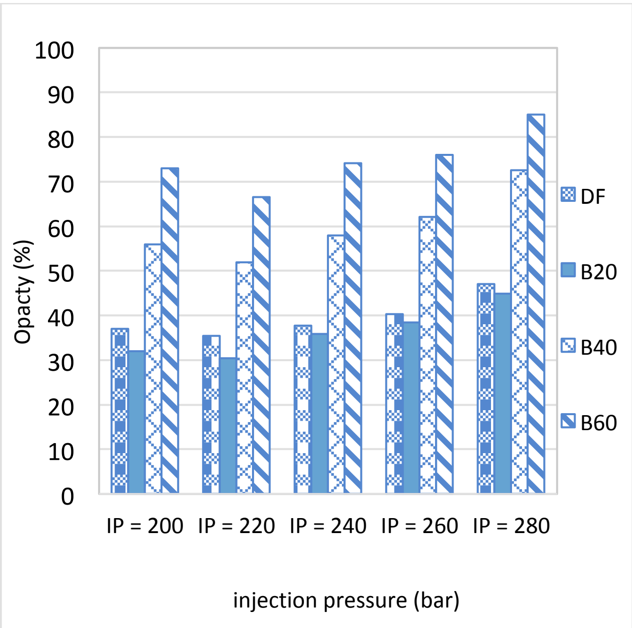

Fig.8. Variation of smoke emissions for different injection pressures

As displayed in Fig. 8., at 280 bar IP, significant opacity levels have been reached (they were acquired as 47.1% for DF, 44.9% for B20, 72.5% for B40, 85% for B60). When injection pressure became too high, ignition delay became shorter which interfered with achieving combustion properly [9].

4. Conclusions

Based on the results of the conducted experimental investigation, the following conclusions have been drawn:

- At the standard injection pressure of 200 bar, the test engine fueled by B20, B40 and B60 developed lower performances compared to DF. The specific consumption increased along with the increase of WCOME volumetric proportion.
- A 10% increase in IP, from 200 bar to 220 bar, generated an overall rise in power and torque for both types of fuels: DF and WCOME blends. But power performances of B20, B40 and B60 remained below DF's.
- A 20% increase in IP, from 200 bar to 240 bar, power performances found to be slightly increasing. The proper atomization led to a better combustion and higher performances. When we increased IP further to 240 bar, power and torque performances found to be slightly increasing compared to IP 220 bar.
- B20 under the IP of 220 bar as well as under the IP 240 bar, in the range between 2200 rpm and 3200 rpm, offered optimal performances compared to DF, to B40 and to B60. In term of specific consumption, the IP of 240 bar was found to be optimum condition for B20.
- At 260 bar, power and torque performances were found to be dwindling compared to those recorded at 240 bar.
- At 280 bar, a sharp loss of power performance was reported for DF, B20, B40 and for B60. But at this IP, the higher the proportion of WCOME in the blend was, the better power and torque performances were.
- Regarding smoke emission characteristics, the effectiveness of implementing high pressured fuel injection in decreasing opacity of WCOME blends is related to the proportion of WCOME in the blend. Furthermore, B20 showed the best smoke emissions level at the IP of 220 bar.
- Increasing the injection pressure has proven its worth but has had limits. Too high IP engendered a disruption in combustion parameters. This disruption was reflected by a sharp decrease in power performance, an increase in specific consumption and by significant opacity levels. The effectiveness of higher IP can be further assisted if associated to an advance in SOI time. Indeed, increasing IP effectiveness can be enhanced if linked with a longer injection delay. Combining these two factors may optimize the combustion process of WCOME even if used in important mixing ratios.

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