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Trilateral correlation of spray characteristics, combustion parameters, and deposit formation in the injector hole of a diesel engine running on preheated Jatropha oil and fossil diesel fuel

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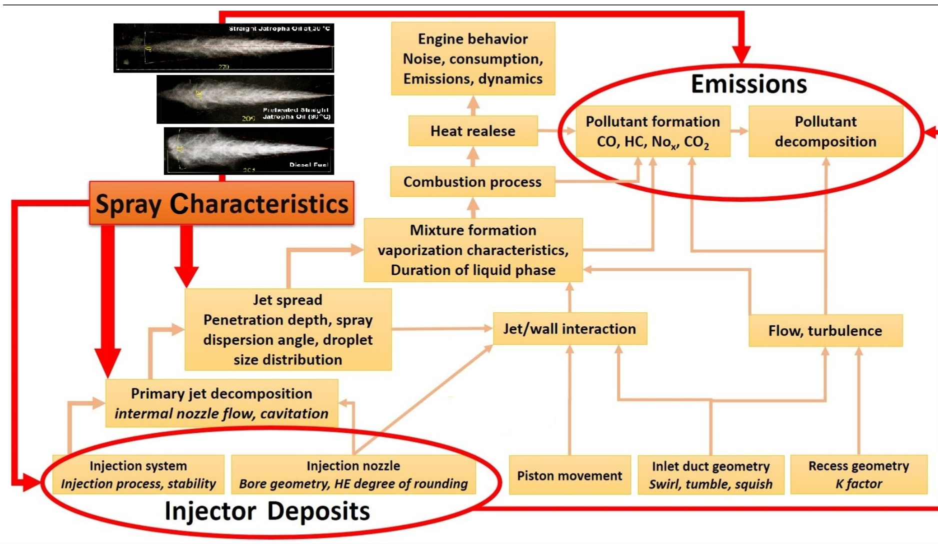
HIGHLIGHTS

- ➢Preheated and unpreheated straight Jatropha oil, and fossil diesel fuel were experimentally compared.
- ➢Spray characteristics, i.e., cone angle and penetration length were investigated.
- ➢Thermal efficiency and emission parameters were tested at 0 h and after 300 h of engine operation.
- ➢Trilateral correlation of spray characteristics, combustion parameters, and deposit accumulation in injector orifices was analyzed.
- ➢Unpreheated straight Jatropha oil cannot be recommended for long term use in diesel engines.

GRAPHICAL ABSTRACT



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ABSTRACT

The long term use of pure vegetable oil in diesel engines should be thoroughly evaluated from different perspectives including engine performance, deposit formation, etc. to ensure its compatibility. In line with that, the trilateral correlation of spray characteristics, combustion parameters, and deposit formation in the injector hole of a high-speed, 4-stroke, direct injection diesel engine fueled with pure Jatropha oil and diesel fuel (DF) was studied. Jatropha oil was investigated at room temperature 30 ºC (SJO30) and in preheated form at 90 ºC (PSJO90). The experimental tests were conducted in two phases: (i)- investigation of the spray characteristics of the fuels including cone angle and penetration length at 200 bar of injection pressure, (ii)- investigation of the combustion characteristics (i.e., thermal efficiency and engine emissions) and deposits formation in the injector hole of the diesel engine at 0 h and 300 h of operation. The results obtained showed large differences between the spray characteristics of SJO30 and the other fuels investigated. Moreover, this fuel led to significant reductions in NOx emissions (14.69-20.30%) and thermal efficiency (3.04-4.41%) but large increases in CO emissions (26.36-77.57%), HC emissions (48.98-77.85%), and smoke (58.43-131.71%). It also resulted in huge deposits formed in the injector hole after 300 h of the endurance test compared to DF and PSJO90 as revealed by optical observations using scanning electron microscopy analysis. Overall and compared to DF, SJO30 cannot be recommended for long term use in diesel engines while preheating or in better words, PSJO90 may only be considered as an alternative fuel in the short term.

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Abbreviations

BSFC	Brake specific fuel consumption
CN	Cetane number
CP	Cloud point
DF	Diesel fuel
HC	Unburnt hydrocarbon
HHV	Higher heating value
LHV	Lower heating value
L_l	Length of liquid
L_f	Flame lift-off
M	Fuel mas
NO_x	Nitrogen oxide
PAH	Polycyclic aromatic hydrocarbon
PM	Particulate matter
PSJO	Preheated straight Jatropha oil
SEM	Scanning electron microscope
SJO	Straight Jatropha oil
η_e	Thermal efficiency

1. Introduction

Growing environmental pollution and the consequent impacts on human health necessitate more dedicated efforts to increase the market share of non/less polluting alternative fuels in the transportation sector. This becomes even more important given the exponential expansion of the transportation means and the resultant per capita energy consumption since the industrial revolution (Hoang, 2018a; Kumar et al., 2018). In line with that, green energy carriers including biofuels or environmentally friendly processes/innovations such as waste heat recovery, exhaust treatment technology, and hybrid engines have been considered as strategies to address these challenges (Demirbas, 2017; Hoang, 2018b; Littlejohns et al., 2018). Biofuels could not only play an important part in satisfying the stringent emissions regulations but also could meet the energy and technical requirements of the existing engines (Cazarolli et al., 2016; Rajaeifar et al., 2017; Hoang and Pham, 2018a).

Among various types of biofueks, bio-oils have received a considerable deal of attention mainly due to the availability of feedstocks (Olarte et al., 2016; Rogers and Zheng, 2016). Moreover, straight vegetable oils` heat content and cetane number are insignificantly lower than those of traditional diesel fuel and they are therefore suitable for use in unmodified diesel engines (Manchanda et al., 2018). However, higher molecular mass resulting in higher density, and higher molecular-linking force leading to higher surface tension and kinematic viscosity compared to traditional diesel fuel are considered as the main cause of low volatilization, poor atomization, heterogeneous mixture, and incomplete combustion, which could adversly affect engine performance and the formation of deposits on the surface of components of the combustion chamber (Salehi Jouzani et al., 2018; Pham et al., 2018). Observations of the deposit formation on the injector (noses, needle, and holes), the combustion chamber wall, cylinder head, and the piston (crown and groove) under certain operating conditions of diesel engines fueled with vegetable oils were reported in numerous studies (Satyanarayana and Muraleedharan, 2012; Hoang and Pham, 2018b). More specifically, deposits are initially formed on injector noses because injector noses are indicated as the lowest-temperature region of the combustion chamber. The intensity of the formed deposits on injector noses is strongly affected by injector configuration, diesel engine type, vegetable oil quality, and how the straight vegetable oils are used. As reported in the published literature, vegetable oils supplemented by additives or preheated showed lower deposits formation than the cases of no-additives or without being preheated (Hoang and Pham, 2019).

There are many hypotheses trying to explain the formation of deposits on the basis of the physicochemical properties of vegetable oils. Reddy et al. (2016) experimentally evaluated the influence of Karanja and Jatropha oil-based fuels on deposit formation and weight loss (due to the wear) on some critical components of fuel injection equipment of a diesel engine such as plunger, nozzle, needle, and valve holder, at 7.4 kW of rated power and 1500 rpm during 250 h of operation. The increase in wear and deposits for the above-mentioned components of the test diesel engine fueled with Karanja and Jatropha oil-based fuels were reported. In another study, Li et al. (2010) set out to study the impact of using vegetable oil on fuel injector deposits. An in-line Perkins Phaser 180Ti diesel engine with 6 cylinders was used. Even short periods of the diesel engine operation running on vegetable oil were associated with significant changes in emissions as well as deposit formation around the injector tip (approx. 400 µm thick deposits formed in the nozzle holes). Similar results were also reported by D'Alessandro et al. (2016) and Barker et al. (2011). Such high deposits formation by vegetable oils could be attributed to their high viscosity resulting in large cone angle and high spray penetration. Such adverse spray characteristics along with their triglycerides content could cause the adhesion of unburnt substances onto the injector parts (Hoang and Le, 2019).

It should also be noted that deposits could result in changes in the shape of the injector as well such as reduction of injector hole diameter and fuel mass as well as reduction of the injector`s capacity of heat transfer (Birgel et al., 2012; Lefebvre and Mcdonell, 2017). These could consequently lead to power loss, reduction of thermal efficiency, and increases in emissions. In a study by Rakopoulos et al. (2014), operation of a high-speed direct injection diesel engine fueled with vegetable oil resulted in power loss, reduction of thermal efficiency, and increased CO, HC, and soot emissions. On the contrary, complete oxidation products such as CO_2 and NO_2 were decreased. Similar changes in emissions in response to the application of vegetable oil were documented by other studies as well (Pipitone and Costanza, 2018).

Obviously, deposit formation in the injector could be a key link in the core correlation of various parameters including fuel properties, spray characteristics, vaporization and mixing, as well as combustion and engine performance. In line with that, more in-depth insights into the interwoven relationship among spray characteristic, deposit formation on the injector, and emission parameters of diesel engines fueled with vegetable oil need to be acquired. Therefore, this study was aimed at evaluating the fuel spray characteristics, deposit formation on the injector, and its impacts on brake specific fuel consumption (BSFC), thermal efficiency, and emissions of a diesel engine after long-term engine operation, i.e., 300 h.

2. Materials and Methods

2.1. Materials

In this experimental work, non-edible straight Jatropha oil (SJO), extracted from *Jatropha curcas L.* seed available in Vietnam was used. The oil was provided by Minh Hoang Gia Lai Corporation, whereas diesel fuel was provided by Petrovietnam group. **Table 1** presenta the physicochemical properties of Jatropha oil and diesel fuel (DF).

Table 1.
Physicochemical properties of Jatropha oil and diesel fuel at 30 ºC.

Properties	Unit	ASTM standard	Fuels	
			Jatropha oil	Diesel fuel
Density	g/cm^3	D1298	0.911	0.850
Kinematic viscosity	mm^2/s	D445	31.4	3.2
Surface tension	mN/m	D971	30.6	25.8
Flash point	ºC	D 93	229	71
Cetane number		D 976	41	45
Higher heating value	MJ/kg	D 240	40	46
Ash content	%	D482-91	0.002 – 0.03	0.006 – 0.1
Carbon mass	%	E777 - 17a	73 – 77.6	83.5 - 87
Hydrogen mass	%	E777 - 17a	11.6 – 12.3	11.5 - 14
Oxygen mass	%	D7607M - 11e1	10.8 – 12.5	0

It can be clearly seen from **Table 1**, cetane number (CN) and higher heating value (HHV) of Jatropha oil were approximately 10% lower than those of DF. On the contrary, three physical properties of Jatropha oil including density, kinematic viscosity, and surface tension were much

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higher than those of DF. The presence of oxygen could be regarded as a highlighted advantage of Jatropha oil compared to DF.

2.2. Fuel processing and fuel types

Heating method was considered to improve the disadvantages associated with the application of Jatropha oil, such as high density, high kinematic viscosity, and surface tension. More specifically, Jatropha oil was preheated by electrical energy and a thermal sensor was used to control the heating temperature. The density, kinematic viscosity, and surface tension of Jatropha oil were respectively 0.854 g/cm^3, 3.5 mm^2/s, and 26.2 mN/m after preheating at 90°C in comparison with 0.850 g/cm^3, 3.2 mm^2/s, and 25.8 mN/m recorded for for DF at room temperature (i.e, 30 °C). Thus, the above-mentioned preheating temperature value (i.e., 90 °C) was used to process SJO (PSJO90). To evaluate thoroughly, different fuel types, i.e., SJO at room temperature (SJO30), PSJO90, and DF were used in the diesel engine experiments.

Moreover, the thermal efficiency (η_e) of the investigated diesel engine was calculated *via* lower heating value (LHV, kJ/kg) or HHV (kJ/kg) as well as BSFC (g/kW.h) following **Equation 1** (Hoang and Nguyen, 2017):

$$\eta_e = \frac{N_e}{1000.(M).(LHV)} = \frac{3600}{(BSFC).(LHV)} = \frac{3600}{(BSFC).(HHV-3.052)} \quad \text{Eq. 1}$$

where N_e stands for rated power (kW) and M denotes mass flowrate (kg/h).

3. Experimental setup and analytical procedures

A high-speed direct injection Yanmar TF120M diesel engine was used in the experiments. The technical specifications of the engine is tabulated in **Table 2**.

Table 2.
Technical specifications of the high-speed, direct injection, 4-stroke, 4 -cylinder, cooled-water Yanmar TF120M diesel engine used in this study.

Technical parameters		Description
Displacement		638.1 cm^3
Bore/ Stroke		92mm × 96mm
Compression ratio		17.7:1
Rated power		7.8 kW at 2400 rpm
Injection	timing	11.5 degree BTDC
	pressure	200 bar
	hole diameter	0.26 mm
	angle	150 degree

The analytical procedures used were as follows:

- Spray characteristics of the fuels were determined under the ambient temperature and pressure by the assistance of a mechanical system that coupled with a high-speed Sony A9 camera and a heating system. Sony A9 is a Mirrorless camera with a sensor 24MP Full Frame, a shutter speed of 20fps (frames/s), a well-matched autofocus system with 693-point phase-detection covering 93% of the image area, and a 3.686 m-dot resolution. A mechanical fuel injector with a delivery valve opening under a pressure of 200 bar (equal to the injection pressure of the Yanmar TF120M diesel engine) was used. The spray characteristics were investigated at room temperature (30 °C) for both Jatropha oil and DF, and at 90 °C for Jatropha oil. The schematic presentation of the test setup used for this purpose is presented in **Figure1**.

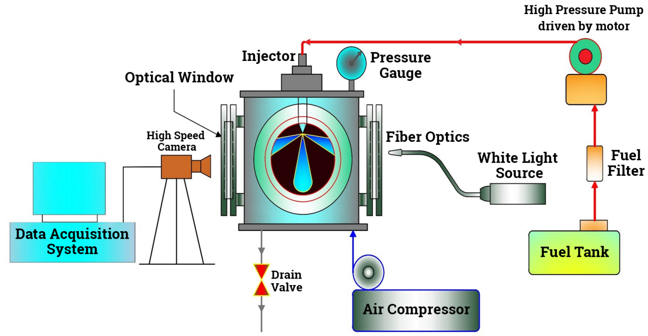

Fig. 1. Schematic presentation of the experimental setup used to test fuel spray characteristics.

- BSFC and emission parameters were measured at 100% load and at different engine speeds of 1200, 1400, 1600, 1700, 1800, 2000, 2200, and 2400 rpm. These measurements were conducted at the first hour (0 h) and at 300 h of operating time. The diagram of the experimental setup used to carry out the engine tests and the instruments used are shown in **Figure 2** and **Table 3**, respectively. The emission characteristics were recorded by a CEB-II cabinet exhaust gas analyzer. The accuracy of the measurements including emissions (HC, CO, NOx, and smoke) are presented in **Table 4**.

Table 3.
Instruments used in the engine tests.

Parameters	Speed (rpm)	BSFC (%)	Emissions			
			HC (ppm)	CO (ppm)	NO_x (ppm)	Smoke (%)
Accuracy	± 5	± 2	± 1	± 3	± 5	± 0.1

Table 4.
Accuracy of the measurements.

Instrumentation	Working parameter
Electric brake, APA100	Rated power 200kW
Cooling device, AVL553	Electric and Pneumatic
Cooling lubrication oil, AVL554	Electric and Pneumatic
Fuel controller, THA100	Automatic
Fuel balance, 733S	Sensor
Combustion Emission Bench, CEB-II	Automatic

- Deposit accumulation measurements in the injector were carried out after 300 h of engine operation at 2400 rpm of engine speed. Deposits in the injector were examined with the assistance of Scanning Electron Microscopy (SEM). The results are averages of three times of measurement.

4. Results and Discussion

4.1. Spray characteristics

Spray characteristics including cone angle and penetration length are considered as the key parameters affecting the combustion process

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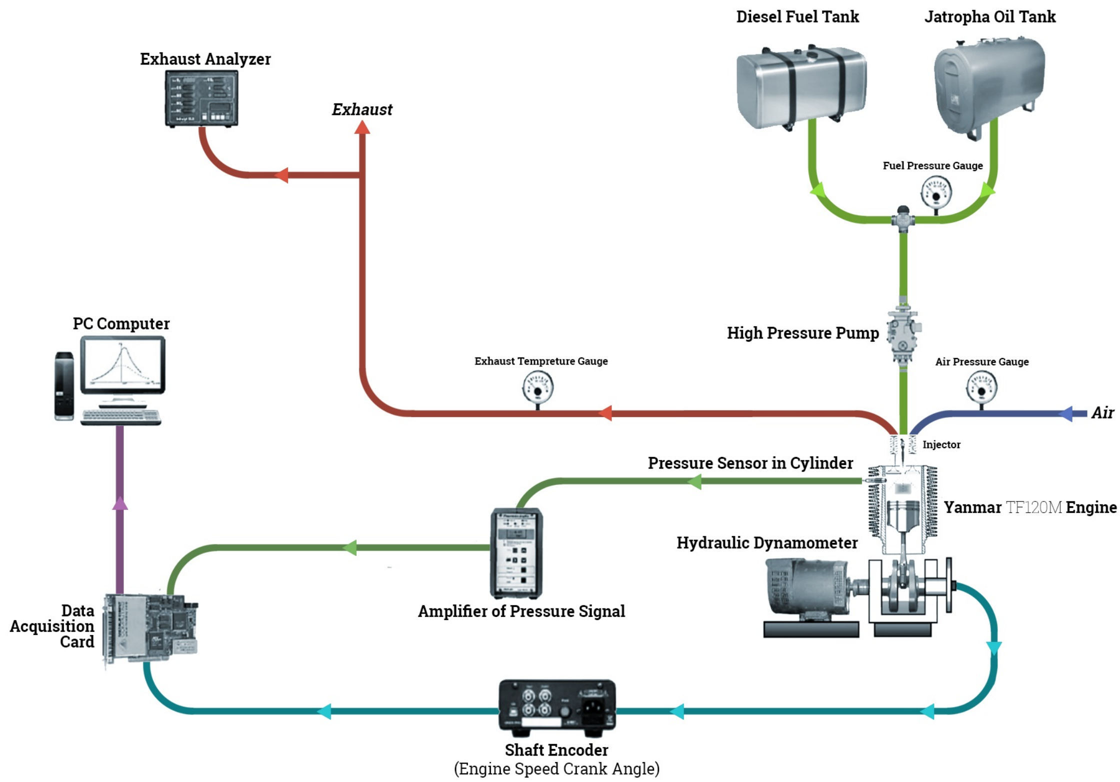

Fig. 2. Experimental Yanmar TF120M diesel engine setup used in the present study.

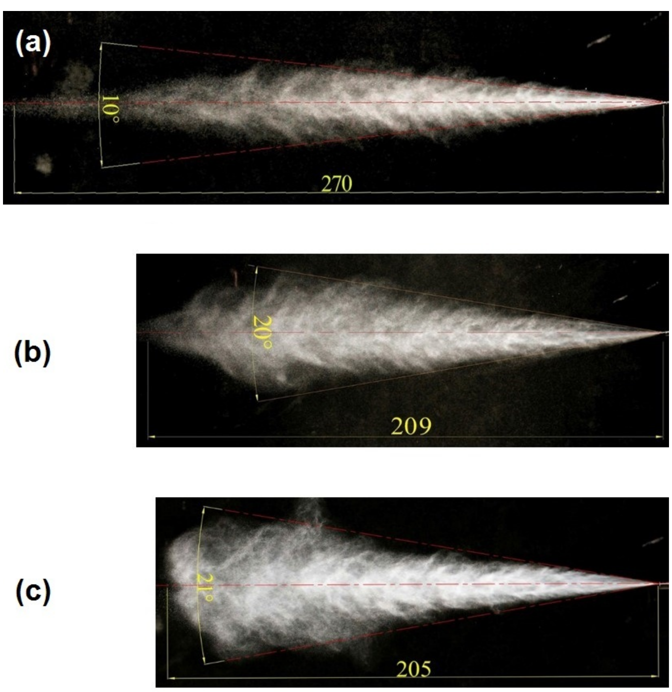

Fig. 3. Spray characteristics of various fuels tested; (a) straight Jatropha oil at 30 ºC (SJO30), (b) straight Jatropha oil at 90 ºC (PSJO90), and (c) diesel fuel (DF).

primarily. On this basis, injection strategies aiming at obtaining maximal energy output from the combustion process of fuel-air mixtures must be controlled and improved so that the emissions produced as well as the deposits formed would be minimized. The spray characteristics of SJO30, PSJO90, and DF at 30 ºC are shown in **Figure 3**.

Jatropha oil has a higher density, kinematic viscosity, and higher surface tension compared to DF at the same temperature of 30 ºC. It can be seen clearly from **Figure 3** that at 30 ºC, cone angle for Jatropha oil was small, corresponding to 10 degrees compared to 21 degrees for DF (**Figs. 3a** and **c**). On the contrary, the penetration length for Jatropha oil at 30 ºC was large, corresponding to 270 mm, compared to 205 mm for DF (**Figs. 3a** and **c**). However, by increasing the heating temperature to 90 ºC, the reduction of density, kinematic viscosity, and surface tension of Jatropha oil led to similar spray characteristics between Jatropha oil and DF. As a result, the cone angle for Jatropha oil increased by 10 to 20 degrees while the penetration length was reduced by 60 mm degree reaching 209 mm (**Fig. 3b**). Overall, insignificant differences were observed between PSJO90 and DF in terms of cone angle and penetration length.

The influence of fuel spray characteristics on fuel-air mixture formation and its combustion characteristics has been reported in the published literature (Lefebvre et al., 2017). Following the commencement of the fuel injection process, fuel droplets are promptly introduced into the combustion chamber where they tend to break into smaller droplets owing to high temperatures, high pressures, and the air disturbance during fuel injection. The distribution of fuel droplet size is much influenced by the above-mentioned three properties of the fuel, i.e., density, kinematic viscosity, and surface tension. In the case of fuels with low kinematic viscosity and density, the intra-molecular force called Van-der-Waals forces is small and the low surface tension results in increasing evaporation rates and consequently, shorter times for breakup and mixing (Deshmukh et al., 2012). Compared to PSJO90 and DF, the kinematic viscosity of SJO30 was around 10 times higher, while its density and surface tension were 10.72% and 11.86% higher, respectively. Therefore, there was insufficient time for the vaporization process of SJO30. In fact, in the case of Yanmar TF120M diesel engine with 11.5º BTDC of injection timing, the time for the piston moving to TDC is around 790 µs at 2400 rpm of engine speed. Such short time would not be sufficient for SJO30 droplets with such high viscosity and surface tension to turn into vapor completely. Thus, a poor mixture of SJO30 vapor and air would be created. Moreover, injection velocity of SJO30 fuel must have decreased due to its high viscosity and fuel mass for similar volume of fuel injected at each time of injection must have increased due to its high density. Based on the theory proposed by Lefebvre et al. (2017), low injection velocity, as in the case of SJO30, could lead to a low Reynolds number and a high Ohnesorge number. Thus, the Rayleigh regime in fuel spray characteristics must have occured in case of SJO30. The primary breakup process based on the Rayleigh regime produce fuel droplets of large sizes (Deshmukh et al., 2012). As reported by Baumgarten (2006), the primary breakup process plays an extremely important role in the evaporation, mixing, and combustion processes of fuels. Different mechanisms for primary breakup process of fuel generating fuel droplets are presented in **Figure 4** (Som and Aggarwal, 2010).

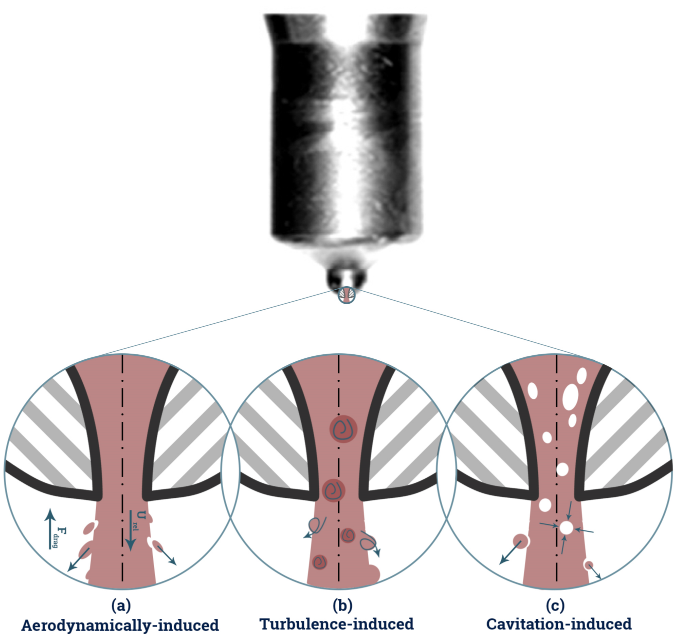

Fig. 4. Schematic presentation of different mechanisms for primary breakup process of fuel and the generation of fuel droplets: (a) aerodynamically induced, (b) turbulence induced, and (c) cavitation induced. Adopted from Som and Aggarwal (2010).

As shown in **Figure 4a** (aerodynamically-induced), it can be understood that the aerodynamically-induced breakup process occurs if the linking force among fuel molecules is so great that the turbulence of air in the combustion chamber and the turbulence of liquid fuel passing through the injector holes are not large enough to break the fuel droplets. In the case of SJO30, very high kinematic viscosity as well high surface tension and density must have resulted in difficulties in break-up and evaporation of fuel particles under such engine conditions. Thus, most of the SJO30 droplets must have been generated aerodynamically following fuel injection and hitting the cylinder wall surface while some must have been generated through turbulence (**Fig. 4b**). As a result, large amounts of SJO30 droplets could not be burnt or were only burnt outside the surface layer rather than the core of the droplets. This could be considered as the main cause of the increase in deposits and unburnt emissions, the reduction of thermal efficiency which will be presented and discussed in the subsequent sections. On the contrary, after being preheated, PSJO90 properties such as kinematic viscosity, surface tension, and density seem to be similar to those of DF. Thus, PSJO90 cavitation-based atomization must have occured similar to DF. Cavitation pattern or the formation of bubbles inside the injector hole takes place when the hydrostatic pressure in an area of the fuel flow is decreased below the vapor pressure. Normally, cavitation bubbles can reach the exit of the injector hole and are near the wall of the injector hole because the pressure inside the bubbles is much lower than that around the emerging fuel-jet (**Fig. 4c**). Because of the above-mentioned pressure differences, cavitation bubbles are collapsed gradually due to the internal fuel-jet turbulence. Thanks to the implosion of cavitation bubbles, jet atomization is enhanced. In this case, the basic assumption is that cavitation bubbles are either burst at the periphery or collapsed due to the turbulence velocity inside the liquid.

As reported by Som et al. (2010) and Shervani-Tabar et al. (2012), the cavitation time-scale depends much on the fuel vapor pressure and density as well as injector configuration. An inverse proportional relationship between the cavitation time scale and fuel vapor pressure and density has been shown in those studies. In a recent study, the utilization of the cavitation mechanism as an injection strategy to improve fuel-air mixture quality was investigated (Hoang and Le, 2019). As shown in **Figure 3**, PSJO90 and DF were effectively turned into vapor after leaving the injector. These results demonstrated the remarkable effects of fuel properties on its spray characteristics. These effects were also reported by previous publications (Mohan et al., 2013; Shameer and Ramesh, 2018).

It is evident that the combination of high injection-pressure and small diameters of injector holes may provide better characteristics including spray characteristics, air entrainment, fuel-air mixing, as well as the homogeneity of the mixture with reasonable fuel-air equivalence ratios. There would be thus fewer over-rich fuel regions. In a study by Hoang and Le (2019), the important effects of injector configuration and diameter of the injector hole on fuel spray and atomization were reported. They showed that a transfigured injector hole (e.g., much deposit) could cause negative impacts reducing spray angles and particle sizes and consequently, increasing spray tip penetrations. As a result, the interwoven interaction between spray characteristics and injector configuration should be taken into account seriously. In better words, any factors affecting injector configuration, could also affect fuel spray characteristics.

4.2. Deposits in the injector hole

After 300 h of engine operation using DF, SJO30, and PSJO90, the diesel engine was partly dissembled to screen the level of accumulated deposits in the injector holes using SEM. The SEM micrograph of the clean injector hole (at 0 h) is shown in **Figure 5a** while the injector holes after 300 h of operation for DF, SJO30, and PSJO90 are presented in **Figures 5b**, **5c**, and **5d**, respectively.

It can be clearly seen from **Figure 5** that deposit accumulation in the injector hole in case of using SJO30 was much higher than when the engine was fueled by DF and PSJO90. Higher temperatures around the injector tips are considered as notable characteristics of advanced diesel injection systems which may also result in the formation of stubborn deposits in the area of the injector tips (Hoang and Le, 2019). Moreover, deposits formation was increased substantially by using PSJO90 in comparison with DF. Compared to the deposits associated with the utilization of SJO30 and PSJO90 (**Figs. 5c** and **5d**, respectively), the deposits formed in response to the usage of DF (**Fig. 5b**) were uniformly formed with a thick layer of carbon. The dimension of the injector hole for DF was around 0.004 mm smaller than that of the clean injector hole, revealing that the accumulation of deposits around the injector tips would not significantly interfere with the injector holes.

Normally, under high temperatures, the decomposition of hydrocarbons or compounds containing carbon, the main compositional element of fuels, and/or polymerization or condensation process or conversion of hydrocarbon components into larger polycyclic aromatic hydrocarbons (PAHs) (which are then nucleated and grown), are considered as two mechanisms leading to the formation of carbonaceous deposits. As discussed earlier in *Section 4.1*, higher kinematic viscosity, density, and surface tension of SJO30 resulted in lower volatility of this fuel, consequently leading to poor atomization and the formation of fuel-rich mixture with larger-sized fuel droplets during the fuel injection process into the combustion chamber. Fuel droplet size and fuel concentration could affect ignition delay strongly. Fuels with higher kinematic viscosity values are associated with longer ignition delays as it takes them more time to turn into vapor. Owing to this reason, deposit formation rate for fuels with higher kinematic viscosity values tends to increase. Furthermore, vegetable

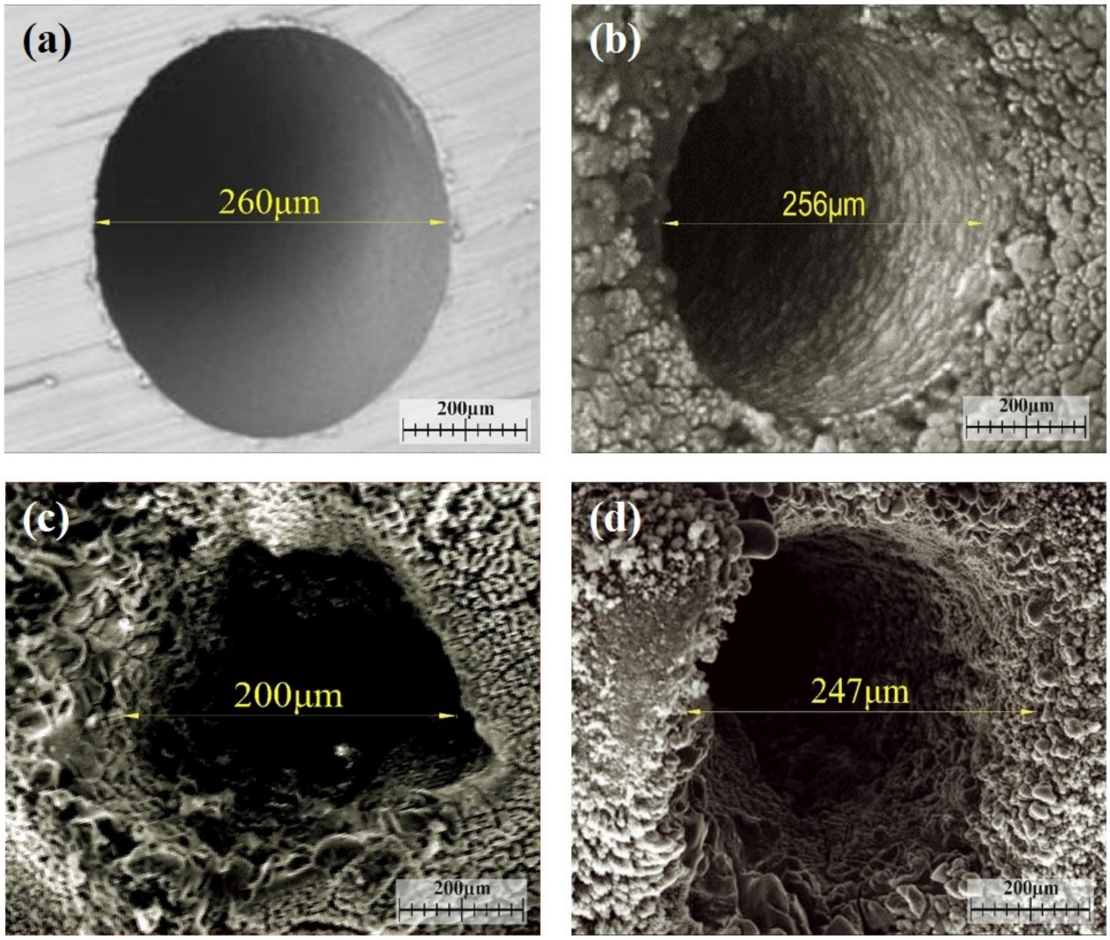

Fig. 5. SEM micrographs of the deposits formed in the injector hole; (a) clean injector hole at 0 h, (b) injector hole at 300 h for DF, (c) injector hole at 300 h for SJO30, and (d) injector hole at 300 h for PSJO90.

oils are usually decomposed at higher temperatures, hence, the possibility of vegetable oils decomposition or conversion into sticky and unburned components during the ignition delay period should be considered as a cause of deposits generation in injector tips and holes.

Deposits formed through the combustion of vegetable oils and their derivatives, i.e., biodiesel, include volatile substances, high boiling point substances, oxidizing substances, carbonization substances, and residual ashes (Liaquat et al., 2013). In addition, the higher iodine value of vegetable oils (resulting from the presence of unsaturated compounds) compared to DF, is also believed to be a contributing parameter to a longer ignition delay (Hoang and Pham, 2018b). Therefore, it could be concluded that there is a cohere relationship between fuel properties and spray characteristics and consequently deposit formation in the injector. The small cone angle and high penetration length for Jatropha oil may have increased the focusing degree of fuel droplets per certain area, reduced the evaporation rate, and fuel injection velocity. These could imply that many fuel droplets must have come into contact with the high-temperature air in the combustion chamber, forming deposits. Low injection velocity could result in retaining a proportion of the vegetable oil volume in the injector. Moreover, high fuel concentration, the molecular mass of fatty acids contained in the vegetable oil, and the sticky properties of the oil are the main factors causing increased deposit formation in the injector as well as an increased metal concentration in the deposits due to the corrosive nature of fatty acids to metallic parts.

In addition, it can be clearly seen from the data presented in **Table 1** that the flash point temperature of Jatropha oil was above 3 times higher than that of DF, whereas cetane number and heat content of Jatropha oil were lower than those of DF. The above-mentioned characteristics of Jatropha oil at room temperature (30 ºC) could be considered as the essence of increasing deposits formation in the injector in the diesel engine running on SJO30. On the contrary, deposit formation in the injector of the diesel engine fueled with PSJO90 (**Fig. 5d**) tended to decrease compared to SJO30, the degree of accumulated deposits in case of PSJO90 was insignificantly higher than that of DF. In another word, the diameter of the injector hole was decreased by 0.013 mm for PSJO90 while this value stood at 0.06mm for SJO30. Besides, the diameter of the injector hole for SJO30 seemed to be disfigured. Based on the diameter of the injector hole, deposits formation using SJO30 was around 5 times and 15 times higher than when using PSJP90 and DF, respectively. The reduction in deposits accumulation for PSJO90 could be ascrobed to the fact that the density, kinematic viscosity, and surface tension of PSJO90 were similar to those of DF, although the molecular mass of PSJO was unchanged in response to preheating and was higher than that of DF. Similar results were also reported by other studies (Birgel et al., 2012; Hazar and Sevinc, 2019).

4.3. Combustion characteristics

As presented earlier in *Section 4.1*, the cavitation and turbulence mechanisms in the process of fuel primary breakup are associated with increased atomization rate, resulting in smaller penetration lengths. This

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implies that evaporation, the formation of a homogeneous fuel-air mixture, ignition and combustion processes are strongly affected by the primary breakup. In an experimental study by Higgins and Siebers (2001), the influences of the length of liquid (L_l) and flame lift-off (L_f) on the primary breakup and the combustion process were investigated. Accordingly, the interaction between L_l and L_f plays an important role in combustion efficiency, thermal efficiency, and emissions of diesel engines. For $L_f > L_l$, the fuel evaporation process terminates before the beginning of the combustion process and the establishment of fuel-rich flames is induced. In this case, fuel would be burnt incompletely leading to an increase in deposits formation and emissions due to lack of oxygen. On the other hand, a two-way coupling between vaporization and combustion occurs in case of $L_f < L_l$, therefore, the temperature of the combustion process decreases because of the enhancement of fuel evaporation under high temperatures. The reduction of flame temperature is reported as the main reason resulting in moving the flame stabilization location to downstream, and an increase in L_f can be clearly seen. Obviously, along with the increase in pressure and temperature in the combustion chamber, the density of the ambient increases, causing a decrease in the injection velocity of liquid fuel at the injector exit. Due to this reason, the flame stabilization location moves to upstream, leading to an increase in deposits formation at low-temperature regions (Som et al., 2010). Besides, oxygen concentration could also strongly affect flame structure and combustion efficiency, and it thus could affect thermal efficiency and emissions. Consequently, the engine could achieve high thermal efficiency and low emissions with high volatility of fuel, sufficient oxygen component, proper fuel properties, and neither rich nor lean mixtures.

4.3.1. Thermal efficiency

Thermal efficiency is a parameter characterizing the effectiveness of the combustion process. Normally, a complete combustion is associated with a high thermal efficiency. Based on **Equation 1**, thermal efficiency is critically dependent on BSFC. The thermal efficiency values of the investigated diesel engine fueled with SJO30 and PSJO90 are compared to that of DF in **Figure 6**.

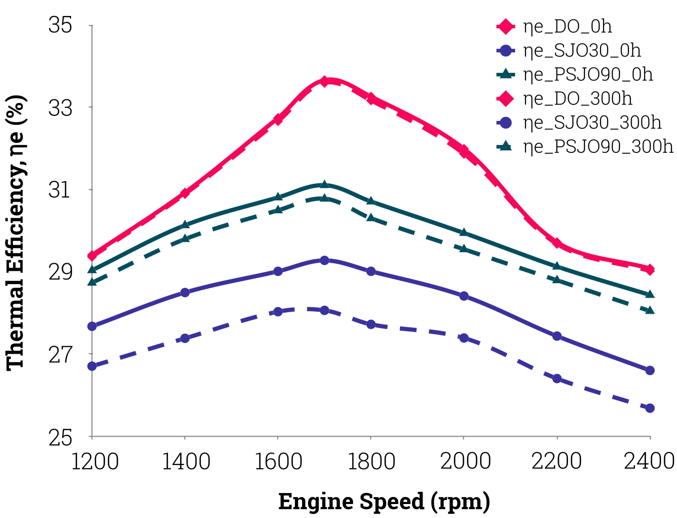

Fig. 6. The thermal efficiency of the engine running on different fuels at 0 h and after 300 h of engine operation.

Based on the data presented in **Figure 6**, thermal efficiency was generally reduced for all the invesigated fuels. However, this reduction was insignificant for DF after 300h of engine operation, i.e., only 0.38% compared to 0 h. While the maximum reduction of thermal efficiency for PSJO90 after 300 h of operation stood at 1.37% *vs.* 4.41% for SJO30. The reduction of thermal efficiency could be ascribed to the increase in BSFC and reduction of combustion efficiency. Although Jatropha oil was preheated to a suitable temperature to obtain similar spray characteristics, its lower heat content and cetane number compared to those of DF could be considered as the main reasons contributing to the lower thermal efficiency recorded. Due to this reason, more fuel was injected into the combustion chamber to maintain the power, as a result, BSFC for Jatropha oil was higher than that of DF. On the other hand, deposits built-up inside the injector nozzle, on/outside the injector tip led to adverse and negative impacts on the BSFC and the performance of diesel engine. The deposits formed mostly inside the injector hole was the main reason resulting in the reduction of fuel flow rate (Hoang and Le, 2019). These findings were in agreement with those presented in **Figure 5** revealing reductions in the hole diameter of the injector. Meanwhile, fuel injection pressure was maintained, resulting in a reduction in cone angle and an increase in penetration length of the fuel spray. As a result, fuel concentration was limitted to a small area on the piston crown and fuel was burned incompletely in the combustion chamber. The reduction of thermal efficiency could be considered as the main factor causing power losses because after all, thermal efficiency and engine power are the final outputs characterizing the combustion process. Similar results on thermal efficiency were reported in the studies conducted by Ozsezen (2012) and Acharya et al. (2014b).

4.3.2. Exhaust emissions

The combustion process in diesel engines occurs at the temperature when fuel-air mixture is ignited under suitable conditions in the combustion chamber. The aim of the combustion process shown in **Figure 7** is to decompose the hydrocarbon components of the fuel and convert them into complete combustion products. Hydrocarbon peroxide radicals (-ROOH) are considered as the initial products of fuel decomposition. These radicals are generated by breaking down the alkane molecules through the dehydrogenation process. In the subsequent chemical reactions, radicals such as H•, O•, and OH• are produced in the disintegration process of fuels. Subsequently, some light hydrocarbons including alkenes (C_2H_4, C_3H_6) and alkines (C_2H_2) along with aldehydes are formed by the chain propagators. Following the oxidation process, intermediate substances are converted into final products. Normally, around 10% of the heat content is discharged for the formation of aldehyde substances while around 40% of the heat content is discharged in the oxidation reactions to genertae CO and the oxidation process of CO into CO_2 releases the reamaining heat content of approximately 45%.

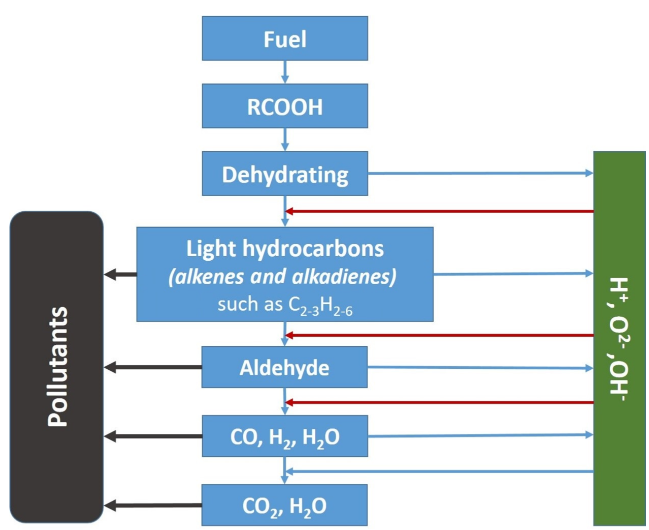

Fig. 7. Schematic presentation of fuel combustion and emissions formation.

As shown in **Figure 7**, it can be seen that oxygenated fuels or added oxygen in the combustion process could facilitate the complete oxidation

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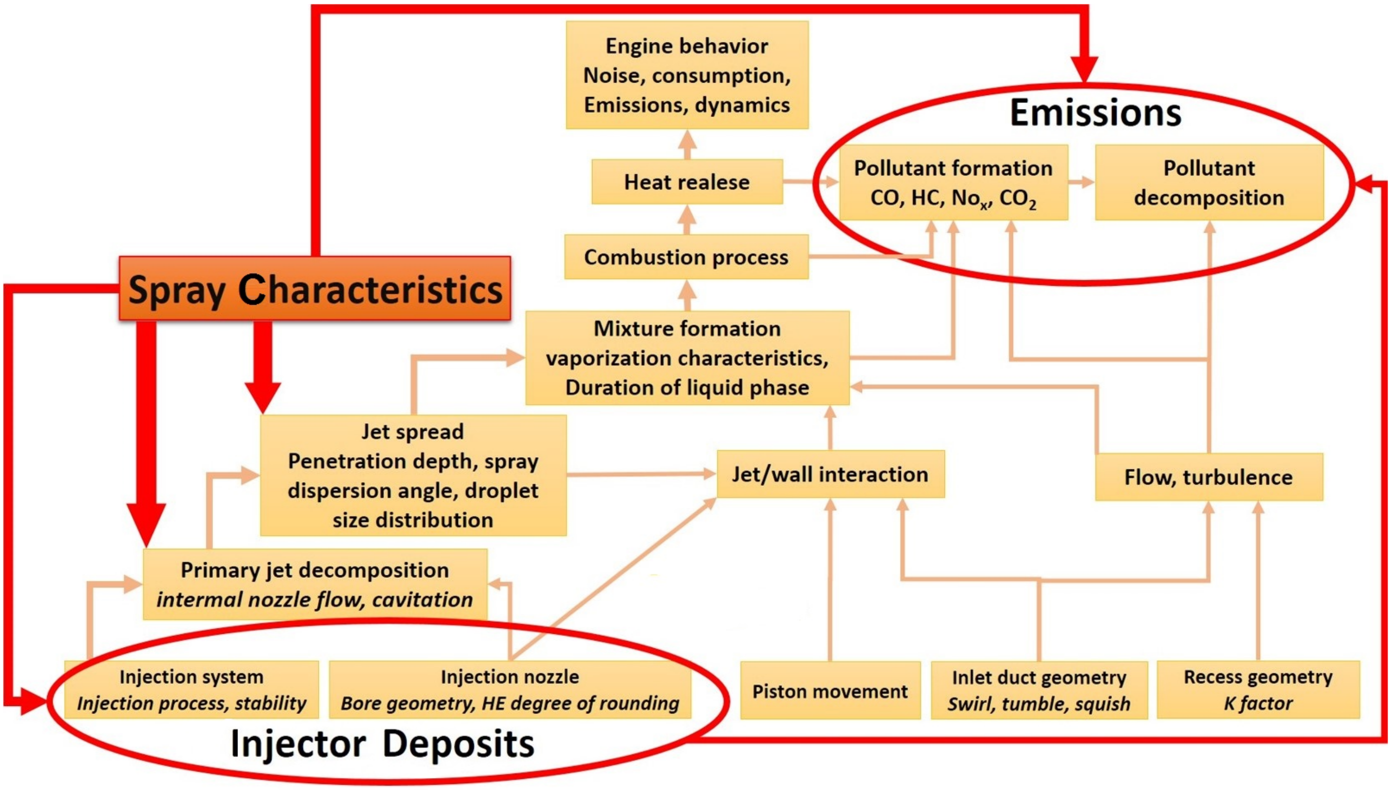

Fig. 8. Schematic presentation of the relationship among spray characteristics, breakup mechanism, and emissions formation.

and conversion CO into CO_2. As a result, much of the released energy could be used for improving and enhancing thermal efficiency and engine power as well as for reducing pollutants (Chen et al., 2019). The relationship among spray characteristics, breakup mechanism, and emissions formation is illustrated in **Figure 8**.

Obviously, changes in emission characteristics, as shown **Figure 8**, highly depend on the combustion process of engines. Complete combustion generates more complete products such as CO_2 than incomplete products such as HC, CO; while, NOx emissions are strongly affected by the temperatures of the combustion process. In the combustion process, the fuel mass burnt in the premixed phase and mixing controlled phase is strongly affected by not only injector configuration and diesel engine design, but also by fuel type and operating conditions (such as engine speed and engine load). For example, since it is difficult to break fatty acids with long carbon-chains and double bonds or aromatic hydrocarbons, higher concentrations of these compounds lead to longer ignition delays.

On the other hand, when fuels are injected fast enough to mix with compressed air homogeneously and completely before occurring the auto-ignition process, the all mixture fuel-air burns rapidly in the premixed phase, creating a large change in the parameters characterizing the combustion efficiency such as high peak pressure, thermal efficiency, and emissions (Hoang et al., 2019). The emission characteristics of the investigated diesel engine fueled with SJO30, PSJO90, and DF are shown in **Figures 9a-d**. As show, there was an overall increasing tendency for HC, CO, and smoke emissions and a decreasing tendency for NO_x emissions *vs.* engine speed.

Carbon monoxide (CO) is produced in the exhaust of diesel engines in response to fuel-rich mixtures and lack of oxygen to convert all the carbon component into carbon dioxide (CO_2). The equivalence ratio of fuel-air is considered as the most important parameter directly affecting CO emissions. CO emission can be described based on the chemical reactions involved in the conversion C-O-H systems into CO through the interaction of C-O-H systems with H•, O•, and OH• (Hoang et al., 2019). As presented in **Figure 9a**, it can be observed that CO emissions associated with SJO30 combustion were 77.57% and 26.36% higher than those of DF and PSJO90 at 0 h. Interestingly, after 300 h of engine operation, changes in CO emissions for DF were insignificant while CO emissions associated with PSJO90 and SJO30 were considerably increased by 43.28% and 111.21%, respectively, compared to the values recorded at 0 h. The results of CO emissions were in agreement with those of thermal efficiency because a large amount of energy was released in the process of CO conversion into CO_2.

Unburned hydrocarbon (HC) emissions are considered as the result of the presence of unburned fuel in the exhaust gas components. There are around 10-20 major species and 100-200 minor species in hydrocarbon chain-based fuels. Most of the exhaust hydrocarbons detected are originated from the parent fuel but some of them are found with altered structures due to clearly-unknown chemical reactions in the cylinder of diesel engines. As a result, a reduction of thermal efficiency and an increase in pollutants are associated with an increase in HC emissions. Normally, HC emissions reach their highest values when diesel engines are started or are warmed up because of decreased vaporization and mixing rate as well as fuel oxidation under these conditions. It was reported by Cheng et al. (1993) that there are six mechanisms involved in increasing HC emissions including: (i) crevices, (ii) oil layers, (iii) deposits (fuel trapped or retained in the injector hole at the end of injection process), (iv) fuel and mixture (fuel-air mixtures so rich or so lean that cannot be ignited), (v) cylinder wall flame quenching, and (vi) the leakage of exhaust valve. Besides the amount of HC emissions caused by the crevice mechanism, fuel properties, lubricating oil degradation, and deposits have been shown to cause the largest amounts of total HC emissions.

As a result of the porous nature of the deposits as well as the smaller size of their pores than the quenching distance, flames are incapable of burning

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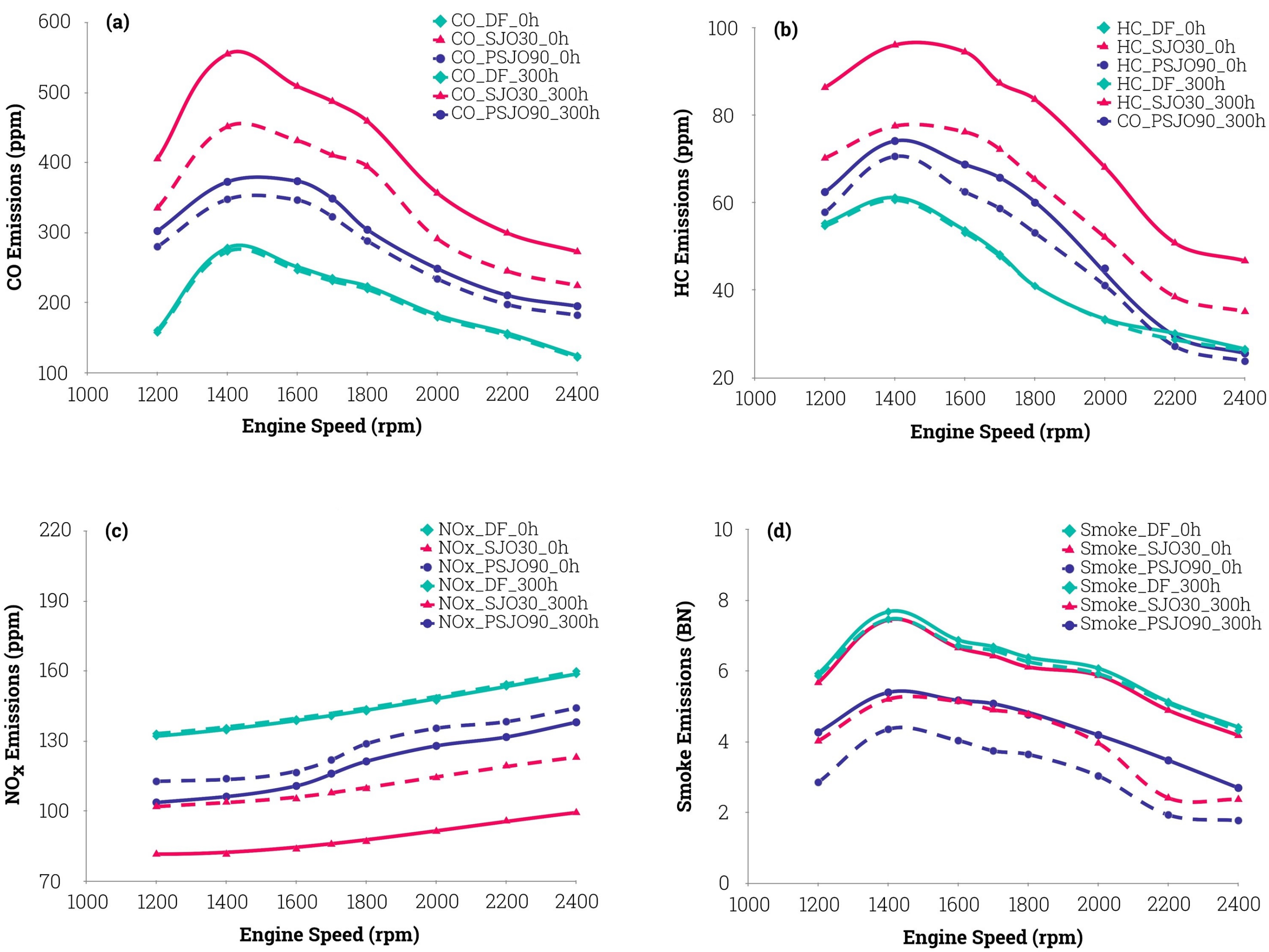

Fig. 9. Emission characteristics of the investigated diesel engine fueled with SJO30, PSJO90, and DF; (a) CO, (b) HC, (c) NO_x, and (d) smoke.

the residual fuel-air mixture (Hoang and Pham , 2018a). This residual fuel-air mixture is believed to come out of the pores in the expansion duration and blowdown duration. On the other hand, the reduction of cylinder gas temperatures and the consequent incomplete combustion reactions are among the reasons considered for increases in HC emissions from diesel engines. **Figure 9b** presents HC emissions of the tested fuels. At 0 h, HC emissions of the investigated diesel engine running on SJO30 was 41.98% and 26.95% higher than that of DF and PSJO90, respectively. After 300 h of engine operation, HC emissions of the diesel engine running on SJO30 and PSJO90 tended to increase significantly, while the HC emission associated with DF was mostly unchanged. HC emissions for SJO30 after 300 h of engine operation were 77.85% and 48.98% higher than those of DF and PSJO90, respectively. This could be attributed to the higher fuel mass injected due to the higher density of SJO30. Moreover, the dispersal area of SJO30 fuel spray was limited, and the penetration length was high due to its higher kinematic viscosity resulting in larger fuel droplets and consequently, in lower evaporation rate as well as the formation of a heterogeneous fuel-air mixture. In better words, when using SJO30, a fuel-rich mixture was produced and oxygen was insufficient to support a thorough burning process leading to increased CO and HC emissions. Nevertheless, as discussed earlier, the large amount of deposits formed in the injector after 300 h of engine operation and the resultant transfiguration of the injector and injector clogging could be regarded the main cause of the huge changes observed in CO and HC emissions of the engine fueled with SJO30. It should be noted that by using PSJO90 some fuel properties and fuel spray characteristics were much improved. However, some unfavorable fuel properties, i.e., lower cetane number, lower heating value, and lower volatility compared to DF, could be highlighted as the reasons contributing to its higher CO and HC emission than those of DF. The findings of the present study on CO and HC emissions were in agreement with those of the other studies published previously (Yilmaz and Morton, 2011; Acharya et al., 2014a).

Nitrogen oxide (NO_x) emissions are formed through the reaction of atomic oxygen and nitrogen under high temperature conditions existing in the combustion chamber. NO_x emissions produced during combustion depend largely on temperature and engine load. Normally, during the start of engine or warm-up process, NO_x emissions are relatively low (Hoang et al., 2018c). There are three reaction mechanisms used to explain the formation and production of NO_x during combustion, i.e., the Zeldovich mechanism (also known as thermal mechanism), the Fenimore (also known as prompt mechanism), and the intermediate mechanism for N_2O (nitrous

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oxide) formation. Nevertheless, the Zeldovich mechanism may be considered as the most significant one for internal combustion engines. After all, NO_x emissions are influenced by fuel properties, fuel-air mixture (fuel-rich or fuel-lean mixture), engine operation conditions, and combustion chamber design. **Figure 9c** shows the trend of NO_x emissions which were inversely proportional to those of HC and CO emissions. More specifically, NO_x emission tended to increase by increase engine speed. Based on the data presented in **Figure 9c**, it can be clearly comprehended that NO_x emissions of SJO30 were 23.42% and 12.31% lower than those of DF and PSJO90 at 0 h, respectively. This observation could be explained by the effects of fuel properties and fuel-air mixture on NO_x emissions. Obviously, DF with higher cetane number, higher heat content, higher volatility, and lower density led to higher combustion tempreture and consequently higher NO_x emissions compared to SJO30 and PSJO90. Similarly, the lower density of PSJO90 (*vs.* SJO30) led to less fuel mass injected and the formation of a more homogeneous fuel-air mixture. This in turn resulted in higher combustion temperatures for PSJO90 than for SJO30, leading to higher NO_x emissions. The results of NO_x emissions were in agreement with those of thermal efficiency as well as HC and CO emissions. After 300 h of operation, NO_x emissions for SJO30 and PSJO90 reduced remarkably by 20.30% and 5.61%, respectively, in comparison with the 0 h; while, NO_x emissions associated with DF were nearly unchanged. The reduction of NO_x emissions *vs.* time of engine operation, could be ascribed to decreased thermal efficiency and increased amounts of deposits, resulting in reduced combustion temperatures in the combustion chamber as previously reported by Rakopoulos et al. (2015) as well.

Smoke is generated in diesel engines due to heterogeneous combustion in diesel engines. Commonly, reduction in NO_x emissions is attributed to increases in PM and smoke emissions (Johnson et al., 2010). This is because reduction in NO_x emission is ascribed to decreases in the temperature of diffuse flames in the combustion chamber, resulting in a reduction of the amount of oxidized soot (Wang and Chung, 2016). Based on the data on smoke emissions depicted in **Figure 9d**, at 0 h, smoke emissions for DF were higher than those of SJO30 and PSJO90, which could be explained by the favorable impact of the oxygen contained in Jatropha oil (approx. 11%). In fact, smoke emissions of PSJO90 at 0 h were 48.48% and 29.96% lower than those of DF and SJO30, respectively. However, after 300 h of engine operation using SJO30, due to the huge amounts of deposits formed in the injector holes, some fuel might be trapped in the injector holes, leading to significant increases in smoke emissions. A similar trend was also observed for PSJO90 after 300 h of engine operation (**Figure 9d**). More specifically, smoke emissions for PSJO90 after 300 h of engine operation were 36.35% and 29.29% lower than those of DF and SJO30, respectively. These findings confirmed the remarkable impacts of oxygenated fuels in reducing smoke emissions. The results obatined in relation to smoke emissions were in agreement with previous reports such as that of Hoang and Nguyen (2017).

5. Conclusions

In this experimental study, the influences of DF, SJO30, and PSJO90 on spray characteristics, deposit formation in the injector, and emission characteristics of a high-speed 4-stroke diesel engine were investigated. The spray characteristics of SJO30 were much different from those of PSJO90 and DF. After 300 h of the endurance test, the amounts of deposits formed in the injector hole using SJO30 were considerably higher compared to PSJO90 and DF, transfiguring the injector hole. This consequently led to increased BSFC and reduced brake thermal efficiency for SJO30 compared to the other fuels investigated. On the other hand, SJO30 was associated with significant reductions in NOx emissions (14.69-20.30%) but large increases in CO emissions (26.36-77.57%), HC emissions (48.98-77.85%), and smoke (58.43-131.71%). In conclusion, SJO30 cannot be recommended for long-term use in diesel engines while preheating or in better words, PSJO90 may only be considered as an alternative fuel in the short term.

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